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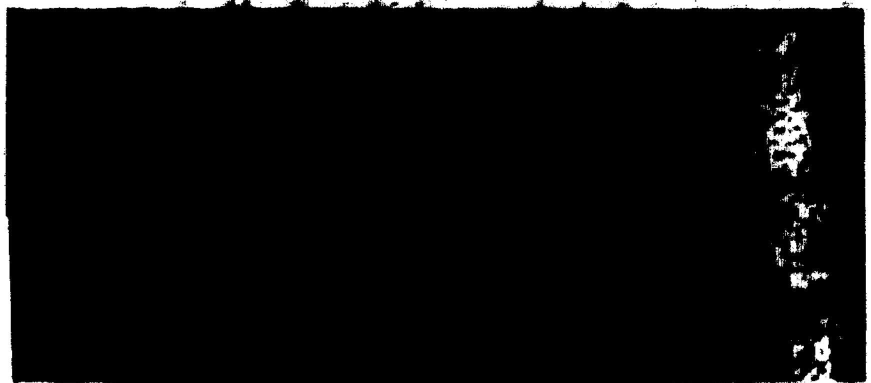

AGARD ADVISORY REPORT No.247

Integration of Externally Carried Weapon Systems with Military Helicopters

(L'Intégration des Systèmes d'Armes Transportés en Charge Externe sur les Hélicoptères Militaires)

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.247

Integration of Externally Carried Weapon Systems with Military Helicopters

(L'intégration des systèmes d'armes transportés en charge externe sur les hélicoptères militaires)

This Advisory Report was prepared at the request of the AGARD Flight Mechanics Panel.

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Preface

The helicopter is fast approaching a half century of service as a weapons system. From humble beginnings in World War II, largely in the roles of observation platforms and search and rescue vehicles, rotorcraft have evolved to a principal in the modern battle scenario. In the war at sea, the helicopter forms an integral part of a task force capable of launching devastating firepower at surface and subsurface targets. Aided by communications and data links, the helicopter effectively becomes the extended sensor of the task force itself. In the air-land battle, technology has made the helicopter into a tank killer, troop transport and night observation platform. Finally, in the most unlikely arena, air-to-air combat, modern weaponry has shown the helicopter to be effective against even high performance tactical aircraft. Certain weapons and tactics have permitted the exploitation of the helicopter's unique ability to point, or aim, rapidly.

Because of its low comparative cost, the helicopter now forms part of the arsenal of many nations. The rapid pace of weapons development is another dominant factor in this issue. Airframe modification programs and weapons kits have made high-technology weapons subsystems a part of older aircraft. In such cases, the system integration effort is sometimes reduced to "cut-and-try". At best, such an approach is inefficient, at worst it is unsafe. Even under ideal circumstances where a new helicopter design is being directed towards certain weapons capabilities, it is important that the weapons integration discipline be a mature part of the design process. An effort to understand and document the complexities of the integration of weapons on helicopters seemed in order and was proposed to the NATO AGARD Flight Mechanics Panel in September 1983, by Mr Peter R.Sully, of Canada, and Mr J.W.Britton, of the United Kingdom. As a result of their proposal, Working Group 15 was formed within the Flight Mechanics Panel with support from the Structures and Materials Panel.

Working Group 15 considered the range of interface problems that exist where weapon systems are mounted externally on helicopters. It was recognized at the outset that problems relative to electronic systems integration were as significant as aero-mechanical considerations. However, the Group's efforts were focused on the aero-mechanical aspects. This document is the final report of Working Group 15. The information contained herein resulted from detailed interrogatories presented to all helicopter manufacturers and related government laboratories in the NATO community. Extensive effort was put into the data searches to assure completeness. It became evident during this process that the convening of Working Group 15 was long overdue and that this report is probably the only compilation of the helicopter weapons integration experience base in existence.

The text of this report contains detailed discussions of the aero-mechanical aspects of helicopter weapons integration as well as a treatment of the purely structural considerations. In addition, operational issues and special problems are discussed. The text material is supplemented by three appendices. Appendix I is a synoptic table which relates each particular undesirable characteristic to various effects and results and, further, suggests solutions. Appendix I should serve as a guideline for any new helicopter weapons integration venture at the design stage. Appendix II is a listing of known helicopter weapons certification programs completed to date that have either produced experimental results or a fully qualified system. Thus, Appendix II should indicate a source of weapons or helicopter manufacturers which the reader could query directly. Appendix III is a compendium of case histories which are referred to by the text and which will serve to explain more fully the phenomena discussed therein.

Special thanks and appreciation are extended to Mr W.R.Lowry, V-22 Assistant Program Manager, Rotary Wing Aircraft Test Directorate, US Naval Air Test Center for his invaluable and energetic support in the development of Chapter III. Finally, the members of Working Group 15 listed below deserve special recognition for their dedication to the difficult and time consuming task of developing this publication. AGARD is fortunate to have had their service.

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Avant-Propos

L'Hélicoptère a bientôt un demi-siècle de service en tant que système d'armes. De ses origines modestes pendant la deuxième guerre mondiale où il a été déployé principalement comme plateforme d'observation et véhicule de recherche et de sauvetage, l'hélicoptère est devenu l'un des principaux acteurs dans le scénarios de conflit modernes.

Dans le cadre de la guerre maritime, l'hélicoptère fait partie intégrante d'un groupement tactique d'une puissance de feu dévastatrice contre des objectifs de surface ou immergées. Soutenu par des liaisons de transmissions et de données, l'hélicoptère devient, en effet, la plateforme de détection à distance du groupement tactique lui-même.

En ce qui concerne le combat aéroterrestre, les technologies modernes ont fait de l'hélicoptère un destructeur de char, un transport de troupes et une plateforme d'observation nocturne.

Enfin, dans un domaine des plus inattendu, c'est à dire le combat air-air, l'hélicoptère s'est montré efficace, même contre les avions tactiques à hautes performances, grâce aux systèmes d'armes modernes. Certaines armes et tactiques ont permis d'exploiter une particularité de l'hélicoptère: sa capacité à pointer ou à viser rapidement.

Aujourd'hui, en raison de son coût relativement modéré, l'hélicoptère fait partie de l'arsenal national de nombreux pays. La rapidité d'évolution des armes est un autre aspect important de cette question. Les programmes de modification de cellule et les systèmes d'armes particularisés ont permis l'integration de sous-systèmes d'armes de pointe dans des avions de la génération précédente. Dans de tels cas, l'intégration du système se résume parfois à une simple méthode empirique. Une telle démarche est au mieux, inefficace et au pire, dangéreuse. Même dans des circonstances qui peuvent être considérées comme idéales, c'est à dire où un nouvel hélicoptère est conçu pour un système d'armes bien spécifique, il faut s'assurer que les techniques d'intégration du système font partie de la méthode de conception.

Il semblait donc opportun d'entreprendre des travaux en vue de comprendre et de se documenter sur la complexité des différents aspects relatifs à l'integration des systèmes d'armes dans les hélicoptères, et ceci fut proposé par M. Peter Sully, du Canada, et M. J.W.Britton, du Royaume-Uni. Suite à leur proposition, le groupe de travail No.15 a été constitué au sein du Panel de la Mécanique du Vol.

Le groupe de travail No.15 a réfléchi à tous les aspects des problèmes d'interface qui se posent quand les systèmes d'armes sont montés "en externe" sur les hélicoptères.

Il a été admis dès le début de l'étude que les problèmes d'intégration de l'électronique étaient tout aussi importants que les considérations aéro-mécaniques. Ceci nonobstant, les efforts du groupe ont porté essentiellement sur les aspects aéro-mécaniques de la question.

Ce document est le dernier rapport établi par le groupe de travail No.15. Les informations qu'il contient sont issues de questionnaires détaillés, présentés à tous les fabricants d'hélicoptères et aux laboratoires d'état appropriés de la communauté de l'OTAN.

Des efforts considérables ont été faits lors des recherches de données pour assurer l'exhaustivité. Alors il est rapidement apparu que l'on aurait dû s'attaquer à ce problème il y a bien longtemps et que le présent rapport était probablement le seul compilation existante d'une base de connaissances dans le domaine de l'intégration des armes sur les hélicoptères.

Ce rapport comprend le texte intégral de discussions approfondies sur les aspects aéro-mécaniques de l'intégration hélicoptère des systèmes d'armes, ainsi qu'un exposé des considérations purement structurales. Le rapport traite également de questions opérationnelles et de certains problèmes spécifiques. Le texte est complété par trois annexes:

— L'Annexe I est un tableau récapitulatif qui donne la correspondance entre les caractéristiques néfastes et leurs effets, avec des propositions de solutions. Elle doit servir de guide au stade de la conception de tout projet d'intégration hélicoptère de système d'armes.

— L'Annexe II est un listing des programmes de certification des systèmes d'armes intégrés aux hélicoptères réalisés jusqu'à ce jour, et qui ont soit fourni des résultats expérimentaux soit débouché sur des systèmes homologués. Il s'ensuit que l'annexe II se devait d'inclure les références de fabricants d'hélicoptères ou de fabricants d'armes, afin de permettre au lecteur de les interroger directement.

— L'Annexe III est un condensé des exemples dont il est fait mention dans le texte et qui doit servir à mieux expliquer les differents phénomènes qui y sont discutés.

Je tiens à remercier tout particulièrement M. W.R.Lowry, le Chef de projet adjoint du V-22 du Rotary Wing Aircraft Test Directorate, US Naval Air Test Center, pour son soutien vigoureux et inestimable tout au long de l'élaboration du chapitre III. Enfin, je tiens à faire reconnaitre le dévouement des membres du groupe de travail No.15 dont la liste figure ci-après, qui ont assumé la tâche longue et difficile de la rédaction de la présente publication. L'AGARD doit s'estimer fier et heureux d'avoir pu bénéficier de leurs concours.

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Summary

This report contains detailed discussions of the aero-mechanical aspects of helicopter weapons integration. Particular emphasis is placed on flying qualities and performance with externally mounted weapons systems as well as weapons separation characteristics. In addition, structural mechanics topics, operational issues, and special problems are discussed. Each technical area is discussed in terms of analytic methodology, ground testing and flight testing procedures, instrumentation, and an assessment of the state-of-the-art, where possible. The text material is supplemented by three appendices. Appendix I is a synoptic table which relates each particular undesirable characteristic to various effects and results and, further, suggests solutions. Appendix I should serve as a guideline for any new helicopter weapons integration venture at the design stage. Appendix II is a listing of known helicopter weapons certification programs completed to date that have either produced experimental results or a fully qualified system. Thus, Appendix II should indicate a source of weapons or helicopter manufacturers which the reader could query directly. Appendix III is a compendium of case histories which are referred to by the text and which will serve to explain more fully the phenomena discussed therein.

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List of Abbreviations and Symbols

<u>ABBREVIATIONS</u>

A/C	- Aircraft
AH-1G	- Huey Cobra Mark G Helicopter
ASAS	- Atkins Structural Analysis System
CAS	- Control Augmentation System
CAS	- Calibrated Airspeed
CST	- Captive Store Trajectory
CG	- Center of Gravity
CFT	- Computer Flight Testing Program as developed by NLR
DTV	- Drop Test Vehicle
ERU	- Electromagnetic Release Unit
FPS	- Feet Per Second
FT	- Feet
IAS	- Indicated Airspeed
IFR	- Instrument Flight Rules
IGE	- In Ground Effect
HQ	- Handling Qualities
MACE	- Minimum Area Crutchless Ejector
MCEP	- Maneuver Criteria Evaluation Computer Program as developed by Bell Helicopter Textron
MBB	- Messerschmitt-Bolkow-Blohm GmbH
NASTRAN	- NASA Structural Analysis
NOE	- Nap-of-the-Earth
NLR	- National Aerospace Laboratory in The Netherlands
OGE	- Out of Ground Effect
RAE	- Royal Aeronautical Establishment in the United Kingdom
RAENEAR	- RAE Version of NEAR Store Trajectory Prediction Program
S80	- Simulation Computer Program as developed by AEROSPATIALE
S-N	- Stress-Number (of cycles to failure)
STAN	- Stability Analysis Computer Program as developed by MBB
TAS	- True Airspeed
T/R	- Tail Rotor
USAF	- United States Air Force
VSAERO	- Vortex Separation AEROdynamics Analysis Computer Program

<u>SYMBOLS</u>

CD	- Drag Coefficient
CL	- Lift Coefficient
CY	- Side Force Coefficient
C1	- Rolling Moment Coefficient
Cm	- Pitching Moment Coefficient
Cn	- Yawing Moment Coefficient
Cpc	- Climb Power Coefficient
CT (Ct)	- Rotor Thrust Coefficient
Cp	- Rotor Power Coefficient
d()/dt	- Derivative with Respect to Time
( )/ ( )	- Partial Derivative
g	- Gravity Constant
h	- Helicopter Height Above Ground Level
I	- Rotor Moment of Inertia
1n	- Neperian Logarithm
N	- Yaw to Sideslip Derivative (Weathercock Stability)
Np	- Yaw to Roll Derivative (Yaw/Roll Coupling)
Nr	- Yaw to Yaw Rate Derivative (Yaw Damping)
M	- Pitch to Incidence Derivative (Incidence Stability)
P_s	- Specific Excess Power
Pl	- Power Required in Level Flight
Pt	- Test Power
R	- Rotor Radius
Re	- REYNOLDS Number
Rs	- Specific Range
V	- Helicopter Flight Speed
V	- Freestream Velocity
Vh	- Helicopter Max Sustained Speed
V1r	- Speed for Long Range
Vmr	- Speed for Maximum Range
Wf	- Hourly Fuel Consumption
Y	- Position Along Rotor Axis System (origin at hub, positive starboard)
α	- Fuselage Angel of Incidence
β	- Fuselage Angle of Sideslip
η	- Climb Efficiency Factor

Λ - Rotor Advance Ratio
μ - Rotor Advance Ratio
σ - Ratio Total Rotor Blade to Rotor Disc Area (Solidity)
ρ - Air Density Ratio
$=$, ξ, τ - Damping Ratio of Oscillatory Modes
Ω - Rotor Speed

1.0 AERODYNAMICS AND FLIGHT MECHANICS

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1.1 INTRODUCTION

When installing external stores on helicopters, aerodynamic effects play an important role on flight behaviour and weapon system operation. To support the stores certification process, manufacturers have developed a large number of prediction methods applicable to aerodynamics and flight mechanics.

The purpose of this chapter is to survey these prediction methods, both analytical and experimental, which are currently used by manufacturers, and point out the main aerodynamic problems occurring on armed helicopters.

This chapter has been broken down into three sub-chapters:

- PERFORMANCE
- HANDLING QUALITIES
- STORE SEPARATION

Each of these sub-chapters is divided into parts related to categories of prediction methods, ie, analytical methods as well as wind tunnel and flight tests.

1.2 PERFORMANCE

1.2.1 GENERAL

Among the procuring agency requirements for a military helicopter, the performance characteristics play a role of particular importance.
The ability to hover and climb vertically in high altitudes and hot temperature conditions, to cruise at fast speed and to carry weapons at great distance are examples of the desired characteristics that the helicopter should have.

Besides the power available, aircraft and external weapon aerodynamic drag are the major factors of the overall performance capability.
Therefore, the best performing helicopter would be that one designed from the beginning expressly to carry the required weaponry either using wings as store carrier or integrating it aerodynamically into the fuselage.
But weapon systems are often required to be installed on already existing helicopters. In these cases, from performance point of view, great care should be used to minimize the aerodynamic penalties by designing streamlined supports and, in case, by adding fairings to the weapons.
Anyway, the influence of the external weapons on the performance has to be predicted or estimated at the beginning of the designing phase. Analythic methods and wind tunnel tests will provide useful data to define the final configuration and to calculate the estimated performance.

Finally, flight testing will permit the verification of the helicopter actual performance and the definition of the operational flight envelope limitations.
The data gathered in this last phase will be used to demonstrate compliance to the requirements and will be included into the Operator's Manual.

1.2.2 ANALYTICAL METHODS

1.2.2.1 GENERAL

When arming helicopters with external weapons, it is general practice to equip the aircraft with weapon systems which are already in use on or are derived from land based vehicles, or even from fixed-wing aircraft. Examples are anti-tank missiles, rockets and guns.

Concerning the aerodynamic aspects, three different situations can be considered:

- On already existing helicopters, the weapon system is installed in the same configuration as used on the land based vehicle, simply by bolting-on to the limited number of available hard points on the fuselage. This leads to complex weapon carrier structures. These support structures and the weapon system itself, in general have a bad aerodynamic shape.

- For already existing helicopters, the weapon carrier is redesigned and/or the helicopter is partially modified in order to minimize the aerodynamic penalties as much as possible. An example is the aerodynamically shaped rocket pod and stub wing of the Mi-24 Hind helicopter.

- Already in the design stage of the helicopter, the configuration is established that minimizes the performance degradation for the required weaponry. This can range from the relatively simple solution as the introduction of a wing with flaps as weapon carrier, to a weapon system aerodynamically integrated into the fuselage.

The installation of external weapons has the following effects on the performance of the helicopter:

- Reduction of the hover and climb performance, due to an increase of the download on the helicopter structure.
- Reduction of the maximum flight speed due to an increase of parasite drag.
- Reduction of the helicopter manoeuvrability due to the increased download and parasite drag.
- Reduction in flight endurance and range due to a decrease in the amount of available fuel.

Concerning flight mechanic performance, the two predominant parameters are the increased download on the helicopter structure and the increased parasite drag of the aircraft.

There will clearly be many situations for which the aerodynamic penalty due to the installation of external weapons has to be predicted or estimated. Analytical methods have considerable saving in time and cost benefits above experimental techniques. The disadvantage is the lower accuracy of the results in the current state-of-the-art techniques.

1.2.2.2 PERFORMANCE CALCULATION

Based on the physical dimensions of the aircraft (aerodynamic data such as rotor blade airfoil characteristics, fuselage drag, wing data, etc) and ambient conditions, the various power parts are calculated which contribute to the total power required. These are the main rotor induced and profile power, tail rotor power, helicopter parasite drag power, power losses due to equipment and transmission and climb power. A description of the calculation method and empirically derived coefficients and correction factors are described in a number of textbooks, eg, References I-1 and I-2.

The performance of the armed version is calculated with the same method as applied for the standard helicopter. The rotor power calculations are based on momentum theory and simple blade element theory. The rotor coefficients and other correction factors are identified from flight tests with the clean aircraft. For performance calculations, the influence of the weapon installation is expressed in a higher main rotor thrust and an increase in parasite drag. In general this method has proven to be reliable enough for performance predictions, provided that the increase in download and parasite drag due to the weapon installation can be determined with sufficient accuracy. There are manufacturers that use more sophisticated calculation models such as full trim calculation of the helicopter based on blade element theory with a non-uniform downwash distribution over the rotor disk.

Analytical estimations of the download and parasite drag are attractive for a first prediction of the helicopter performance in the process of finding an optimal solution for the weapon installation. More reliable predictions can only be made when more accurate data become available for the download and parasite drag from wind tunnel tests.

1.2.2.3 HOVER AND CLIMB PERFORMANCE

In the hover and at low forward speed the rotor downwash velocity creates a vertical force or download on the helicopter structure. In climb the flight speed contributes to this effect. So the rotor thrust must increase to compensate for the download. Adding external weapons to the basic clean helicopter will increase the download on the helicopter by a certain amount and so an increase in rotor thrust for the same helicopter weight is needed. The extra download is particularly high when large stub wings are mounted on the fuselage, eg, as weapon carrier.

The extra fuselage download can be calculated by combining the estimated vertical drag coefficient of the weapon installation with the downwash distribution based on analytical predictions (Reference I-3) or preferably on wind tunnel testing.

The simplest method for the estimation of the drag coefficient is to use data given in Reference I-4. However the accuracy of this method is limited by the difficulty of estimating the interference effects between the basic airframe and the weapon installation, the weapon carrier and between the various components of the installation. If wind tunnel test results are available for similarly shaped installations, corrections can be estimated for the interference effects.

More advanced airflow computational methods, such as the three dimensional panel methods seem hardly usable for download predictions due to the large wake created by the weapon carrier or other upstream components.

1.2.2.4 FORWARD FLIGHT PERFORMANCE

The maximum flight speed depends to a large extent on the amount of parasite drag of the aircraft. This drag is composed of the drag of the basic aircraft and an addition from the weapon installation.

At high forward speeds the rotor wake skew angle is very large and in many cases the weapon system can be assumed to be outside the rotor wake.

The simplest way to estimate the parasite drag coefficient of the armed helicopter is by using published aerodynamic drag data and the method as described for the hover performance, taking into account the angle of attack of the fuselage at that particular flight speed (typically between 0 and -5 degrees at maximum flight speed, depending on the type of helicopter). This angle is derived from the fuselage pitch angle and the deflection of the undisturbed airflow due to the presence of the main rotor wake. As a result of the assumption that the main parts of the armed helicopter are outside the rotor wake at the higher flight speeds, techniques may be used for the estimation of the parasite drag as applied for fixed-wing aircraft. These are discussed comprehensively in AGARD Advisory Report 107

(Reference I-5). The most promising analytical methods are the three-dimensional panel techniques as applied for fixed-wing aircraft by MBB, Dornier, RAE and NLR (References I-6, I-7, I-8 and I-9). These methods have been used with relative success in the prediction of store aerodynamic loads. It is expected that the extension of these techniques to helicopter applications for the higher speed range creates no special problems.

For helicopter/store calculations at lower airspeeds, where the rotor wake has a strong influence on the airflow field at the stores, the VSAERO panel method computer program adapted to helicopters permits an improved estimation of the interference effects and consequently captive store loads (Reference I-10). This topic will be further discussed in later sections.

1.2.2.5 MANOEUVRE PERFORMANCE

In many military operations, the helicopter manoeuvrability and agility have been described as the drivers of combat effectiveness. Manoeuvrability can be described as the ability to change the vehicle flight state or flight path, either through a change of energy (acceleration along the flight path, and climb) or a change of direction (application of normal acceleration). It can be measured as the limiting values of linear acceleration, normal load factor, turn rate/radius and climb rate. It is influenced by performance parameters such as excess power, rotor aerodynamic limits and structural constraints. Agility can be described as the quickness through which manoeuvre states can be changed. It is measured in terms of pitch, roll and yaw accelerations, build-up of linear and normal accelerations and pilot workload. It is greatly influenced by the vehicle handling qualities and engine response characteristics.

Helicopter manoeuvre performance can be expressed as energy management that involves control of the energy level through the various energy contributions and the rate of transfer between energy levels (References I-11 and I-12). This rate of transfer is proportional to the excess power. The following expression shows the options available to the pilot for energy management:

$$P_s = \frac{\text{Pavail-Prequired}}{\text{weight}} = \frac{dh}{dt} + \frac{V}{g}\frac{dV}{dt} + \frac{I\Omega}{\text{weight}}\frac{\Omega}{dt}$$

The specific excess power P_s can be used to increase altitude (dh/dt), to increase flight speed (dV/dt) and to increase rotor speed (dΩ/dt). The power required depends among others on the rotor thrust which is determined by the normal load factor. For a given helicopter weight the energy rate is defined by the excess power, which is the available power minus the power required at the desired level flight condition. So for a given normal load factor the magnitude of specific excess power defines the options available to the pilot for controlling his flight path.

Work-energy considerations can be used to estimate the manoeuvrability of the helicopter. Based on given engine power available, calculated power required for various load factors and the estimated rotor thrust limit, the manoeuvre diagram can be constructed as shown in Figure 1.1 for the AH-1G Huey Cobra helicopter (Reference I-11). In a first instance for the armed helicopter the rotor thrust limit in terms of C_t/σ can be assumed to be the same as for the basic aircraft. It is noted that for a given helicopter configuration this diagram changes with altitude, aircraft all-up weight and maximum engine power setting. The diagram has lines of constant energy rate P_s, constant turn radius and constant normal load factor. For a turn at constant airspeed it gives the relationship between the turn rate or radius and the available energy rate that can be used for climb, acceleration or a combination of both. The zero energy-rate line (specific excess power $P_s = 0$) gives the maximum sustained turn rate or minimum radius as function of flight speed. The intersection of the zero energy-rate line with the lines of constant normal load factor defines the steady state boundaries. Also of interest are the maximum turn rates and minimum turn radii that can be obtained for specified energy rates, eg, specified climb rates. Another important area of operation is the region outside the zero energy-rate line. Here the values of normal load factors, which for a given airspeed determine the turn rate and turn radius, are for negative values of energy rate. This means that for maintaining the desired turn rate or radius, the aircraft must be decelerating or losing altitude. An example of the application of the energy method is shown in Figure 1.2 (from Reference I-11). For an AH-1G helicopter at 8750 lbs gross weight and at an altitude of 2400 ft the penetration distance and the time to execute a 180 degree level decelerating turn are calculated for 150 kts entry flight speed and a number of specified airspeeds to be reached at the end of the manoeuvre (90, 100 kts, etc).

In order to aid in the development of manoeuvre requirements, which provide the necessary manoeuvre capability to perform the desired mission, Bell Helicopter Textron has developed the Manoeuvre Criteria Evaluation Program (MCEP) under contract for the US Army (Reference I-13). Based on the energy rate concept, the controller in the programme "flies" the helicopter through any of several predefined manoeuvres by commanding the acceleration along the flight path, the flight path angle, the wind axis roll angle and the normal load factor. Besides the excess power, aircraft characteristics are used as input such as angular rate time constants, maximum angular rates, and maximum and minimum attitude angles. These have to be determined separately in advance. The predefined manoeuvres are manoeuvres typical for military helicopter operations. Examples are level acceleration/deceleration, level decelerating turn, dive/rolling pull-out, push-over, bob-up and climbing/descending return to target (Figure 1.3). The MCEP manoeuvres were calibrated against flight test data for the AH-1G helicopter, but have not yet been validated for non-Bell helicopters.

1.2.3 WIND TUNNEL TESTING

1.2.3.1 GENERAL

In the present state of our knowledge, wind tunnel tests are still the best method to accurately estimate the aerodynamic characteristics of airframes and other bodies of complex shape. This is why the majority of helicopter manufacturers use this type of test to obtain the data required for performance and handling qualities computations.

Wind tunnel tests are all the more necessary in the armed helicopter context in that estimations by computation are difficult and fairly inaccurate. This is partly due to the configuration of external stores installation on helicopters:

- Stores are often installed on existing helicopters not originally designed to take external loads. The limited number of hard points on the fuselage structure leads to define supports of complex shape fitted with reinforcing struts in some cases. Fixed wing aircraft have, from that standpoint, a definite advantage since the wings offer an already existing stores support.

- External stores installed on helicopters are derived most of the time from weapon systems used on land vehicles, eg, anti-tank missiles, rockets. As a consequence, ammunition containers often have poor streamlined shapes and generate strong wakes.

- A large amount of the total installation drag is due to weapon/weapon support/airframe interferences.

All these particularities make the aerodynamic effects of stores installations on helicopters difficult to predict by calculation. In some conditions, however, valid drag estimations can be obtained, without wind tunnel tests, from basic aerodynamic data such as those given in Fluid Dynamic Drag by S.F. Hoerner (Reference I-4). This particularly applies when the stores installation presents the following characteristics:

- It is possible to breakdown the installation in simple shape elements of known drag coefficients.

- Assembly geometry is such that aerodynamic interferences are minimized.

This method is mainly used at the pre-project stage or when drag does not play a critical role in the observance of performance specifications. Estimations accuracy can be significantly improved when wind tunnel results are already available for some of the breakdown elements or for installations of similar shape.

The airflow computation methods are not technically advanced enough to allow computing drag of complex shape bodies where boundary layer separations occur. These methods can however be profitably used to study airflow in non separated areas and analyse interference effects. Although no drag value is obtained, this can help optimize shapes to reduce the installation's overall drag.

Analytical methods should prove better adapted in the future to predict the aerodynamic characteristics of armed helicopters since, independently of improvements in computation programmes performance, external stores installations will probably be much better streamlined than the current installations (to meet speed requirements) and even integrated with the fuselage.

1.2.3.2 TEST PROCEDURES

The wind tunnel tests used for performance prediction of armed helicopters consist in measuring its aerodynamic characteristics when fitted with external stores (drag, stabilities).

The helicopter can in these tests be represented with either an isolated airframe model or a full helicopter model equipped with rotors (powered model).

Airframe model tests allow solving the majority of problems inherent to external loads installation satisfactorily. Model manufacture as well as test procedures tend to be relatively cheap (see Figures 1.4, 1.5 and 1.6).

Powered model tests allow taking into account the effects of rotor/airframe interactions which in some flight conditions (low speed flight, climb), can be relatively high. These tests are however much more expensive and complex than airframe only tests. So far, they have mainly been used by US manufacturers for their new range of military helicopters (UTTAS, AAH). Although experienced with these tests, Aerospatiale reserves powered model tests for specific interaction studies (see Figures 1.7 and 1.8).

This section deals essentially with measurements of aerodynamic characteristics on airframe models.

The aerodynamic effects of the stores installation are not generally measured directly but obtained by difference between clean and armed configurations of the helicopter. Likewise, the aerodynamic effects of stores alone (missiles, torpedoes, etc) are obtained by difference between measurements made on the helicopter both armed and fitted with supports only.

Interference effects between stores installation and basic airframe as well as stores and their supports are therefore included in the characteristics obtained; it thus becomes necessary to test every store carrying configuration that may occur during the mission. To measure specific stores characteristics, tests must be performed on isolated bodies free from interference. This type of test is rather the weapon manufacturer's responsibility since specific stores characteristics are used mainly to compute firing trajectories. However, these characteristics can also be used to compute separation trajectories.

A typical wind tunnel test program applicable both to armed and clean helicopter airframes calls for two main kinds of tests:

- Drag measuring tests where incidence and sideslip are fixed.

- Tests determining longitudinal and lateral characteristics performed with incidence and sideslip sweeps.

1.2.3.3 DRAG MEASUREMENTS

Drag measurements are mainly used as a basis for performance calculations. Tests are generally performed for two typical fuselage incidences:

- $\alpha = 0°$ provides a reference value for comparison with available data bases.

- Another incidence close to that of fast cruise, $\alpha = 0°$ to $-5°$ depending on the helicopter type, determining the drag value to be used in performance calculations.

Furthermore, measuring drag for $\alpha = 90°$ can prove useful. Although the flow of induced speeds from the rotor is far from being uniform, this gives an idea of the fuselage download to be considered for hover performance prediction.

For drag measurements to be representative, some precautions must be taken during tests, particularly as concerns Reynolds number and airframe pitching moment:

- Since tests are most of the time performed with small scale models, airflow around some of the weapon installation components may be sub-critical (Re < critical Re). This may entail a significant drag overestimation in the absence of any correction.

  To make these corrections, the installation areas around which airflow may be sub-critical in wind tunnel testing conditions need to be identified first. The critical Reynolds numbers of the various elements can easily be estimated from data available in aerodynamic documents. Corrections of the components discussed here consists, as in airfoil tests, in adding artificial roughness on the model to fix the boundary layer transition at a given station.

  To avoid these Reynolds-number related problems, one can also proceed with large scale drag measurements with a 1/2 or 3/4 scaled mini-body where local stores installation shapes are reproduced. Working on a larger scale allows for a better representation of the installation details (release units, surface imperfections, slots and ports).

- Although the complete helicopter trim analysis is usually undertaken after wind tunnel tests with specific computation programmes, it is important to check during the first runs that the aerodynamic characteristics of the fuselage fitted with external stores remain compatible with the helicopter's general characteristics. Indeed, the addition of external stores can significantly modify longitudinal balance, particularly on small or medium helicopters where the stores installation's aerodynamic influence is relatively high compared to that of the bare fuselage.

  It is generally noted that the stores installation generates a nose-down pitching moment. This comes mainly from the fact that the parasitic drag force generated by the installation applies below the helicopter's center of gravity, thus generating a nose-down pitching moment. However, other causes may also apply. As example, the reduction of dynamic pressure in the stores installation's wake can reduce the stabilizer's download and subsequently produce a nose-down pitching moment. In the particular case of stubwing mounted stores, the combination of installation's wake and wing downwash may generate a nose-up pitching moment (see Figure 1.9).

From a flight mechanics standpoint, a pitch down effect (Δ Cm < 0) increases hub stresses under load factor (turns, pull-ups) and decreases static longitudinal stability. In no case must the pitch moment for $\alpha = 0°$ be negative since the airframe must generate a nose-up aerodynamic moment (Cm > 0) to provide static stability in cruise flight. Whenever the differences between the armed helicopter's and the clean helicopter's pitch moment become too great, the following corrective actions must be envisaged:

- Stabilizer setting modification, provided this modification remains limited so as not to significantly affect the trim states in unarmed configurations or after stores release.

- Modification of shape or position of stores installation.

These modifications usually have a significant influence on drag. This is why airframe pitching moment needs to be checked prior to drag measurements.

1.2.3.4 LONGITUDINAL AND LATERAL CHARACTERISTICS

A knowledge of the helicopter's longitudinal and lateral characteristics is necessary to study trim states and handling qualities. These characteristics are determined in the wind tunnel with incidence and sideslip sweeps:

- Incidence sweeps are used to record the aerodynamic coefficients which directly influence the helicopter's longitudinal equilibrium, ie, drag (CD), lift (CL) and pitching moment (Cm) coefficients. An incidence sweep at zero sideslip usually gives sufficient data to study the helicopter's longitudinal stability.

- Lateral effort (Cy), rolling (Cl) and yawing moment (Cn) coefficients are recorded from sideslip sweeps. Contrarily to the above, several sideslip sweeps are required for various fuselage incidences, eg, $\alpha = -5°$, $0°$, $+5°$, since airframe lateral characteristics may very significantly with incidence. A reduction in weathercock stability is usually noted when the incidence becomes positive (descent and autorotation).

Prior to starting the tests, it may be useful to set some stability objectives for the airframe fitted with stores and in particular, to define minimum acceptable levels. This can be obtained with some simulation runs using modified clean helicopter data.

The effects of external stores usually depend on the weapon installation position. Although many installation configurations can be adopted, these are primarily divided into lateral installations (missiles, rockets, etc) and nose installations (gun turrets).

External stores installed on the fuselage sides often decrease the airframe's pitch stability ($\partial Cm/\partial\alpha$) over a definite incidence range. Stability reduction is related in most cases to a loss of horizontal stabilizer's efficiency. This loss of efficiency may result from several causes:

- A reduction of dynamic pressure on the stabilizer when it is interfered by the store installation's wake.

- An airflow deflection similar to that noted behind a lifting surface, which effect is to reduce incidence variations on the stabilizer.

The first type of interaction mainly occurs when the stores supports are poorly (or not at all) streamlined. This induces a local stability reduction in the pitch moment curves ($\partial Cm/\partial\alpha$ slope) at incidences where the stabilizer is interfered by the installation's wake. Whenever stubwings are installed (AH-64, A-129, HAP/PAH project), the loss in stabilizer efficiency may result from the two types of interaction. The presence of a deflection is noted in the pitch moment curves by the fact that the stability decreases over a large incidence range and progressively (see Figure 1.9). The deflection can also be evidenced with airflow visualization.

The respective contributions of external stores and their supports are evidenced by comparing tests with and without stores. The wake behind streamlined stores (missiles, torpedoes, etc) is usually weak at low incidences. To minimize drag and interactions with the stabilizer, it is important that settings be adapted for fast cruise incidence to be almost zero. This practically imposes settings positive by a few degrees with respect to the helicopter's fuselage. When fitting air-to-air missiles initially developed for fighter aircraft, in particular, these may have to be set in such a way that incidence is definitely positive on launching to compensate for the lack of initial speed. Rocket or anti-tank missile containers generate a relatively strong wake because of their high cross section, often associated to a poorly streamlined shape. It becomes then important to ensure that this wake does not interfere with the stabilizer at fast flight incidences (cruise, manoeuvres). It must be envisaged to modify the container's position if such an interference is noted. This could also be considered as a criterion to optimize the stabilizer location on new helicopters.

As reported above, stubwings generate a flow deflection in the vertical plane which reduces longitudinal stability. Should stability reduction prove too high, the only efficient solution would consist in increasing the stabilizer size and this is not always possible on an existing aircraft. This explains why, amongst other things, stubwings, although they have a low drag, are mainly used on aircraft initially designed for external stores carriage. Airflow deflection by the stubwings can have a favourable effect on the stores' wake. This is the case on the HAP/PAH project where for a positive incidence, the downward deflection of the airflow prevents the wake generated by the HOT missile containers from interfering with the stabilizer. The remarkable result of this is that the pitch moment curves are perfectly identical with and without containers. Pitch stability can also be modified when the stubwings are offset with respect to the helicopter's center of gravity. Stubwings lift produces stabilizing or destabilizing moment depending whether it is forward or aft of the center of gravity. To avoid high CG changes upon stores release however, the stubwings are in most cases located straight below the rotor center.

Lateral installations sometimes deteriorate the yaw characteristic of the airframe. This occurs mainly in descending flight when the stores installation's wake runs on both sides of the fin; the aerodynamic restoring moment of the fin is then decreased upon sideslip.

Weapons installed under the aircraft nose, eg, gun turret tend to increase the yaw instability of the fuselage. This induces on the overall airframe characteristics (fuselage + fin) a yaw stability deterioration or a higher instability when the fuselage/fin assembly is already unstable in yaw. This effect has already been noted on the HAP/PAH project where the fuselage of the HAP version equipped with a gun turret has proved to be significantly more unstable in yaw than that of the PAH anti-tank version.

The only efficient solution to compensate, if necessary, this destabilizing effect consists in increasing the yaw restoring moment generated by the aft surfaces (fin size augmentation or addition of end-plates on horizontal stabilizer).

1.2.4 PERFORMANCE FLIGHT TESTING

1.2.4.1 GENERAL

Often in the past, integration programs of weapon systems with military helicopters have been carried out after the determination of the basic performance characteristics of the "clean" aircraft.

In this case, after the installation of the external stores, performance flight tests are planned to evaluate possible limitations of speed and altitude of the yet established operational envelope and to determine the performance changes in respect to the "clean" configuration due to the increased parasite drag.

The following sections cover the flight testing of the performance characteristics that are mostly influenced by external weapons, whose results are used to build the performance charts of the Operator's Flight Manual, and one section is dedicated to the evaluation of the manoeuvre performance typical of a military helicopter.
For the above reason, the flight testing required to determine the takeoff and landing performance and the H-V boundaries are not treated.

Powerplant performance is considered yet fully determined and the available power known at any engine rating and flight regime.

More detailed information about performance tests planning, flight testing techniques and data reduction methods can be found in dedicated books (References I-15, I-16, I-17) and in an AGARD lecture (Reference I-18), covering also the handling qualities flight testing.

1.2.4.2 INSTRUMENTATION

To determine most of the performance characteristics described in the following sections there is no need of complex instrumentation packages, not only because the relevant parameters are few but also because they are recorded during quasi-static conditions.

Thus, in these cases it is not essential to use magnetic tape recorders (which allow high data density) but it is sufficient to record manually or to photograph the readings of the cockpit instrumentation, previously calibrated.

However, the test aircraft is usually completely instrumented (see 1.3.4.2) and the following list reports the parameters that are normally recorded and their normal sample rate.

Parameter	Sample per Second
Pressure Altitude	32
Free Air Temperature	8
Indicated Airspeed	32
Vertical Speed	32
Main Rotor Speed	8
Main Rotor Shaft Torque	512
Tail Rotor Shaft Torque	1024
Fuel Content or Fuel Used	8
Engine(s) Torque	128
Gas Generator Turbine(s) Speed	8-16
Power Turbine(s) Speed	8-16
Turbine(s) Temperature	8
Elapsed Time	—
Event Marker	8

In the case of testing in proximity of the ground, ie, hovering flight, the following parameters should be recorded also:

Ground Pressure Altitude
Ground Air Temperature (both out and in the rotor wake)
Wind Direction and Speed
Wheel Height AGL
Load Cell Readings (tethered hovering)

1.2.4.3 AIRSPEED AND ALTITUDE CALIBRATION

For any external configuration, at pertinent loading and CG position condition, flight tests should be carried out to determine the correction required to obtain the calibrated (CAS) and the true (TAS) airspeed from the indicated airspeed (IAS) and the correction for the altimeter indication, possibly in function of the IAS.

Calibration flights are executed in level, climb, descent and autorotative flight at incremental speed and the standard anemometer system indications are compared with those provided by a pitot and static source trailed by the helicopter at such a distance to be out of the disturbed airflow region (Figure 1.10).

The airspeed measured by the trailing sensors is free of the position error and is called calibrated airspeed. The true airspeed may be obtained from it by correcting for the air density.

$$TAS = CAS/\sqrt{\sigma}$$

Where σ = air density ratio

The difference of altitude provided by the two static sensors (the standard and trailed) at various IAS is the altitude correction.

Whenever it is possible, one may use the simpler method of flying in formation with a pace aircraft and compare directly the two systems readings.

If a low speed air data system is installed, it should be optimized in level flight with the ground speed course method.

1.2.4.4 HOVER AND VERTICAL FLIGHT PERFORMANCE

Tests should be carried out to determine the power required to hover at different heights from in ground effect (IGE) to out ground effect (OGE), at various weights and rotor speeds.

Different external weapon configurations may require different power to hover if their vertical drag differ sensibly.

Test should be conducted in calm air (wind < 3 kts) at the desired height above ground accurately measured and with the helicopter well stabilized to avoid a too large scatter in the results.
To cover the full range of operational weights and altitudes, at least two test sites should be utilized - near sea level and at high altitude. Two test techniques are normally employed: the free hovering flight, simple but requiring time to continuously ballasting the helicopter to change weight and some device to control the height and tethered hovering, which require systems to record the cable tension - to be added to the helicopter weight to obtain the rotor thrust - and to ensuring the cable verticality.

Test data at each ground height are then summarized in diagrams of a dimensional coefficient of power (Cp) and thrust (Ct), (Figure 1.11).

$Cp = f(P/\sigma\ ,\ 1/Nr^3)$ $\qquad$ $Ct = f(W/\sigma\ ,\ 1/Nr^2)$

Where P = power required
W = A/C weight
σ = air density ratio
Nr = rotor speed

The rotorcraft flight manual data can be obtained from these curves by substituting the power required with the power available at the desired power settings and at any altitude and temperature.

Vertical performance is measured from the rate of climb established by increasing incrementally the power from the hover OGE values up to the maximum.
Test data treatment is the same outlined in the forward flight climb performance section and the results give an idea of the power margin available in vertical manoeuvres.

1.2.4.5 LEVEL FLIGHT PERFORMANCE

The installation of any external weapon system has without doubt the effect to reduce the maximum sustained speed (Vh) and decrease the range and endurance capability of the "clean" aircraft.
In fact at a given speed, more power is required to overcome the increased parasite drag and thus also the fuel consumption is higher.

If the level flight performance data relative to the "clean" configuration are yet known, only three or four speed polar tests are to be flown in the armed configurations in order to determine the new values of the flat plate area of equivalent drag from the difference of the power coefficients (Cp) at equal thrust coefficient (Ct) and advance ratio.

$(\mu = f(TAS,\ 1/Nr))$

Whenever possible, it is convenient to do direct comparisons between the "clean" and armed configurations, by testing one just after the other at the same weight, altitude and air temperature.

Otherwise six to nine speed polar tests should be run in the desired armed configuration, at incremental speeds from 40 kts up to maximum, to cover the full range of operational weights and altitudes.
For each test the helicopter should be flown at a constant Ct value by adjusting altitude and rotor speed at each airspeed stabilization.

From these tests a family of power required curves is obtained (Figure 1.12) from which the level flight performance characteristics can be derived at any combination of weight, altitude and temperature.

Vh is the speed where the power required is equal to the maximum delivered continuously by the powerplant system.

The speed where the required power is minimum is the speed for maximum endurance and for optimum climb.

The hourly fuel consumption (Wf) can be obtained at any condition during the level flight tests if a fuel flow-meter has been installed or more simply it can be derived from the relationship between the generalized power and fuel flow obtained from the engine specification and corrected for the installation losses (Figure 1.13).

Thus the speed for maximum (Vmr) and long range cruise (Vlr) can be obtained at any weight, altitude and temperature from the curve of the specific range (Rs) vs true airspeed (Figure 1.14).

$Rs = TAS/Wf$

1.2.4.6 FORWARD FLIGHT CLIMB AND DESCENT PERFORMANCE

Sawtooth climb and descent tests should be carried out at different weights and through two or three bands of altitude (2000 ft each) at incremental or decremental power settings, at the optimum speeds determined during level flight tests. The elapsed time should be recorded at passing 500 or 1000 ft, depending on the rate of climb.

Some tests should be repeated with one engine inoperative (if applicable) and other may be carried out at higher speeds, close to the cruising ones.

The measured rates of climb are then corrected in true rates of climb (RC) by multiplying for the ratio of the absolute test and standard temperatures at the test pressure altitudes.
The climb power coefficients (Cpc) are determined by the difference between the test power (Pt) and the power required in level flight (Pl) at the same condition.

$Cpc = f((Pt-Pl)/\sigma, 1/Nr^3)$

The above climb parameters are then generalized to remove the weight as independent variable and diagrammed (Figure 1.15) in order to determine the climb efficiency factor (η).

$\eta = GVV/3\ GCpc$

Where GVV = generalized vertical velocity
GCpc = generalized climb power coefficient

This climb efficiency factor is normally constant at any rate of climb for a range of climb speed near the optimum and is the measure of the efficiency of the conversion of the excess of power into rate of climb at the given weight.

1.2.4.7 MISSION-RELATED PERFORMANCE

As reported in section 1.2.2.5, the modern combat helicopter, to operate successfully throughout the battlefield at NOE heights during anti-tank or combat rescue missions or to fly higher and faster in air-to-air combat mission, must have a high degree of manoeuvrability and agility.

Both these two qualities are obviously a function not only of performance characteristics but also of handling qualities. The complementary aspect of the question is discussed in section 1.3.4.7.

From the performance point of view the principal factors that affect agility are the excess thrust available and the engine response.

Then at the maximum mission weight, with weapons installed, level acceleration and deceleration tests should be carried out. Level and climbing maximum turn rates should be determined.

To obtain a quantitative evaluation of the manoeuvre performance capability, the time required to perform stylized mission elements should be measured.
These performance task elements may be of the same type of the "aggressive tasks" of Reference I-19 (see section 1.3.4.7) provided that they were easily flight testable and reproducible.

Among them: bob-up, bob-down
dolphin (hurdle, roller coaster)
slalom
climbing return to target
assault landing, etc

1.3 HANDLING QUALITIES

1.3.1 GENERAL

The mission efficiency of an armed helicopter does not only depend on its weapon system's efficiency. Other factors, handling qualities of the helicopter fitted with its weapon system amongst them, may significantly affect mission performance. A helicopter with good handling qualities offers the following advantages:

- Pilot workload reduction and, consequently, increased crew availability for navigation or target detection.

- Flight path more accurately controlled during weapon system operations.

- Improved ability to perform evasive manoeuvres upon detection by the enemy.

Since handling qualities cover a wide range of aspects which sometimes are difficult to quantify, it is useful to refer to existing standards when defining armed helicopters specifications. In most military contracts, handling qualities requirements are drawn from US MIL-standards such as MIL-H-8501A and MIL-F-83300 (References I-20 and I-21). Compliance with a standard does not necessarily prove that the helicopter characteristics have been optimized as regards to mission effectiveness, but guarantees that the A/C will not present objectionable HQ deficiencies within the operational flight envelope. Demonstration of compliance with HQ standards is therefore one of the main tasks of helicopter manufacturers involved in weapon systems installation. This is why it is important to perform specific handling qualities' studies when installing external stores on helicopters.

Simulation and flight tests are the main tools in the study of handling qualities. Simulation tends to play an increasing role because it significantly reduces the amount of flight testing to be done and consequently, the development costs. Furthermore, pre-flight simulations provide the test crew with a better knowledge of the safety margins when demonstrating the flight envelope boundaries or critical conditions.

The methods of handling qualities analysis for armed helicopters are not fundamentally different from those of other helicopters. Nevertheless, care should be paid to the characteristics on to which the weapon system has a definite influence. Some areas of concern for armed helicopters are listed below:

- Inertia increases due to weapon installation significantly reducing the A/C controllability and, consequently, its ability to perform NOE tasks. This can set the helicopter characteristics outside of the areas recommended in sensibility-damping diagrams (Reference I-22, Figure 1.16). In some cases the helicopter's response must be boosted with an artificial control augmentation system (CAS).

- Longitudinal static stability which, in some cases, has deteriorated compared to that of the clean A/C. Static stability must remain positive within the operational flight envelope as requested in all applicable standards, ie, increasing speed requires more forward longitudinal cyclic for a fixed collective pitch setting. Longitudinal static stability of helicopters depends not only on the angle of attack's stability as for fixed wing A/C, but also on many other parameters; this makes analytical prediction difficult. In case of local negative stability, it is sometimes necessary to perform a fairly high number of flight tests to find the appropriate solution.

- Longitudinal dynamic stability. Both short and long period (phugoïd) modes can be influenced by external weapon installation. The reduction of airframe incidence stability which often occurs when fitting weapons in a lateral position (see 1.2.3.4) directly influences the pitch stability derivative M_α which has a major impact on longitudinal eigen modes. In addition, weight increases and aft C.G. also tend to increase M_α in the unstable sense. A too unstable, ie, positive, M_α leads to a periodic divergence of the short term pitch's response and also to a negative manoeuvre stability. Such behaviour is unacceptable with regards to MIL standard requirements and must be corrected by appropriate aerodynamic changes or control system augmentation. Decreasing the incidence stability also reduces phugoïd damping (Figure 1.17). Care shall therefore be taken not to have a time doubling amplitude below the minimums required in applicable standards for IFR operations.

- Lateral static and dynamic stability can also be affected by external weapon installations. As noted in 1.2.3.4, this is often the case with nose mounted gun turrets which reduce airframe weathercock stability. The static stability requirement along yaw axis is generally expressed as follows: Pedal displacement versus sideslip must be stable (more pedal to increase sideslip) within the airspeed-sideslip envelope or up to full pedal travel, whichever is the lowest. Reduction of airframe weathercock stability can make it difficult to meet this requirement for some sideslip-incidence combinations, such as in descending flight where the tail fin is less effective.

Dynamic stability requirements for the Dutch roll mode are expressed in terms of frequency and damping ratio. These characteristics are also related to yaw static stability and can consequently fall outside the acceptable limits when weathercock stability (derivative N_β) is reduced. However, some other parameters can have a significant impact on Dutch roll characteristics. For example, the cross derivative N_p (yawing moment induced by roll rate) mainly depends on the forward tilt of the main axis of inertia (Reference I-23). Adding a gun turret under the helicopter nose tends to increase the main axis of inertia's tilt forward and, consequently, the yaw-roll coupling.

1.3.2 ANALYTICAL METHODS

1.3.2.1 GENERAL

Battle field Nap-of-the-Earth (NOE) operations with unarmed and armed helicopters involve agile flight at extremely low altitude to take advantage of the cover afforded by trees, creek beds, ridges, etc. This is required in order to reduce the possibility of detection and vulnerability to sophisticated weapon systems either on the ground or in the air (fixed-wing aircraft and helicopters). To be effective in this NOE environment, it is necessary that the helicopter is also very agile and possesses very good handling qualities to perform its mission. Very good NOE handling qualities will allow the pilot to concentrate his attention on the outside world. The pilot's workload is very high and the effect of handling qualities on the mission effectiveness is significant.

For armed helicopters the mission effectiveness depends also to a large extent on the effectiveness of the weapon. Besides the effectiveness of the weapon system itself, also the handling qualities of the aircraft are important in this aspect; for weapon delivery the helicopter must be manoeuvred and held in the best position to achieve the delivery time window.

During weapon delivery, the firepower may have such an effect of the movements of the helicopter, that it will restrict the operation or application of the weapon. Improvements of the handling qualities, eg, by some kind of stability augmentation, will reduce the restrictions. An example is the use of a gun turret under the nose of the helicopter, where the azimuth range for weapon firing can be restricted by the available stability and controllability of the helicopter in yaw and roll.

As with performance, analytical handling qualities prediction methods are attractive for a first estimation. The final prediction of the helicopter behaviour is carried out by simulation with the pilot in the loop.

1.3.2.2 HELICOPTER MATHEMATICAL MODEL

Similar to fixed-wing aircraft, the helicopter handling qualities are determined by the controllability and stability characteristics of the aircraft and the control positions in trim. All these are closely tied to the thrust and moments the main and tail rotor can produce about the helicopter center of gravity. In fact, the main rotor not only takes care of the lift and propulsive force, but also plays the dominant role in the pitch and roll behaviour of the aircraft.

For analytical predictions of handling qualities, a non-linear flight mechanical mathematical model is used, which is often also the driving model of flight simulators. However for handling qualities predictions, this model and especially the representation of the main rotor and its induced flow field can be more detailed, as there is no time constraint as for simulation models.

a. Rotor

Concerning rotor dynamics, a correct representation is necessary for at least the first mode of blade bending in flapwise direction. For flight mechanical purposes a hingeless rotor can be simulated by an articulated rotor with an equivalent blade hinge-offset that provides the same first bending mode frequency under rotation. An improvement can be obtained when blade torsion is also taken into account. The induced flow field has to be modelled for low speed flight as well as for the higher speed regime, in such a way that it will account for a non-linear variation along the blade span and around the azimuth. A good example of such a distribution is given by Mangler and Squire (Reference I-25). The rotor forces and moments can be calculated in two different ways. With the quasi-steady model, the rotor forces and moments are obtained by averaging for each time step the calculated blade sectional values along the span and around the azimuth. These quasi-steady values are then used as the rotor contribution to the body motions.

The other way is the simultaneous integration of the motion of each blade and the rigid body motion of the helicopter. Here the time step depends on the number of azimuth points required for the rotor, and as a result of the necessary accuracy this step is very small compared to the step size necessary for the body equations. For flight mechanical purposes the quasi-steady rotor calculations are sufficiently accurate.

b. Fuselage

The aerodynamic characteristics of the fuselage including the weapon installation are given as input data for the computer program, such as lift, drag, sideslip, and the pitch, roll and yaw moment coefficients about the center of gravity. These have to be determined in advance. The horizontal and vertical tailplane aerodynamic characteristics are given as separate input data. This is required in order to account for the influence of the main rotor wake and the wake generated by the fuselage, which can intersect the horizontal and vertical tailplanes at positive fuselage angles of attack (descent and decelerating manoeuvres).

c. Trim Condition

For a prescribed flight condition, which is determined by flight speed, altitude, turn rate, climb rate and slip angle, the linear and angular velocities, aircraft attitudes and position of the flight controls are calculated so as to attain a force and moment equilibrium around the helicopter center of gravity. The six rigid body equations and the three rotor equations for the blade flapping and coning are solved for the unknown parameters (linear and angular velocities, attitude angles and control positions) with an iterative algorithm which can be found in standard textbooks on numerical analysis. The trim algorithm as used by the NLR applies Taylor series expansion, and as a result of the calculation method, the control and stability derivatives of rotor and helicopter can be obtained beside the trim values (Reference I-28).

1.3.2.3 HELICOPTER WITH MOUNTED STORES

The installation of external weapon systems has the following effects which influence the handling qualities of the basic aircraft:

- Increase of the moment of inertia in pitch, roll and yaw directions. Lateral mounted installations mainly increase roll inertia and somewhat yaw inertia; installations under the nose of the helicopter mainly increase pitch and yaw inertia.

- Shift of the center-of-gravity position. For nose mounted stores the CG is removed to a more forward position. That may result in an unfavourable CG position or range.

- Increase of the mission weight of the aircraft. This will reduce the angle-of-attack stability (the destabilizing effect of the rotor increases with increasing rotor thrust).

- Modification of the aerodynamic characteristics of the aircraft. Of special importance are the aerodynamic fuselage pitch, roll and yaw moment coefficients and the contribution of the tailplanes to these coefficients.

a. Control Characteristics

The control sensitivity and damping have to be within certain limits. If the control sensitivity is too high, the pilot can have problems with chasing the aircraft motions;

when it is too low then the pilot will complain with sluggishness. The two parameters which measure the control characteristics are the final angular rate and the time constant (time to reach 63% of the final angular rate). When the time constant is short, the helicopter will follow the control motions more directly, ie, the angular velocity will be better in phase with the control motion. The final angular rate and the time constant are determined by the control sensitivity (ratio rotor control moment/aircraft moment of inertia) and the ratio rotor damping/aircraft moment of inertia.

When mounting stores the increased aircraft moment of inertia can result in such a reduction of angular acceleration and helicopter damping (for example refer to Figure 1.16), that the required minimum values cannot be reached. Military specifications such as References I-20, I-21 and I-21a provide criteria for the required control and stability characteristics in the hover and forward speed.

b. Aerodynamic Characteristics

The aerodynamic force and moment coefficients have to be available for the full range of angle-of-attack and sideslip angle in which the helicopter will operate. For NOE operations this means a range of ±90 degrees for the fuselage angle of attack and ±180 degrees for sideslip.
A simple method is to start from the basic helicopter for which the characteristics are known. By analysis and from wind tunnel data of similarly armed configurations an estimation can be made of the influence of the external weapon system and carrier.
However, due to the large interference effects and airflow separation wake effects, the estimated fuselage moment coefficients as function of angle of attack and sideslip angle are of very limited value, especially for the larger angles. Another aspect is the modification of the fuselage wake at the tailplanes due to the external stores and stores carrier that cannot be estimated. This modification of the wake and the airflow deflection can change the contribution of the tailplanes to the pitch, yaw and to a lesser extent roll moment coefficients of the airframe. The pitch and roll moment coefficients may also be modified in those regions where the rotor wake has a strong influence at the weapon installation. This may be with side mounted weapons and stub wings.

Awaiting more reliable analytical methods for the estimation of especially the moment coefficients, it is preferred at the moment to determine the total airframe coefficient by means of wind tunnel tests.

1.3.2.4 HELICOPTER BEHAVIOUR DURING STORE RELEASE

The helicopter motions, rotor tip path plane excursions and pilot control response as a result of store release can analytically be predicted with piloted flight simulation. However, for these short term manoeuvres, investigation time and costs can be reduced considerably by applying computer flight testing techniques, such as the C-81 programme of Bell Helicopters Textron and the CFT programme developed by NLR (References I-29, I-30). In the CFT programme, the non-linear flight dynamical model of the helicopter is coupled to a theoretical pseudo pilot model (Figure 1.18). The basis of the pilot model is rooted in optimal control theory as applied to linearized dynamic systems. There are connections with human factor analysis work, in that the controller may be regarded as a highly motivated and well trained pilot having a more or less perfect information about the state of the helicopter (Reference I-31). An example of the calculated helicopter motions and pilot control action is shown in Figure 1.19 for a normal and a decelerated flare. Transient forces which lead to these short term manoeuvres have to be determined separately in advance, and are used as input to the computer programme. Examples are the aerodynamic forces generated on the horizontal stabilizer or other parts of the helicopter from the blast of the weapon, and the impulse at a particular point of the aircraft from gun firing.

In comparison to piloted flight simulation, the application of computer flight testing programmes has the following advantages:

- No complicated hardware is required.
- There is no severe constraint as to the available computing time per time step in the integration process of the aircraft motions.

1.3.3 WIND TUNNEL TESTING

1.3.3.1 GENERAL

As for performance, wind tunnel testing provides the airframe data required for handling qualities studies. Three types of tests can be envisaged:

- Basic uncoupled tests providing data for trim states and stability studies. Test runs are usually performed during drag measurement trials and are described in Para 1.2.3.4.
- Tests providing airframe characteristics for simulation programs. To this end, aerodynamic characteristics must have been determined for every incidence-sideslip combination that could occur in flight.
- Powered model tests, as noted in Para 1.2.3.2, are used to study rotor/airframe interactions problems.

1.3.3.2 SIMULATION DATA BASES

Most of helicopter simulation programs use wind tunnel test characteristics to compute aerodynamic forces and moments acting on the airframe. Pure analytical prediction methods are not accurate enough to establish such a data base; this is mainly due to difficulties incurred in the calculation of fuselage characteristics, taking into account boundary layer separation and interference effects.

Some programs, such as STAN (MBB), CFT (NLR) and C81 (BELL), use wind tunnel data for the fuselage only; the stabilizing surfaces characteristics are calculated by classical lifting surface theories. However, some empirical corrections must often be applied to the fin and stabilizer characteristics to incorporate interference effects in the model. AEROSPATIALE's S80 uses wind tunnel test data for all airframe components including body, stabilizer and fin. This allows for a pretty good modelization of stabilizing surfaces characteristics; the local efficiency changes due to fuselage interferences such as those occurring on the vertical fin around zero sideslip are then taken into account. Stabilizer and fin characteristics are determined by difference between complete airframe and isolated fuselage tests.

The accuracy required of airframe aerodynamic characteristics depends on the flight conditions to be simulated. For hover and low speed flight, airframe aerodynamic forces are low compared to those of the main and tail rotor. It is therefore not necessary to know the airframe characteristics for every incidence-sideslip combination that could occur in these flight conditions. On the other hand, at cruise speeds airframe aerodynamic forces have a high influence on the helicopter's equilibrium and need to be accurately modelized. This leads to the definition of two kinds of wind tunnel runs, depending on the incidence-sideslip range:

- Coupled sweep runs providing aerodynamic characteristics for every incidence-sideslip combination within the (α, β) range for forward flight.

- Large angles un-coupled sweeps: α varying from -90° to +90° for β=0° and β varying from -180° to +180° for α =0°. Interpolation formulae provided are accurate enough to estimate the characteristics for other large incidence-sideslip combinations since this essentially corresponds to hover and low speed flight.

In the particular armed helicopter configuration, the weapon installation's aerodynamic characteristics need to be measured once it has been fitted on the fuselage to take into account the interference effects (see 1.2.3). Consequently, it is not possible to create a separate simulation data set for the weapon system only. Two series of runs must be performed: the first with a clean fuselage for clean aircraft data and the second with the weapon installation fitted on the fuselage for armed aircraft data.

Modelling of measured characteristics depends on simulations programs. Some programs use wind tunnel measurements directly, calculating the characteristics between measurement points by *linear* interpolation (MBB's STAN refers). Other programs (AEROSPATIALES's S80 refers) convert measurements into parametric formulae with a regression algorithm.

1.3.3.3 POWERED MODEL TESTS

Powered model tests are required to study rotor wake/airframe and rotor wake/weapon interaction problems. To perform these tests, the helicopter model is equipped with a scaled-down main rotor with cyclic and collective pitch remote control. The rotor is driven by an electrical or compressed air engine located inside the model (Figures 1.7 and 1.8).

Fitting the model with a scaled-down tail rotor is not necessary, except for specific T/R-fin interaction studies. Rotor induced velocities are scaled-down when observing the rotor advance ratio and the rotor thrust coefficient Ct. Rotor flapping is adjusted via the cyclic pitch to obtain the same longitudinal and lateral tilt as that predicted with trim state analysis. Trimming the A/C directly in the wind tunnel, ie, balancing drag and pitch moment, can also be done but requires observing the following additional scaled-down parameters:

- Model's drag must be consistent with full-scale aircraft's drag. This means that additional drag sources, such as internal powerplant or infra-red suppressor drag must be modelized or taken in account by a correction coefficient when balancing the helicopter.

- Rotor dynamics must be scaled-down, ie, hub flapping offset and blade dynamic characteristics must be similar to those of the full-scale aircraft. This increases model costs and complexity and is not, in addition, always feasible because of technological limitations.

Scaling the rotor torque is not necessary because this has no influence on induced flow and blade flapping. Blade airfoils and Mach number conditions can therefore be different from those of the full-scale aircraft.

In the specific armed helicopter configuration, the rotor wake/weapon installation interferences are significant mainly in climb and at low speed. This increases download and drag on external installations and, in some cases, also generates additional pitching moment. The effects of these interferences on the weapon installation can be directly measured with an internal 6-component balance located at the fuselage/weapon support's junction. If no knowledge of aerodynamic airloads acting on the installation is required, as is often the case on helicopters where crash loads are the most critical, a global measure of interference effects can prove sufficient. This is determined by difference between clean and armed runs, thus avoiding the need for an additional internal balance.

Powered models can also be used to study weapon/airframe separation problems with rotor wake effects taken into account. In this case, however, analytical computation of induced flow (momentum or vortex theory) may prove to be a more cost-effective investigation method.

1.3.4 HANDLING QUALITIES FLIGHT TESTING

1.3.4.1 GENERAL

Installations of external stores produce aerodynamic effects on the airframe and modify the CG position and inertia characteristics of the helicopter.

As a consequence, the armed helicopter should be flight tested to evaluate the possible deterioration of some handling qualities in respect of those of the "clean" aircraft and to prove, notwithstanding it, the accomplishment with the applicable requirements.

Currently two standards for HQ requirements exist: MIL-H-8501 and MIL-F-83300.

For a long time, the standard most used for military helicopters was the MIL-H-8501 (Reference I-20), which is also now in use in spite of a few proposals for updating. Among these, the more recent (References I-19, I-19a) is oriented to sub-divide the operational missions defined by the procuring activity in mission-task-elements; for each of them, the flight procedure and the results evaluation criteria is detailed, mostly based on qualitative judgements, expressed by pilots by a slightly modified Cooper-Harper rating scale.

The following sections are dedicated to a review of the canonic flight testing for the definition of the basic handling qualities that can be influenced by external stores and that is mainly concerned with the helicopter capability to transit safely from one flight state to another and to withstand the atmospheric disturbances without excessive pilot's skill and workload.

The last section covers the handling qualities more related to a specialized military helicopter.

More detailed information about HQ concepts and testing techniques can be found in dedicated books (References I-16, I-32) and in the yet cited AGARD lecture (Reference I-18).

1.3.4.2 INSTRUMENTATION

The helicopter should be comprehensively instrumented to obtain the necessary quantitative results during the basic phase of flight testing, particularly when flying for the determination of the handling qualities.

The following list reports the parameters that are normally recorded and their normal sample rate:

Parameter	Sample Per Second
* Flight controls displacements	32
cyclic pitch - longitudinal	32
- lateral	32
collective pitch	32
tail rotor pitch	32
* Flight controls forces	32
cyclic pitch - longitudinal	32
- lateral	32
tail rotor pitch	32
* Helicopter attitudes - pitch	64-256
- roll	64-256
- yaw	64-256
* Angular rates and acceleration - pitch	256
- roll	256
- yaw	256
* Pressure altitude	32
* Free air temperature	8
* Indicated airspeed	32
* Vertical speed	32
* Main rotor speed	8
* Engine(s) torque	128
* Load factor	128
* Sideslip angle	32
* Event marker	8

The electrical signals provided by each sensors are then modulated and grouped by using normally the PCM technique (Pulse Code Modulation) and on-board recorded on an analogic tape recorder.

Testing in the extreme regions of the flight envelope also requires careful monitoring of some critical stresses (rotor, control levers, etc) via a radio link. At the ground telemetry station the signals are recorded, processed in real-time and the critical parameters are displayed in engineering units to the flight engineers, thus allowing a safe approach to the extreme conditions.

Furthermore, a better flight productivity may be obtained if further calculations are executed in real-time and final results are made available just at the end of the flight, in order to proceed rapidly to the next flight.

For low speed testing in proximity of the ground a pace vehicle is normally used to establish true airspeed, unless a reliable low speed indicator system is available.

1.3.4.3 CONTROL MARGINS AND CONTROLLABILITY

The flight tests described in this section are carried out to establish the possibility to trim the helicopter with adequate control margins for manoeuvring and to evaluate the helicopter capability of moving around its axes.

For the first objective the helicopter is trimmed in level, climb and autorotative flight at various conditions of loading, altitude, rotor speed, airspeed and controls positions are recorded.
The more critical conditions for a single anti-clockwise rotor helicopter are at max aft CG, max weight, high airspeed, minimum rotor speed and max power (climb flight).

Enough cyclic control margin should exist to produce at least 10% of the maximum attainable hover pitch and roll moment (Reference I-20) or other possible requirements of the procurement authority.
Besides, the slope of the cyclic control curve in function of airspeed should be positive. This characteristic is known also as apparent speed stability (Figure 1.20).

Further tests should be carried in low speed and sideways flight to demonstrate that control margins are enough to maintain hovering flight with wind up to 35 kts from any direction (Reference I-20).

Tests should be carried out in calm air with a pace vehicle. The helicopter is trimmed at incremental speeds in sideways flight for azimuth angles increasing of 30 or 45 degrees.
The critical control is the tail rotor pitch and the worst conditions are high altitude, minimum rotor speed, max weight, max left lateral CG and wind azimuth angles from 60 to 120 degrees (right quartering flight).

Tests for the second objective are carried out by applying to any control a time, fixed to the others, step of various sizes from the trim position, in both the directions. A mechanical jig may be used to insure precise control inputs.
The control should be maintained fixed, if possible, till the maximum angular rate or acceleration around the interested axis is established (Figures 1.21, 1.22).

Pitch and roll axes are of more interest according to actual military spec (Reference I-20) and hovering and forward flight are the regimes to be investigated.

The controllability is defined essentially by:

* Control sensitivity (angular acceleration/control motion)

* Control effectiveness (angular rate/control motion)

* Control power (attitude in a specific time)

As these control response features allow establishment of the short-term handling characteristics and give an idea of the overall manoeuvrability of the helicopter, current proposed revisions of handling military specification, such as in Reference I-19, propose new or more detailed requirements and test flight techniques to demonstrate the compliance.

1.3.4.4 STATIC STABILITY

The evaluation of the static longitudinal stability characteristics consists in measuring the control position required for balancing the pitching moment around the helicopter CG.
It is required that the helicopter, after leaving a trimmed condition following an atmospheric disturbance, may regain that condition once the disturbance is ended.

The first aspect is the speed stability, defined as the change of longitudinal cyclic control position for airspeed increments at constant collective pitch (Figure 1.23).

The helicopter is trimmed at the desired speed and then it is re-trimmed in a series of speed increments above and below the test speed by using cyclic and pedals controls only.
The modes of flight to be investigated are level, climb, partial power descent and autorotation.
The worst test condition is normally associated with max aft CG loading, max airspeed and minimum rotor speed.

Also the control force is to be recorded in order to verify that the control motion is associated to a force proportional to the motion itself.

A certain degree of speed instability is normally allowed in the low speed region where it is assumed that the pilot controls speed with both cyclic and collective.

The second aspect of the longitudinal static stability is the analysis of trim change due to power, associated with the pitching moment resulting from change of the collective pitch setting. An increase in pitching moment should require forward movement of the longitudinal control.

Stabilizations are made at speeds from best climb to maximum at different power settings from autorotation to max power climb (Figure 1.24).

Under the term lateral-directional static stability, are investigated the directional stability, as indicated by the variation of directional control position with sideslip, the dihedral effect, as indicated by the variation of lateral control position with sideslip and the side force characteristics, as indicated by the variation of roll attitude with sideslip.

Flight tests are carried out at various airspeeds, weights and altitudes by trimming the helicopter for steady heading, zero sideslip in level, climb and autorotative flight. With the collective control fixed, the helicopter is then stabilized at incremental sideslip angles up to the limit, both right and left, while maintaining a steady heading at the trim speed (Figure 1.25).

Positive lateral-directional static stability is indicated by lateral control to the left, directional control to the right and roll to the left with left sideslip (with the converse also being true).

The tendency of the helicopter to return or to diverge from level flight when disturbed in roll is called spiral stability.

Flight tests are carried out in level, climb and autorotative flight by rolling the helicopter with the lateral control from a trim condition. Longitudinal control is used to maintain trim speed, pedals and collective control are held fixed and lateral control is re-trimmed to hold the bank angle. The stabilizations are repeated in both directions for a desired range of bank angles (Figure 1.26).

The helicopter exibits positive spiral stability if lateral trim changes in the direction of the bank angle.

1.3.4.5 MANOEUVRING STABILITY

Stability characteristics during manoeuvring flight are very important in order to fulfill the precision flying requirements of military missions.

According to current military spec (Reference I-20), the measure of the manoeuvring stability is given by the longitudinal cyclic changes required to produce a normal acceleration above or below 1 g. The stick forces are also measured because the transient longitudinal response characteristics greatly affect the manoeuvring flight.

In some helicopters this stability has to be provided artificially.

The manoeuvring stability is positive when is required, to increase the load factor, aft movement of the longitudinal cyclic (Figure 1.27) with increasing stick force (Figure 1.28).

Tests should be carried out through the full range of operational conditions but normally the critical ones are high altitude, max aft CG loading, high airspeed and load factor.

To build up normal accelerations, symmetric pull-up and push-over manoeuvres and steady turns are carried out with the collective pitch constant at the trimmed initial level flight speed value.

For the pull-up and push-over tests an aft cyclic step is firstly applied to achieve the desired load factor; then the cyclic is pulled to re-trim the helicopter at the same speed and altitude in level flight.

For steady turn tests the helicopter is trimmed in level flight at the desired speed. With the longitudinal control force trimmed to zero, constant speed descending turns are executed both to right and to left, at 15 degrees bank angle increments up to 60 degrees. Rotor speed should not be adjusted during the turns except to maintain it within the power-on limit. Balance may be maintained with pedals.

1.3.4.6 DYNAMIC STABILITY

The dynamic stability tests analyze the way in which the helicopter returns to the stabilized condition left following a disturbance (ie, natural stability characteristics).

Figure 1.9 and Figure 1.17 show how a reduction of airframe pitch stability (resulting from an external weapon installation) affect the longitudinal eigen-modes of the helicopter.

The helicopter response to an external disturbance is an oscillatory movement, generally coupled, which can be divided in two types, short and long-period.
According with the requirements, the oscillation should be not divergent but damped or of period long enough to allow the pilot to regain the desired speed and flight path without much effort.

If not yet installed, a stability and control augmentation system could help to accomplish the requirements and flight testing for dynamic stability may produce also data to optimize it.

Tests are to be carried out on all the flight envelope in hover, level, climb and autorotative flight.
Data recording starts with the helicopter trimmed in the desired condition, then a quick pulse is applied by displacing a control one inch from trim position, holding it for approximately one second, returning to the trim position and holding the control fixed. A mechanical jig may be used to guarantee precise control inputs.

Control pulses are to be applied in the two directions and to all four controls, holding the others fixed till the helicopter regains the stabilized condition, unless it may jeopardize safety (Figure 1.29).
The more critical conditions normally occur with aft CG loading and high altitude.

In order to better investigate the short-term characteristics, double pulse input (doublet) should be used, generally in hover and low speed tests.

The damping ratio of the oscillatory movement of the attitude along the interested axis gives a quantitative support to the judgement of the test results. It is computed as follows:

$$\xi = \frac{1}{N.\pi} \ln \frac{Ai}{Af}$$

Where Ai, Af = initial and final amplitude
N = number of oscillatory semi-periods between Ai and Af

If a weak directional stability has resulted from the tests described in section 1.3.4.4, dynamic stability tests may highlight some dutch roll instability.
In order to improve this kind of instability, design modifications were made in the past during the development phase to the tail section of a few helicopters (endplates on the horizontal tailplane - MBB and Aerospatiale - addition of a ventral fin - Agusta) to increase the total fin area.

1.3.4.7 MISSION-RELATED HANDLING QUALITIES

The results of the basic flight tests described in the previous sections are sufficient to qualify a multipurpose military helicopter but are generally not enough to demonstrate the suitability of the helicopter to a specialized role.

The need of the industry to have guidelines to design and the need of the certification agencies to obtain data to formulate new flying qualities requirements for the new generation of modern military helicopters has lead both US and European research centers to conduct studies and experiments having these needs as objectives (a review is reported in Reference I-27).
The desired missions have been divided in specific mission elements, each defined in detail and flight tested, like vertical displacement terrain avoidance manoeuvre, dolphin, slalom, circle manoeuvre and others.
The pilot control strategy to perform this kind of task optimizing task performance and pilot workload has been studied (References I-33, I-34) and flight test data were analysed to support and correlate the qualitative pilots' comments.

Based on these experiences, the NASA sponsored document cited earlier (Reference I-19) has defined the procedures of a series of precision tasks and aggressive tasks to be flight tested to demonstrate by qualitative judgements the manoeuvrability of the helicopter.

Another important point to investigate, covered by some specification, like that for the AAH (US Army), is the behaviour of the helicopter during stores release and firing tests.
Positive separation without contact should occur throughout the desired flight envelope without exceeding limits with control held fixed for five seconds.
The helicopter should remain controllable and should be possible to regain the trim condition with little control displacements and without excessive control forces.
Also during firing tests no sharp changes of attitude, requiring large control displacements, should occur.

1.4 STORE SEPARATION - PREDICTIVE TECHNIQUES AND FLIGHT TESTING

1.4.1 GENERAL

1.4.1.1 HELICOPTER/STORE AERODYNAMICS

The use of a rotary-wing aircraft as a platform for carriage and release of stores creates complicated problems due to the transient environment which surrounds the launch platform. This environment is caused by the magnitude of the rotor induced flowfield velocity which fluctuates in time and space.

The perturbated flowfield induced by the rotor wake, fuselage, suspension system and adjacent stores can have a significant effect on the store separation trajectory. Some operational concepts in air launched weapons emphasize that helicopters must operate at nap-of-the-earth conditions and take advantage of terrain features during store release. The rotor induced flowfield effects during store release are significant at these conditions and are maximized during hover deployment of certain weapons (eg, anti-tank weapons/missiles). Thus, the store is vulnerable to rotor upsetting disturbances during the initial segment of its separation trajectory.

During release or jettison, the store should not collide with the helicopter or with any other stores and must not interfere with helicopter operations. Helicopter skids represent a potential obstacle to unpowered stores released from the helicopter side (see case histories F and H). The position of stores relative to rotor wake can have a strong effect on the separation trajectory of the store therefore creating a potential for collision. In addition, critical safe separation situations are often encountered in steep descent or in autorotation when the fuselage angle of attack reaches the highest values.

The behaviour of low weight unstable stores after jettison, such as empty launchers, canisters or fuel tanks, is strongly dependent upon the perturbated flowfield, Reference I-35. Those stores whose aerodynamic loads are large in comparison to their weight and moments of inertia, are unstable when jettisoned. Being unstable, even a small aerodynamic disturbance will cause large deviation in the separation trajectory. Also being light in weight, the store may be moved with small disturbances. This results usually in large angular and displacement departures during separation. Because large angular displacements could result in tumbling, many store prediction methods will not accurately simulate the separation trajectory of unstable stores.

Figure 1.30 depicts a typical helicopter speed envelope (horizontal speed versus vertical speed for power on and power off conditions) showing safe and critical areas for release or jettison of stores. An envelope similar to this exists for every helicopter. The boundary between safe and critical areas depends upon the store mass properties, ejection forces and aerodynamic loading acting upon the store.

A qualitative description of the rotor perturbated flowfield is given in order to get a very general understanding of the helicopter/store aerodynamic environment.

1.4.1.2 HELICOPTER FLOWFIELD ENVIRONMENT

In hover, the rotor wake is divided into two parts: strong rolled up tip vortices; and inboard vortex sheets. The vortex sheets contract and move down rapidly below the rotor plane. The tip vortices contract, roll up and move down less rapidly than the vortex sheets, Figure 1.31. However, because of the interaction between vortices, flow fluctuations, fuselage effects and various manoeuvres, the geometry of the wake may vary with time. As soon as the helicopter gains forward speed, the vortex sheets and tip vortices are skewed back and they mix together.

In hover and very slow forward flight conditions, the greatest component of the rotor induced velocity is the downward component while the lateral and longitudinal components are relatively small, References I-36, I-37 and I-38. As a result, under these conditions, the angle of attack of a side mounted store at its carriage position may reach 90 degrees with a large sideslip angle, Figure 1.32. It has also been observed, Reference I-38, that the ground effect at a height of one rotor radius may reduce the total and vertical velocities by as much as 50 percent of the out of ground effect values.

The position of the intersection of a store trajectory with the rotor wake boundary is most significant as it determines the length of time a store remains in the higher induced velocity region inside the wake. It also determines the location where the close proximity of the wake boundary results in a high induced velocity on the store, thus producing supplementary loads and moments. In hover and low speed forward flight, the rotor induced velocities are the highest and large impulsive type, induced velocity variations with time will occur at points on the store trajectory near the wake boundary. These variations are caused by the passage of the rotor tip vortices. These variations decrease rapidly at points away from the rotor wake boundary and are negligible at high speed. The frequency of the flow fluctuation in the wake is the rotational frequency times the number of blades. This is considered high enough that stores which are immersed in the rotor wake will not respond to these rotor blades passage flow fluctuations, Reference I-39.

Also, in hover and low speed flight conditions, as a store moves from within the rotor wake toward the wake boundary position, the downward velocity increases. As a store moves outside the rotor wake, the magnitude of the downward velocity decreases abruptly and becomes rapidly insignificant, Figure 1.33. This causes large flowfield incidence changes on the store during the separation trajectory and can significantly modify the trajectory of stores.

In forward flight conditions, the rotor wake boundary is skewed back, and for a single rotor light helicopter at a forward speed greater than about 30 knots, the forward wake boundary passes behind the position where fuselage side mounted stores are usually launched, Figures 1.34 and 1.35. The result is that rotor effects in that area are small compared to those of the free stream velocity. Thus, the rotor induced effects on a store trajectory decrease with increasing flight speed. The rotor wake boundary skew angle is a function of flight conditions, mainly flight speed, and rotor disk loading.

1.4.1.3 STORE SEPARATION - PREDICTIVE TECHNIQUES

In supporting the installation of a weapon system on a helicopter, aerodynamic analyses are made to determine aerodynamic coefficients of the weapon system and to predict the store separation trajectory. Methods to predict store aerodynamic coefficients and store separation trajectories may be categorized into three broad groups: theoretical, analogy and empirical. These three groups are distinguished by their different aerodynamic approaches and each offers advantages and disadvantages.

Store separation theoretical predictions utilize fluid equations which can be coupled or uncoupled to solve the equations of motion. By coupling the fluid equations to the equations of motion, one can solve for the new attitude of the store at a specified interval of time in the store trajectory and then use this new aircraft/store physical relationship to calculate a new flowfield. Using the new flowfield parameters, the aerodynamics is updated and the process is repeated for a complete store trajectory.

A store separation trajectory can also be predicted by analogy. The analogy relies on past experience with a store of similar aerodynamic shape and mass properties and using its known separation characteristics to predict the separation behaviour of a new store.

Empirical methods are based on wind tunnel techniques which range from simple qualitative flow visualization tests to detailed measurements of force and velocity fields. These methods provide more accurate data of the helicopter-weapon system aerodynamic environment and loads. The wind tunnel approach can be used to carry out a specified survey of points throughout the flowfield and to produce stores aerodynamic data. These data are recalled in a trajectory prediction program when the store moves to a new point and/or attitude.

1.4.2 ANALYTICAL METHODS

1.4.2.1 THEORETICAL PREDICTIVE METHODS

Prediction of store separation behaviour depends upon reliable prediction of the store aerodynamic coefficients. For fixed-wing aircraft, theoretical and experimental methods to predict stores air loads are discussed comprehensively in Reference I-5. The calculation of store aerodynamic forces and moments due to the free stream, fuselage and rotor interference effects can be evaluated using analytical methods. As discussed in Reference I-35, purely analytical predictive methods used to determine the captive loads on stores mounted on fixed-wing aircraft utilize various panel methods that solve the linear Prandtl-Glauert equation. A general three dimensional boundary value equation is then solved for the configuration of interest. Panel methods have evolved to the point where rather complex configurations can be addressed. Higher order versions of panel methods allow a linear source and quadratic doublet variation on each panel. These improvements have helped to make panel solutions less sensitive to panel spacing and density allowing more complex configurations and problems, such as helicopter/store aerodynamic environment, to be studied.

Some computational panel methods, such as the National Aerospace Laboratory (NLR) panel method, NEAR and VSAERO, References I-8, I-9 and I-10, have been used extensively for the calculation of the aerodynamic characteristics of complete fixed-wing aircraft configurations. The NLR panel method has been used for the prediction of aircraft-store interference effects data of the Northrop F-5 aircraft. These data have been used relatively successfully in the prediction of store aerodynamic loads and trajectories.

Such panel methods can be adapted for helicopter/store interference calculations provided that the rotor induced flowfield about the released store can be represented accurately. The VSAERO panel method, Reference I-10, has been adapted to the helicopter aerodynamic environment and permits a full description of the highly interactive helicopter flowfield, including the mutual interference effects of the rotor, fuselage and stores, Figure 1.36. This method calculates the store loads and predicts the store trajectory.

Recently, the Royal Aircraft Establishment store trajectory prediction program for fixed-wing aircraft, RAENEAR, has been modified to predict trajectories of stores released from a helicopter at low forward speed, less than 30 knots, References I-9 and I-40. The main modifications to RAENEAR are the modelling of the rotor wake induced flowfield and an adaptation of the force calculation method on the store body and lifting surfaces at high angle of attacks. RAENEAR calculates the flowfield then the store loads and uses the equations of motion to calculate the trajectory.

In the modified RAENEAR, the rotor wake pertubated flowfield around a helicopter is calculated from the vortex induced velocities of a prescribed wake geometry developed from a series of wind tunnel tests, Reference I-41. In the wake, the rotor blades are modelled by bound vortex lines divided into a number of segments each having a different circulation strength corresponding to the variation of the radial load distribution. Trailing vortices originate at the ends of blade segments and take a prescribed contracting helical path below the rotor. The rotor wake is set up using a prescribed wake geometry which has two parts, an inboard vortex sheet, and a strong, rolled tip vortex, Figure 1.31. The vortex sheet moves down rapidly below the rotor and its vertical displacement varies linearly with the blade radius. The tip vortex rolls up and moves down less rapidly than the vortex sheet. The tip and vortex sheet radial and vertical displacements are found for a given blade azimuth position as a function of thrust coefficient, rotor solidity, number of blades and blade linear twist. The modified RAENEAR was validated using wind tunnel flowfield data for the Huey Cobra helicopter, References I-36 and I-37, and was found to be sufficiently accurate for preliminary prediction of store loads and separation analysis.

Some separation trajectories have been simulated using the modified RAENEAR for Sea Skua missile and a rocket launcher. The stores were simulated gravity released from the fuselage side launch position of a Westland Lynx helicopter at forward speed less than 30 knots. It was found that for a store having a high mass (320 lbs) and high pitch and yaw moments of inertia (44 slug-ft2), the rotor wake has negligible effects on the store. For a low mass store, such as an empty rocket launcher, only the angular displacement in pitch is significantly affected by the rotor wake. In all cases, the lateral and longitudinal displacements and angular displacements in yaw and roll were small. It was also found that the angular displacement in pitch is a function of the helicopter forward speed and the store position relative to the rotor wake forward boundary position. At low forward speeds, the Sea Skua separation trajectories predicted by the modified RAENEAR gave a good correlation of drop flight trials, Reference I-42. At speeds greater than 30 knots the rotor wake is not modelled, as the rotor wake effects on a helicopter launched store are assumed to be small, and the modified RAENEAR program operates as for a fixed-wing aircraft case.

Another type of store trajectory prediction method is to use the aerodynamic coefficients of the store, when they are known, as inputs to a computer store separation trajectory program. Unfortunately, the use of this method is strongly limited by the following considerations:

a. the freestream aerodynamic coefficients given by the store manufacturer, when available, are often limited to a small incidence range. This is not sufficient to predict a store trajectory where large incidences can occur just after release in the hover or at low speed cases. Also, modern anti-tank and air-to-air missiles are located in jettisonable containers for which the aerodynamic coefficients are usually unknown. Thus, wind tunnel testing must be conducted to obtain aerodynamic coefficients over a wide incidence range; and

b. it is difficult to accurately model the interference effects between the airframe and the weapon suspension system.

The confidence level in theoretical predictive methods, such as VSAERO and modified RAENEAR, for speeds between 0 to 30 knots is expected to be fair. At higher speeds, more confidence exists in the theoretical methods based upon their successful use by the fixed-wing aircraft community. However they have yet to be applied extensively by the rotary-wing aircraft community. While the analytical predictive methods are valuable design tools, the ultimate proof of a predicted safe separation trajectory for a store is found through wind tunnel and flight tests which are conducted to validate critical conditions.

1.4.2.2 ANALOGY PREDICTIVE METHODS

The second approach to predict separation trajectory of a store is to proceed by analogy when similarly shaped stores have been previously tested. As discussed at Reference I-35, this approach is advantageous when a preponderance of data shows that from similarity the new store can be tested in a low risk manner. In these instances, many store characteristics are compared between the two stores - the new store and the store that has already been tested. The store analogy is established on the basis of mass, moments of inertia, centre of gravity position and physical similarity between the two stores including the platform areas.

Freestream aerodynamic data are generally compared between the stores and if experimental data are not available, semi-empirical aerodynamic estimation codes are used to generate a comparison. A simple technique to estimate freestream aerodynamic characteristics of a store is to use standard publications such as the Engineering Science Data Unit Items, Reference I-43, or "Fluid Dynamic Drag" and "Fluid Dynamic Lift", References I-4 and I-14. These standard publications are based on wind tunnel test results for different shapes, Mach number and incidences. However, it must be noted that these standard publications are limited to stores immersed in a uniform flowfield and for given Mach number, shapes and incidence ranges.

A number of semi-empirical aerodynamic estimation codes, based on wind tunnel tests for similar shapes, may be used in conjunction with freestream data bases. These codes provide a first order estimate when freestream data are not available. These codes are also used to produce freestream aerodynamics to be used with wind tunnel techniques, such as flow angularity and grid data, as inputs to six degree of freedom trajectory programs. Most semi-empirical codes compute the aerodynamic coefficients for the geometry, Mach number/angle of attack range of interest for first order estimates of store captive loads and release behaviour.

In attempting to establish the flowfield analogy, the missing data are generally the interference flowfield effects and one should consider differences in where the stores are positioned in the flowfield. The accuracy of the analogy method is somewhat limited by the difficulty inherent to the estimation of the interference effects between the basic aircraft components (fuselage, rotor and stub wings) and the weapon installation and also, between the various components of the weapon installation itself.

For a helicopter, the perturbated flowfield is strongly dependent on the helicopter weight, height above ground, forward and sideslip speeds and aircraft manoeuvres. One should ensure that these parameters are similar for a given helicopter when establishing an analogy. The authors of this paper believe that comparison of stores attached to different helicopters should be approached with caution due to the potential differences in the helicopters weight and fuselage characteristics, rotor aerofoils, blade twists, diameters and rotational speeds. The location of each store lifting surfaces at various locations in the flowfield should be noted as well as the similarity in the suspension and release system. A primary consideration is any variation of the centre of gravity relative to the ejection force.

The basic advantage the analogy method offers is a minimal cost program for generating a flight clearance by circumventing the cost and lead time required for wind tunnel testing and/or theoretical analyses. The technique is best suited to minor design changes for previously cleared stores, or for stores of similar shapes. The greatest disadvantage is in the relative risk and the amount of judgment and experience that must be relied upon in deciding upon the approach for a particular problem.

1.4.3 WIND TUNNEL TESTING

1.4.3.1 EMPIRICAL PREDICTIVE METHODS

The third approach to determine the store aerodynamic coefficients and predict separation characteristics is to conduct wind tunnel tests. Wind tunnel tests are conducted on a complete scaled helicopter model or part of it.

Generally, the helicopter models do not have the main and tail rotors modelled, and therefore the wind tunnel methods are limited only to produce accurate data for moderate to high speed forward flight. Some helicopter manufacturers/laboratories have developed powered rotor systems which can be mounted on various airframe models. However, the powered model tests are expensive and time consuming and are therefore normally used only when an unexpected result occurs during analysis or appears during the flight test program. It has been demonstrated from wind tunnel tests that for a single rotor light helicopter at a forward speed greater than about 30 knots the main rotor induced flowfield does not impinge upon stores that are mounted on the fuselage sides. At high speeds, the confidence level in wind tunnel testing to determine the store aerodynamic coefficients and store trajectory is good.

The store freestream aerodynamic coefficients can also be measured in a wind tunnel. These coefficients can be used as inputs to a separation trajectory program which requires freestream aerodynamic coefficients and to validate semi-empirical estimation codes.

There are basically four wind tunnel techniques that are used to predict store separation trajectories. These techniques are: the captive trajectory system, grid, flow angularity and freedrop. A description of these techniques, as presented at Reference I-35, follows. The freedrop technique is emphasized in this paper as an accurate technique to predict the trajectory of stores launched from helicopter.

To support Captive Trajectory System (CTS) testing, wind tunnels are equipped with articulated dual sting arrangements. One sting supports the aircraft model while the store model with an internal balance is mounted on a separate sting capable of commanded movement in all six degrees of freedom. Aerodynamic forces and moments on the store are measured by an internal strain gauge balance that may measure from five to six force and moment components. The aerodynamic data measured by the balance are fed to a computer during the test run. These forces and moments are combined with other required data such as store mass properties, ejection forces and moments of inertia which are needed to solve the equations of motion and predict the stores next position relative to the aircraft for a simulated increment of time. Then the store is positioned to the calculated new position and the cycle is repeated to obtain a complete trajectory.

The grid technique is essentially a flowfield mapping technique in that the store is positioned to preselected positions and attitudes with respect with the aircraft model. The store/balance combination then measures total aerodynamic coefficient data at each point. A matrix of coefficient data is obtained through a region of the aircraft flowfield that can be expected to encompass the subsequent trajectory path for a particular configuration. By subtracting the stores' freestream aerodynamic coefficients from the total aerodynamic coefficients, a set of interference aerodynamic coefficients can be calculated as a function of position and attitude with the aircraft flowfield. The matrix of interference coefficients becomes a data base available for subsequent trajectory calculations. Also, by using this technique, store captive forces and moments can be measured for different helicopter-weapon system configurations and flight conditions. Usually the aerodynamic coefficients for all stored configurations are measured for small helicopter incidence and sideslip ranges.

The flow angularity method is also used for determining interference flowfield aerodynamics. Aerodynamic data are obtained using a velocity probe attached to a sting in place of the store/balance combination. The velocity probe is used to measure velocity components at various locations in and around the aircraft flowfield within a volume that is expected to include the store's anticipated trajectory. From this information, the store local angles of attack are determined and freestream lift curve slope is used to generate the interference coefficients rather than measuring the interference coefficients themselves.

1.4.3.2 FREEDROP WIND TUNNEL TESTING

In the freedrop wind tunnel technique, also called dynamic drop, scaled store models are constructed to obey specified similarity laws and are released from the aircraft model in the wind tunnel. This technique appears to be the preferred wind tunnel testing method used at the time this paper was written to predict separation trajectory of unpowered stores released from helicopters.

High speed photography is made under stroboscopic light and video cameras are used to record the store trajectory. Multi-exposure photographs are taken to illustrate the variation of position and attitude in time. The film is read to extract time position data that can be used to understand the separation events and to assess the relative risk of flight testing. Figure 1.37 shows a stable separation trajectory and Figure 1.38 shows an unstable separation trajectory of stores released from helicopters in an Aerospatiale wind tunnel.

Static aerodynamic forces and moments acting on the store are properly scaled when the model geometry and flowfield are matched to full scale flight conditions. The accelerations of the model will be similar if the total forces and moments, mass, centre of gravity, and moments of inertia are also properly scaled. The model is scaled to one of the three scaling laws: heavy, light and Froude. Selection of the most suitable scaling law depends on the nature of the separation problems. A detailed discussion of the scaling laws commonly used is given at Reference I-35. It appears that for helicopter store separation testing the Froude scaling law is the most commonly used.

Freedrop testing generally offers the best approach where model size or shape precludes a suitable store-balance-sting combination design. Freedrop testing is particularly suitable for unstable stores where tumbling motion can be continued without the constraint of CTS sting mechanical limitations and allows studying multiple stores releases from racks in the ripple or salvo modes.

In most wind tunnels, the freestream is horizontal and perpendicular to the gravity vector. When testing descent or climb flight configurations this leads to a systematic error due to the fact that the gravity component parallel to the relative freestream cannot be simulated. In descent, which is usually the critical case, the simulated store path always tends to pass closer to the tail surfaces than it does during actual flight testing. Consequently, the systematic error is in the right direction for safety aspects.

The greatest disadvantages to freedrop testing lay in its cost when compared with theoretical methods and the rather limited use of the data for future study.

In summary, when compared with flight tests, wind tunnel tests offer a number of definite advantages, Reference I-35:

a. no flight safety implications;

b. lower cost;

c. measurements can easily be made directly on the model as well as in the surrounding flowfield;

d. the model can be adapted to the test objectives:

(1) small scale models for studying general helicopter-weapon system configurations, and

(2) full scale models for measuring the aerodynamic loads on stores and weapon support installation; and

e. the effect of individual components of the suspension system and store can be isolated.

Conversely, problems arise in the following areas resulting in deviations from true flight conditions:

a. Reynolds number effects;

b. wind tunnel wall and airstream blockage effects;

c. interference due to model support structures; and

d. geometrical inaccuracies in the model itself.

From past experience in the helicopter community, the freedrop wind tunnel technique has proven to be sufficiently reliable to avoid unpredicted collisions with the tail surfaces during the actual store separation tests of unpowered stores. The confidence level in wind tunnel freedrop testing is only medium to high due to the lack of rotor induced flowfield effects and store scaling problems. However, it has been observed, from actual store drop trials that the rotor wake has no significant effects on the trajectory of a high inertia store. This could be explained by the low dynamic pressure that exists in the rotor wake.

1.4.3.3 WIND TUNNEL INSTRUMENTATION

Wind tunnel instrumentation particular to helicopter/store release simulation consists mainly of:

a. camera placed orthogonally to the released store;

b. stroboscopic light flashing at a determined time interval; and

c. event and time markers.

The authors believe that wind tunnel instrumentation has been discussed in an array of publications and for this reason the reader is directed to References I-44, I-45 and I-46 for detailed discussion of this topic.

1.4.4 STORE SEPARATION - FLIGHT TESTING

1.4.4.1 GENERAL

Store separation flight tests are of great importance, since they are the ultimate step in verifying theoretical or empirical predictions of a store trajectory and can be used to expand the predicted separation envelope. Thus, the main objectives of store separation flight testing are to:

a. provide store trajectory data to verify results of pre-flight analysis, to complement the analysis where predictive methods are inexact, and to document the results of store separations;

b. obtain full scale store aerodynamic coefficients in the helicopter perturbated flowfield using a force balance store;

c. acquire basic flowfield data about the helicopter;

d. determine the effect of the rotor induced loading on the weapon system installation;

e. assess the helicopter behaviour during and immediately following the store launch/jettison; and

f. establish the safe flight envelope for launch/jettison of stores.

The actual perturbated flowfield around a helicopter-weapon installation from hover to high forward speed can only be determined during flight tests. The complex flowfield of a helicopter-weapon installation, that can not be simulated completely in a wind tunnel, is related to the presence of the engine air intake suction and exhaust and, rotor induced flowfield. Although good flowfield data can be obtained in a wind tunnel at moderate to high advance ratios, for forward speeds less than about 30 knots, the store aerodynamic coefficients and separation trajectories can only be evaluated accurately by flight trials.

The store captive aerodynamic coefficient measurements in the carriage position are measured directly using a five to six component balance for different helicopter-weapon configurations and flight conditions. These measurements are used to validate and improve predictions of theoretical prediction methods and to correlate wind tunnel test measurements. The test force and moment measurements can be used as inputs to theoretical trajectory predictive method which leads to a preliminary release envelope and flight release data.

While analytical store separation prediction methods and wind tunnel testing are used to define the initial flight envelope for a particular helicopter/store configuration, the results of the flight test program are used to validate and possibly expand the predicted flight envelope for safe release and jettison of weapons, launchers and canisters. Also, actual drop trials are done to ensure that the store trajectory is satisfactory and, if applicable, that the store attitudes are within the allowable specifications for seeker heads to track their intended target (see case histories J and K).

1.4.4.2 FLIGHT TEST MEASUREMENTS

In order to accurately compare flight test data to predictions and to confirm safe separation for all stores over the full release flight envelope, accurate and detailed flight test data must be obtained.

a. Captive Store Aerodynamic Coefficients

The store aerodynamic coefficients are measured using a five to six component force balance for various helicopter configurations and flight conditions. The parameters measured during the testing are:

Store Airload Parameters:

- normal, side and axial forces,
- pitch, yaw and roll moments, and
- attack and sideslip angles.

Helicopter Flight Condition Parameters:

- altitude,
- airspeed,
- helicopter weight,
- helicopter attitude angles and rates,
- helicopter velocities and accelerations, and
- outside air temperature.

In ground effect:

- atmospheric conditions and wind direction/speed, and
- wheels/skids height above ground.

In order to measure store loads, a five to six component force and moment balance, built into a shape representing the store, and magnetic tape recorder onboard the helicopter are necessary to record the loads and flight conditions. Also, strain gauges are employed to measure stress directly or to measure axial loads or bending moments on store or suspension system.

These parameters are measured for various flight conditions such as:

- hover in ground effect,
- hover out of ground effect,
- horizontal flight at different altitudes,
- climb and descent,
- autorotation,
- sideslip flight, and
- manoeuvring flight.

b. Store Separation Trajectory

In orde to acquire sufficient data to analyse the store separation trajectory the following parameters, in addition to the helicopter flight condition parameters as presented in sub-paragraph a., should be recorded:

Store Mass Properties:

- weight,

- centre of gravity, and
- moments of inertia.

These should be determined prior to flight testing for each store released.

Store Drop Conditions:

- store carriage position,
- store attitude angles and rates (pitch, yaw and roll),
- store accelerations, and
- time of release.

Store Separation Trajectory Data:

- store attitude angles, and
- store linear and angular displacements.

1.4.4.3 FLIGHT TEST INSTRUMENTATION

The test instrumentation should be set-up so that it does not alter the aerodynamic flowfield in the proximity of the weapon system installation. The flight test instrumentation needed to acquire store separation data are as follows:

a. a central time code to time-correlate all acquired data whether on the ground or airborne;

b. 16 mm high-speed motion picture cameras for airborne photometric analyses which can be augmented by video camera systems. These cameras are mounted in or on the project aircraft fuselage and are used to:

(1) provide time/position history information to document the separation characteristics of the stores under various release conditions,

(2) monitor arming wires and lanyard behaviours, ejectors, release sequencing and debris, and

(3) provide a pilot's eye view of store separation;

c. cameras mounted on, or hand held aboard, a chase helicopter can also be used to provide a global perspective of the store separation. Occasionally, hard mounted cameras experience vibration problems but these can be mitigated by the use of stabilization platforms for electro-optic sensing systems, such as the Tyler or Westcam platforms. These platforms can accommodate cine or video cameras; and

d. a magnetic tape recorder to record the helicopter flight and store release parameters.

At the heart of obtaining detailed store separation trajectory data lies the camera. Selection of the proper camera, film, frame rate, lens, aperture and camera locations are all extremely important. The reader is directed to Reference I-35 where a detailed discussion on flight test instrumentation is presented.

An alternative to measure store attitudes during drop tests is to install an instrument pack within the released store. The store attitude data acquired via accelerometers during a drop is transmitted to a data recording system by telemetry or via fibreoptic cables. The use of fibreoptic cables at MBB has proven to be a very reliable method of transmitting data (see case history L).

1.4.4.4 FLIGHT TEST INSTRUMENTATION TOLERANCES

Reference I-35 suggests tolerances for the allowable accuracies of the flight instrumentation systems for fixed-wing aircraft. The suggested instrumentation measurement tolerances are as follows:

Store Mass Properties:

weight	+/- 1%
centre of gravity	+/- 0.25 inch
moments of inertia	+/- 1%

Aircraft Flight Conditions at Stores Release:

altitude	+/- 50 feet
airspeed	+/- 5 kcas
pitch and roll angles	+/- 2 degrees
acceleration in all axes	+/- 0.01 g
yaw angle	+/- 1 degree

Store Trajectory Data:

angular measurements	+/- 2 degrees
linear measurements	+/- 1 inch
time	+/- 0.01 second

The authors of Reference I-35 believe that these tolerances are adequate for trajectory analysis. However, the authors of this paper believe that the altitude and airspeed tolerances should be +/- 5 feet and +/- 2 kcas respectively. A more stringent accuracy may necessitate a costly and sophisticated instrumentation and data reduction system that is just not needed.

1.4.5 ASSESSMENT OF THE STATE-OF-THE-ART

The techniques used to predict stores airloads and to certify stores for safe separation from fixed-wing aircraft can be followed and adapted for rotary-wing aircraft.

The analytic prediction methods presently in use in the fixed-wing community are limited to Mach number above 0.3. However, since some analytic methods have proven to predict separation trajectories for stores released from a fixed-wing aircraft to a high confidence level, they should be adapted as the basis for helicopters.

The authors believe that the best approach to helicopter/weapon integration is to conduct a program which is balanced in terms of use of analytical methods, wind tunnel and flight tests to evaluate all aspects of a particular helicopter/weapon integration problem. The adaptation of computational panel methods to the helicopter aerodynamic environment, such as VSAERO, NLR and RAENEAR, to estimate the store captive loads and store separation trajectories could reduce significantly the wind tunnel and flight testing requirements for the certification of a weapon system on a helicopter. In parallel to the development of store captive loads and separation trajectory prediction methods, wind tunnel and flight tests should be conducted to provide validation data for the analysis. No matter what the state-of-the-art becomes in store aerodynamics and separation prediction techniques, flight testing should not be eliminated.

The techniques used in North America and Europe to predict the separation trajectory of stores released from a helicopter are presently evolving at a rapid rate. Present technologies are, in a technical sense, still immature, and potential improvements are envisioned within the next decade as the warfighting capabilities of the helicopter are fully exploited.

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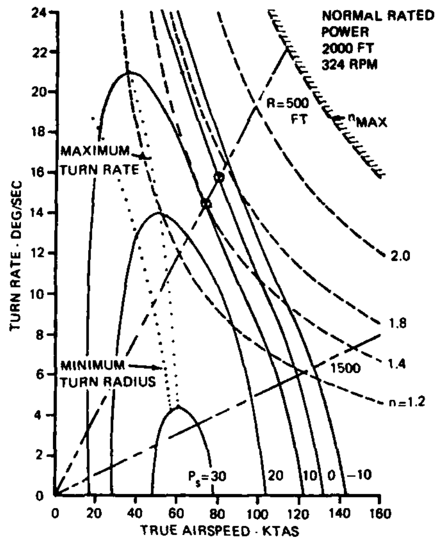

Fig. 1.1 Manoeuvre diagram for AH-1G helicopter at 9000 lb gross weight

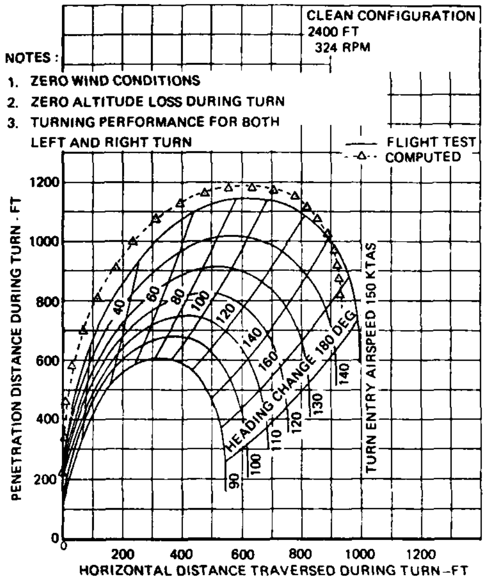

Fig. 1.2 180 Degree Turning Performance for the AH-1G Helicopter at 8750 lb gross weight

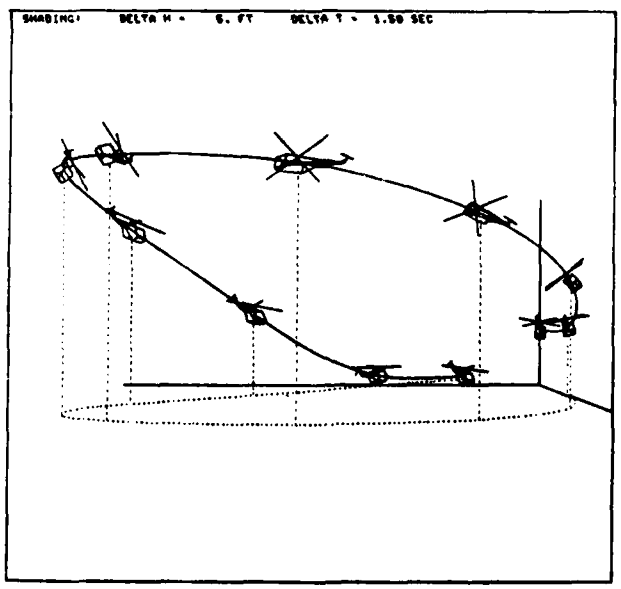

Fig. 1.3 Climbing/descending return to target MCEP manoeuvre for AH-1G helicopter at 9500 lbs all-up weight

Fig. 1.4 HAP Project with 30 MM Gun Turret, Rockets and AA Missiles

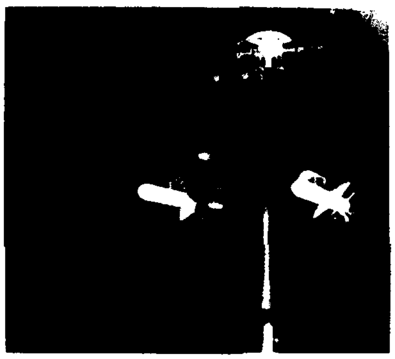

Fig. 1.5 AS 332 "Super-Puma" with 2 AM 39 "Exocet" ASSW Missiles

Fig. 1.6 AS 365 N with 4 AS 15 ASSW Missiles and "Agrion" Radar

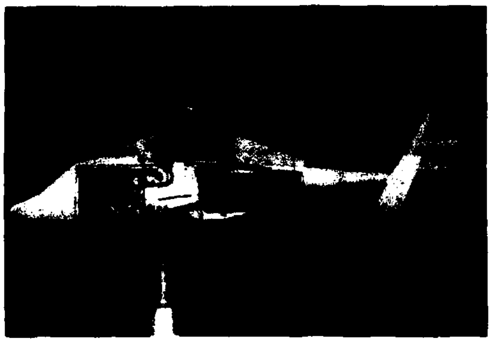

Fig. 1.7 AS 365 N Powered Model (1/7.7 Scale)

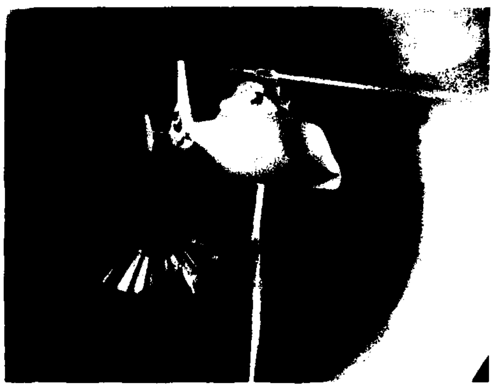

Fig. 1.8 AS 365 N Powered Model In Aerospatiale Wind Tunnel (Marignane, France)

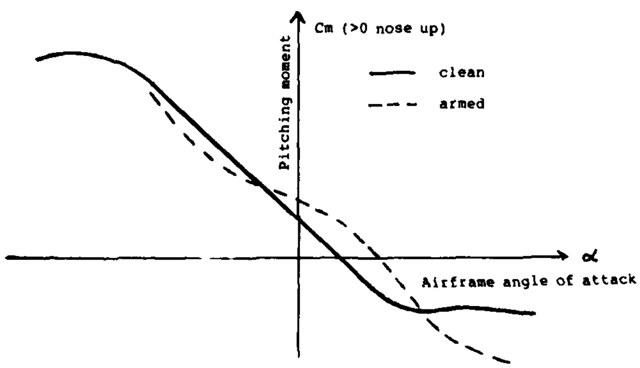

Fig. 1.9 Effect of Stubwing Mounted Weapon System

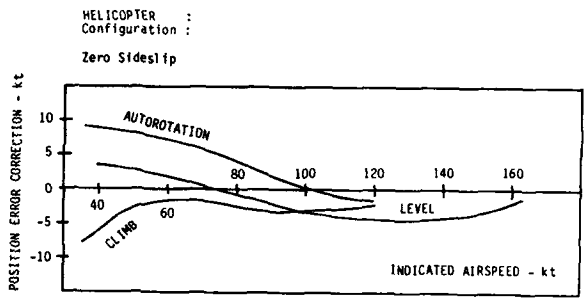

Figure 1.10 - AIRSPEED CALIBRATION

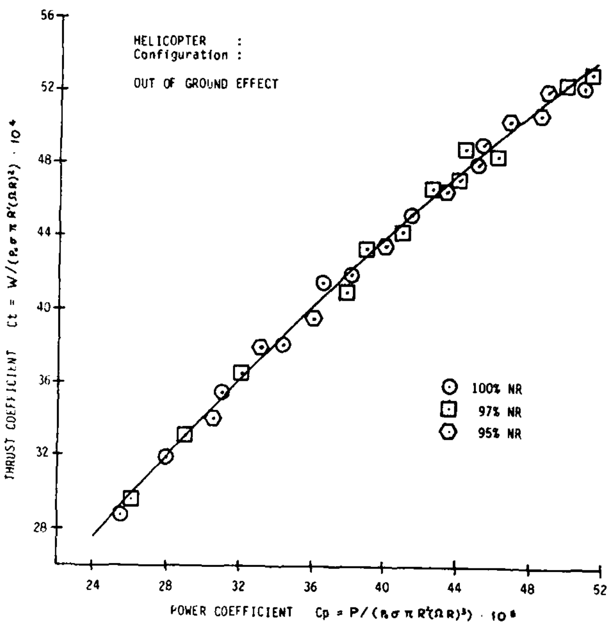

Figure 1.11 - NON DIMENSIONAL HOVERING PERFORMANCE

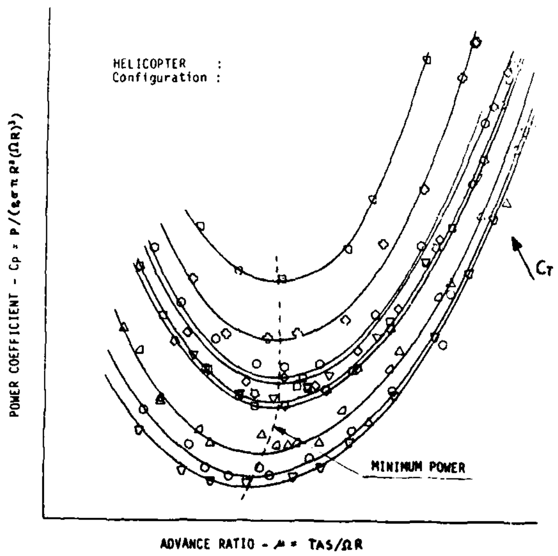

Figure 1.12 - NON DIMENSIONAL LEVEL FLIGHT PERFORMANCE

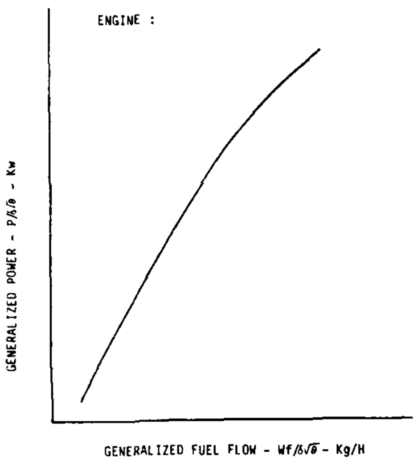

Figure 1.13 - HOURLY FUEL CONSUMPTION

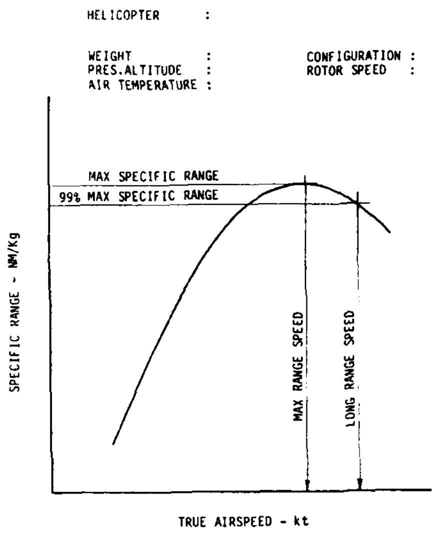

Figure 1.14 - SPECIFIC RANGE

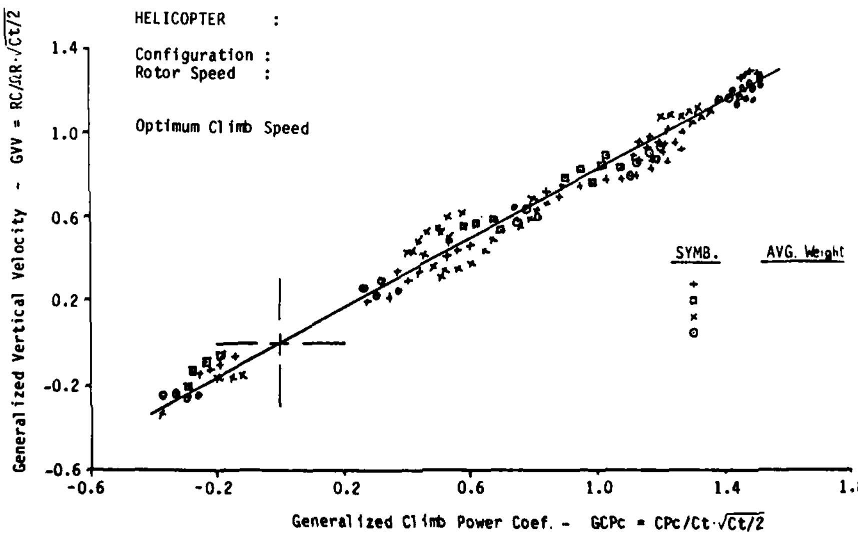

Figure 1.15 - GENERALIZED CLIMB PERFORMANCE

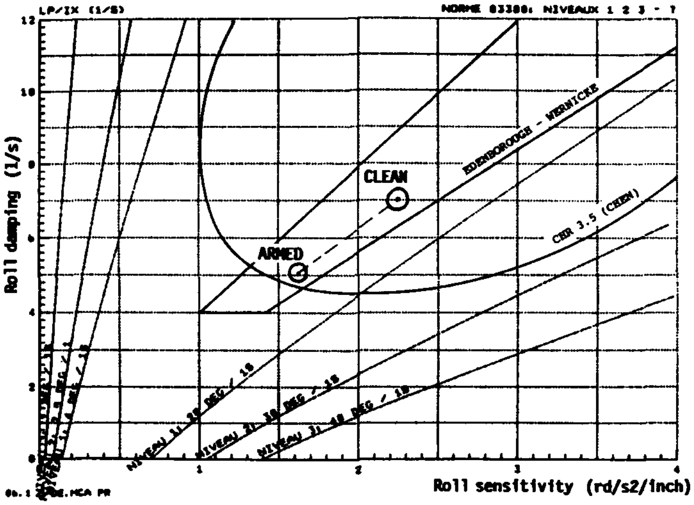

Fig. 1.16 Effect of Roll Inertia Increase on Controllability

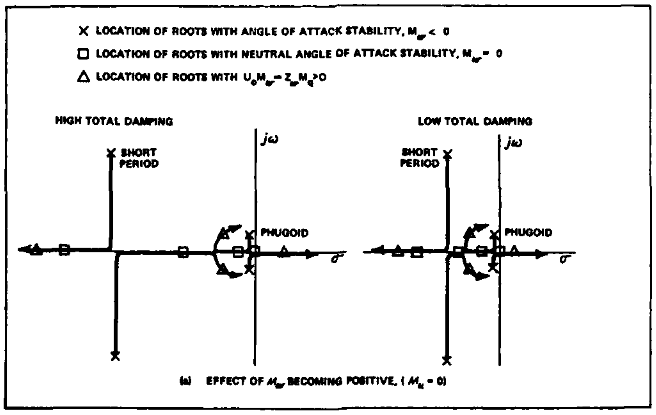

Fig. 1.17 Effect of Angle of Attack Stability on Longitudinal Dynamic Stability (from Ref I-21)

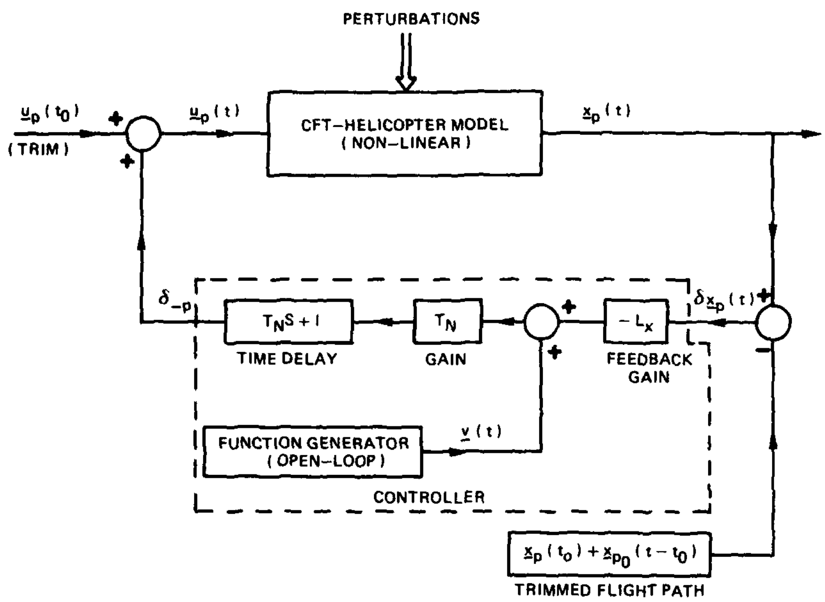

Fig. 1.18 Operational scheme of the controller, combined with the non-linear CFT-model

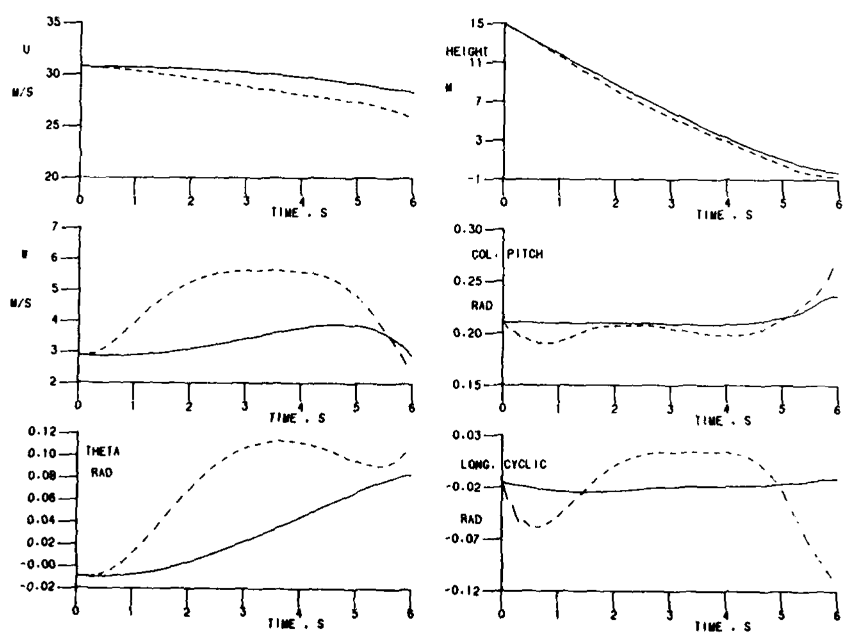

Fig. 1.19 Time histories of state and control elements during normal flare (solid line) and decelerating flare (dashed line)

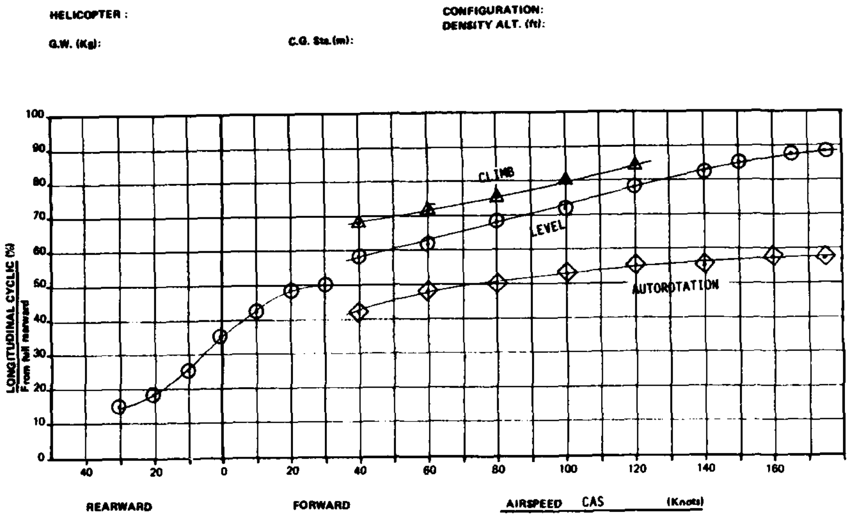

Figure 1.20 - CONTROL MARGINS - LONG. CYCLIC

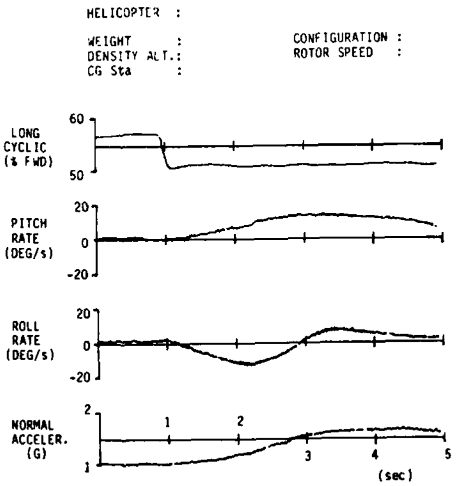

Figure 1.21 - CONTROL RESPONSE LONG. RWD 80 Kt

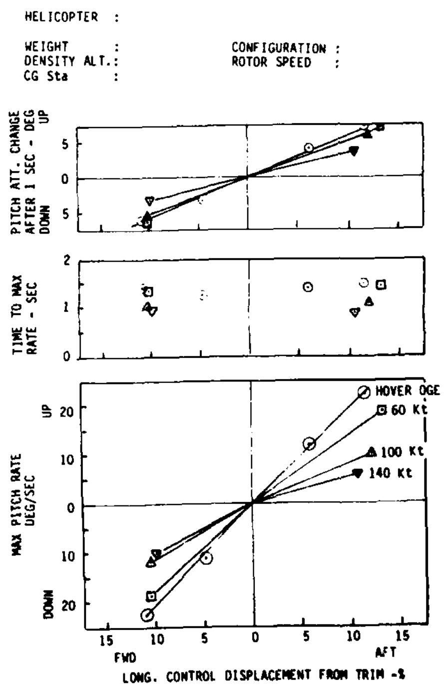

Figure 1.22 - LONGITUDINAL CONTROL RESPONSE

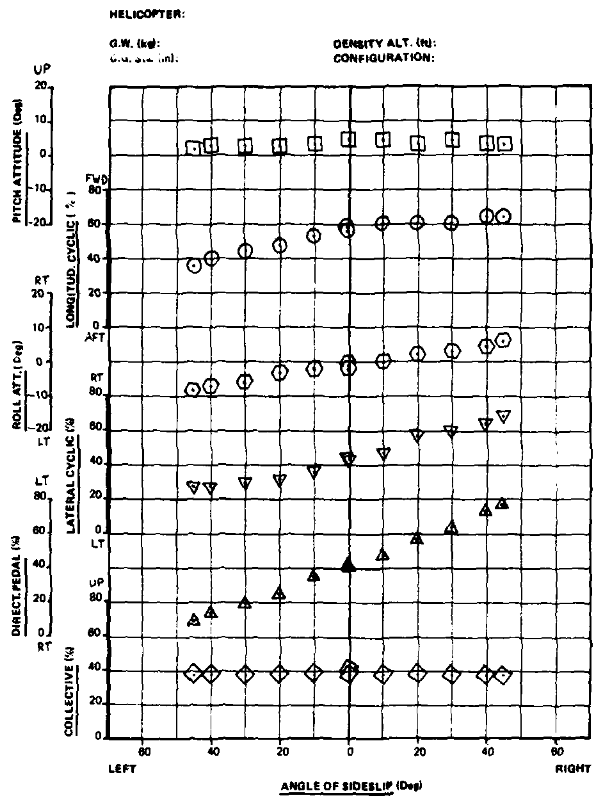

Figure 1.25 - LATERAL-DIRECTIONAL STATIC STABILITY

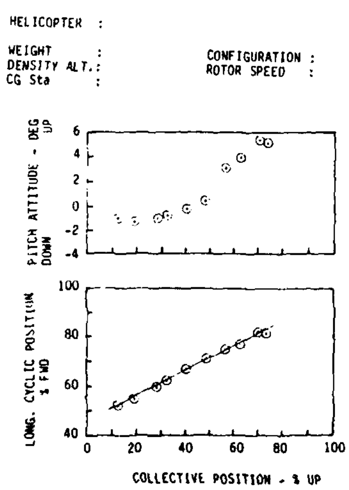

Figure 1.24 - TRIM CHANGE WITH POWER
LEVEL FLIGHT 100 Kt

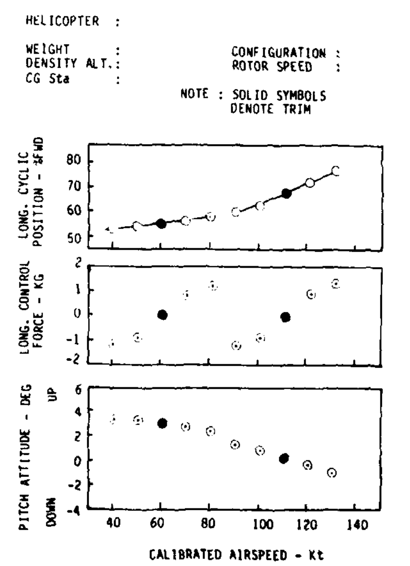

Figure 1.23 - LONGITUDINAL STATIC STABILITY

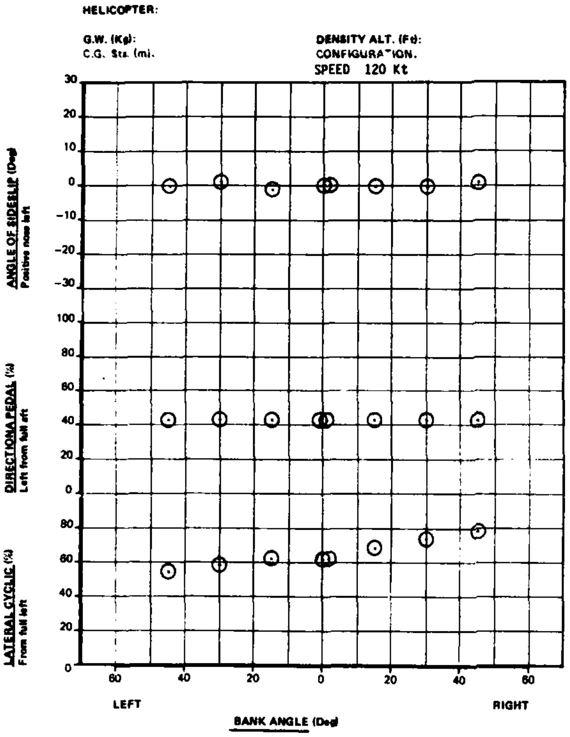

Figure 1.26 - SPIRAL STATIC STABILITY

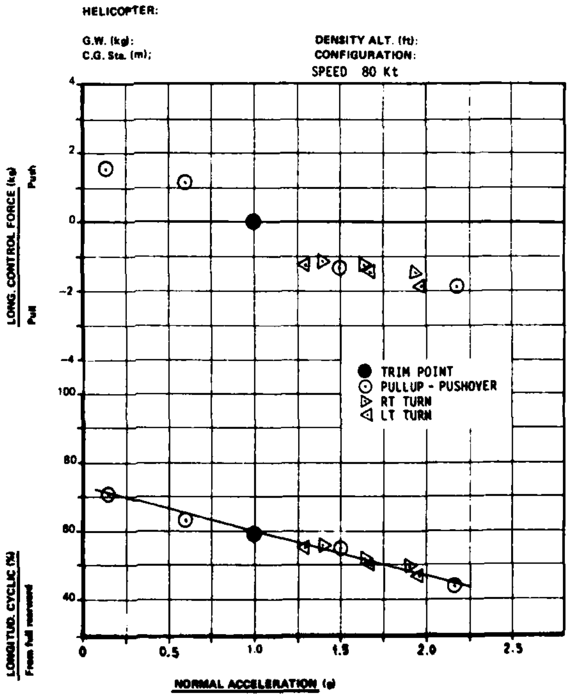

Figure 1.27 - MANOEUVRING STABILITY

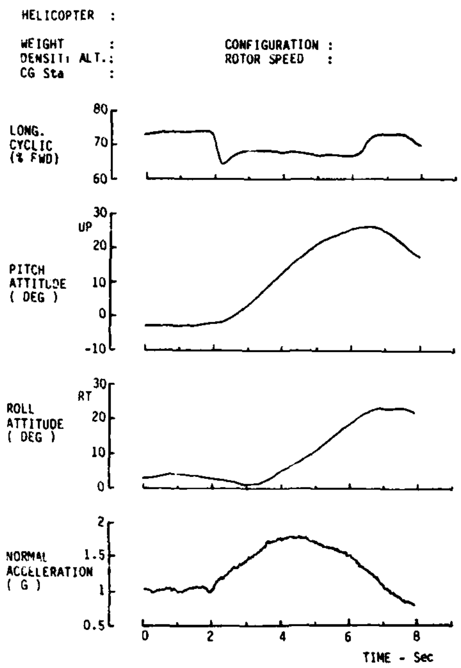

Figure 1.28 - MANOEUVRING STABILITY - PULL-UP 110 Kt

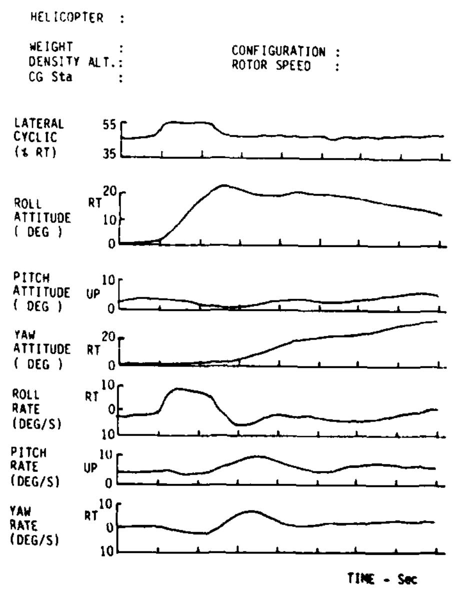

Figure 1.29 - DYNAMIC STABILITY - LAT. CYCLIC PULSE

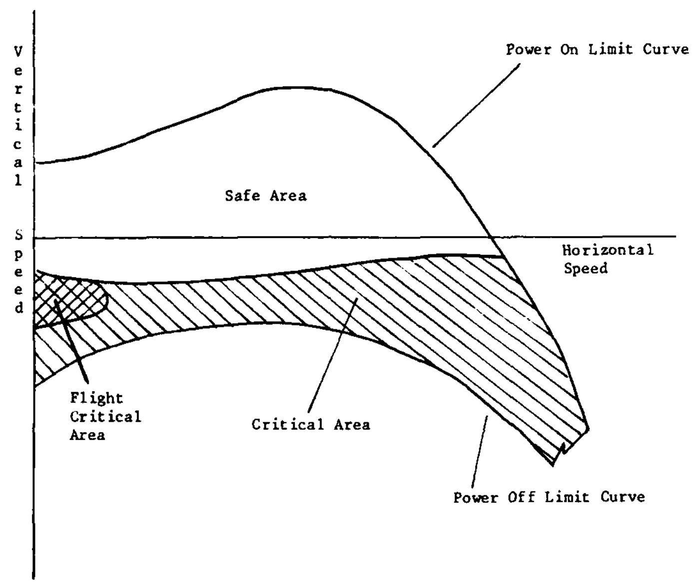

Fig. 1.30 Typical Helicopter Horizontal Speed Versus Vertical Speed Store Separation Flight Envelope (Power On/Power Off)

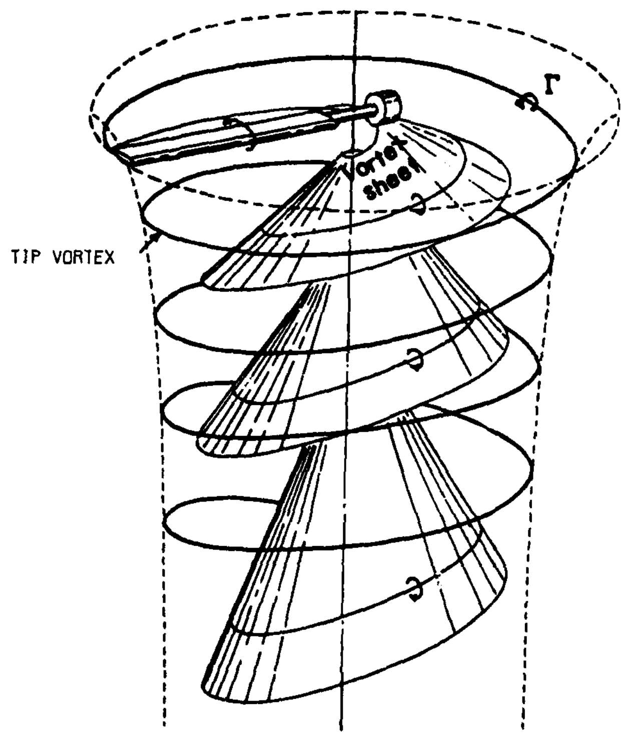

Fig. 1.31 Rotor Hover Prescribed Near Wake
(Reference I-41)

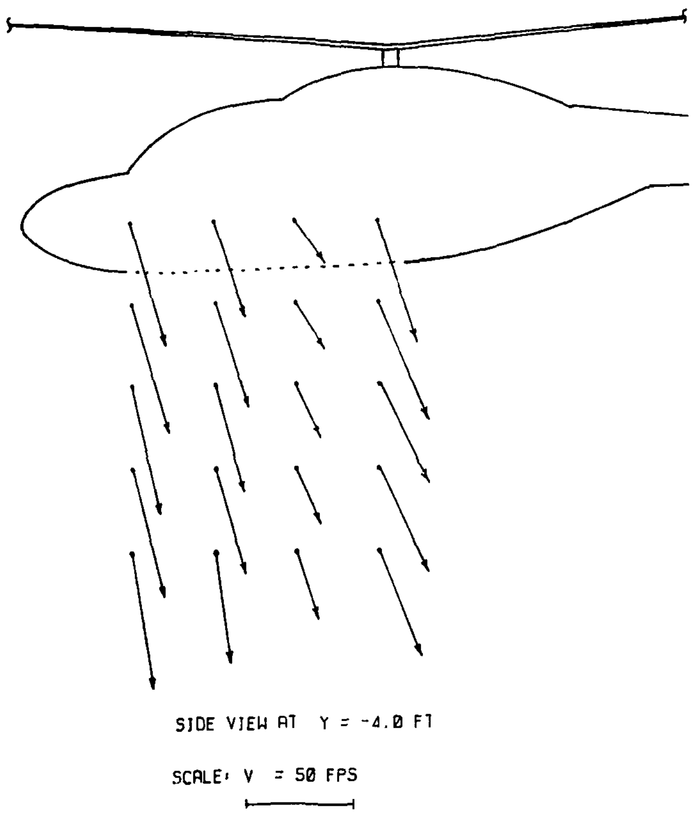

Fig. 1.32 Modified RAENEAR Lynx Helicopter Calculated Flowfield
C_T = 0.00610 V_∞ = 0 Knot (Hover)
(Reference I-40)

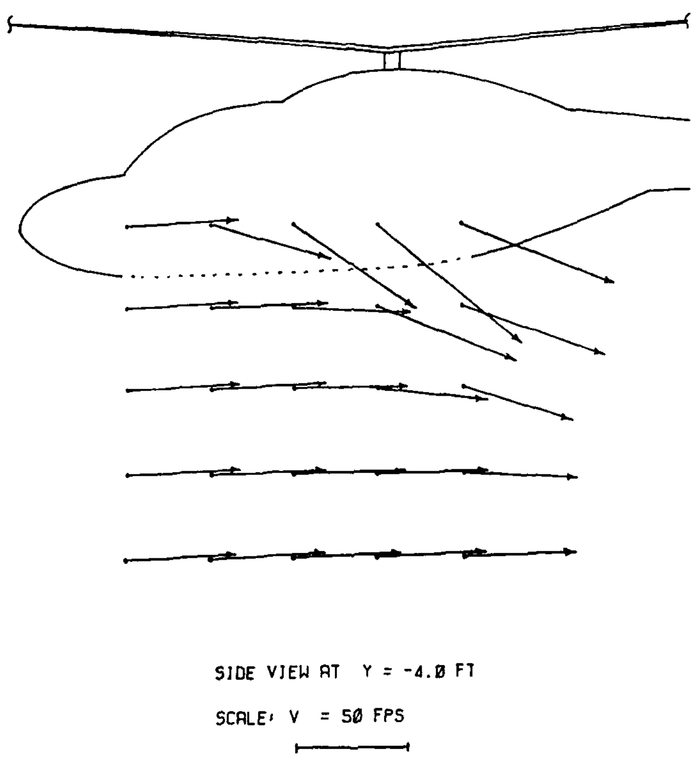

Fig. 1.33 Modified RAENEAR Lynx Helicopter Calculated Flowfield
C_T = 0.00610 V∞ = 30 Knot
(Reference I-40)

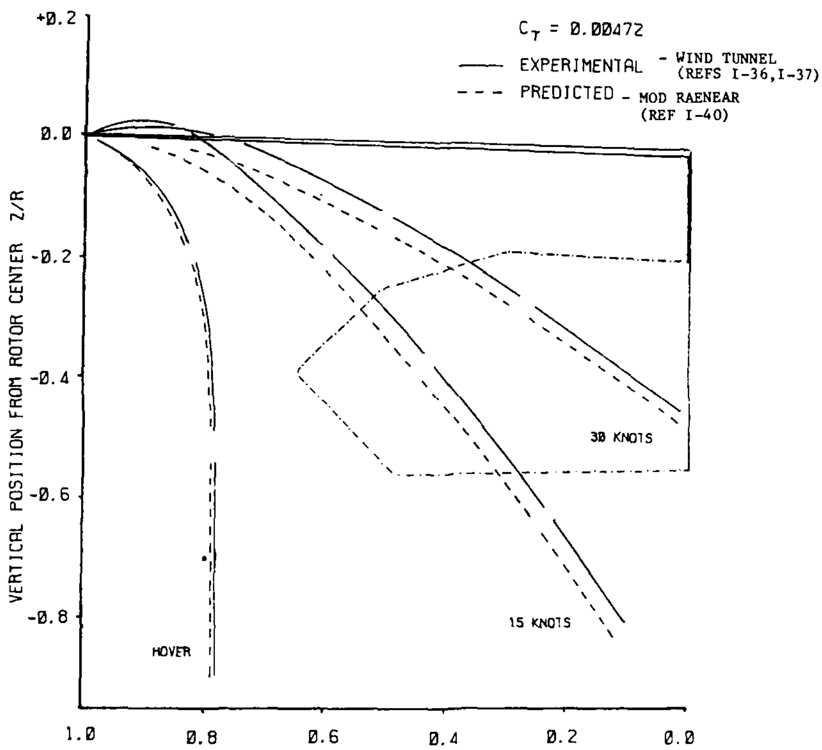

Fig. 1.34 Front Rotor Wake Boundary Position Variation with Forward Speed Flight AH-1G Helicopter

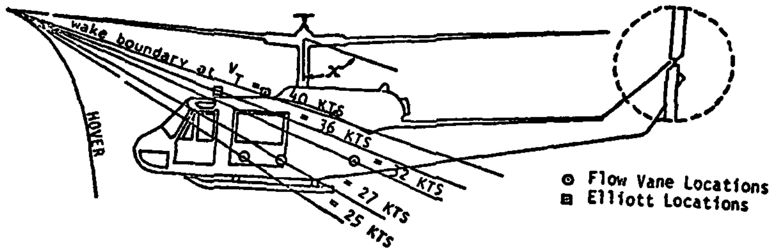

Fig. 1.35 Rotor Wake Boundaries In Forward Flight
UH-1M Helicopter
(Ref I-39)

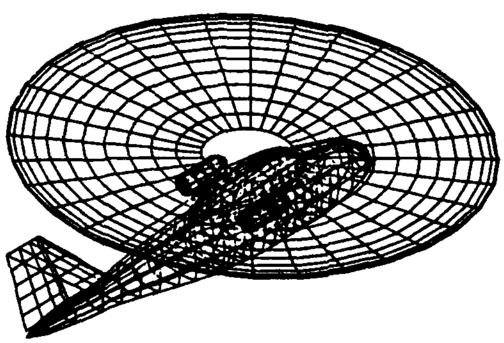

Fig. 1.36 Basic Body Model with Nacelles and Tail Surfaces
(Ref I-10)

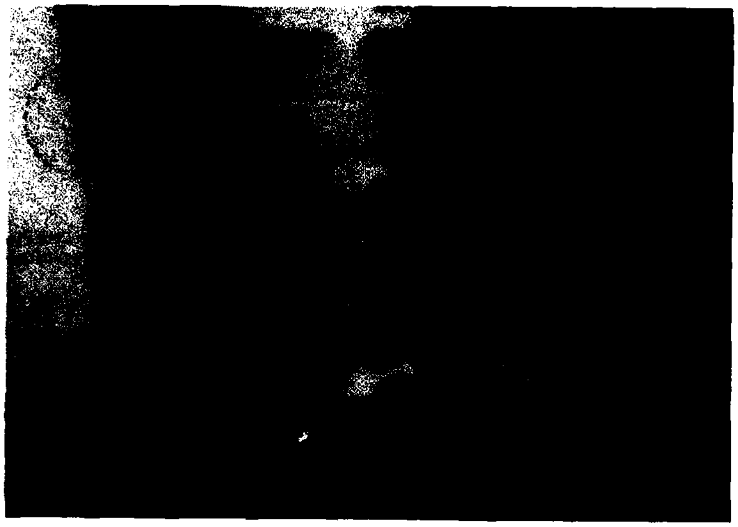

Fig. 1.37 Exocet Anti-Ship Model Missile Released From An Aerospatiale Super-Puma Model Helicopter

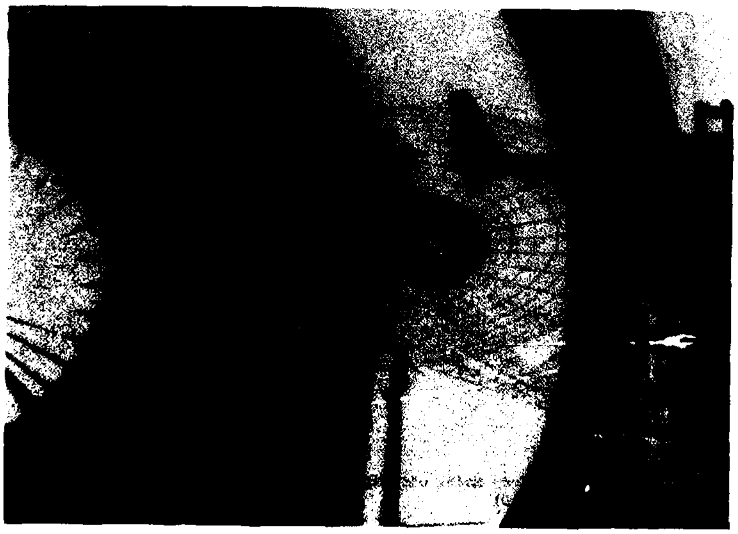

Fig. 1.38 Rocket Container Model Released From An Aerospatiale Gazelle Model Helicopter

2.0 STRUCTURAL MECHANICS

Authors:

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- Frederick H. Immen, US Army Aviation Systems Command, St. Louis, USA

2.1 Loads

2.1.1 General

Weapon carriage produces loads due to aerodynamic forces acting on the weapon and due to the inertia of the weapon. The latter will include vibratory loads induced by the rotors, which are addressed in Section 2.2. In addition, weapon operation can produce loads due to blast, recoil or exhaust gas ingestion by the engine.

2.1.2 Analytic Methods

From the point of view of static design cases for weapons, carriers and airframe support structure, aerodynamic loads are not very significant at current helicopter speeds. Estimates are made from standard sources such as the ESDU Data Sheets (Reference II-1) or "Fluid Dynamic Drag" (Reference II-2) and for structural strength calculations these are normally adequate. More detailed calculations of aerodynamic loads may use computer programs (Reference II-3) such as the VSAERO 3-d panel method used by Bell Helicopter Textron, but these would be done mainly in connection with performance or launch trajectory predictions.

The major loading cases are those associated with hard landings which can easily produce load factors higher than the 3 to 3 1/2g maneuver capability of current helicopters.

Calculation of accelerations due to landing needs to be done with some care to avoid unnecessary conservatism, but at least 4g vertical acceleration would not be unexpected during a hard landing. When assessing the effects on the weapon, dynamic amplification due to flexibility of the carrier should not be overlooked. In the worst case this could double the accelerations seen by the weapon.

Prediction of blast or recoil loads is currently done on the basis of previous experience of measurements of the pressure field made during the particular or similar weapon firing. No validated analytical prediction methods appear to be available, although some are known to be under development. Neither does there appear to be a means of accurately predicting the torque pulse caused by engine surge due to missile exhaust gas ingestion.

2.1.3 Ground Tests

Wind tunnel measurements of the aerodynamic loads caused by external weapons are made by most companies. Six component balances are often used and the measurements cover a range of angles of attack and sideslip. Rotor downwash however is not usually simulated which may limit the usefulness of the measurements in the hover and low speed regimes. Wind tunnel measurements are made mainly to provide data for stability or performance calculations or for the prediction of launch trajectories.

Loads and accelerations associated with hard landings are sometimes measured on a "Drop Test Vehicle" (DTV). This can be a real airframe or a girder structure ballasted to aircraft mass and inertias and fitted with real undercarriage units. This technique allows the limit cases in the aircraft specification to be more accurately investigated than would be possible during actual aircraft landings. Such a DTV could be used to measure the response of weapons to landing impact but care would have to be taken to simulate accurately the stiffness of the airframe mountings and local support structure for weapon carriers if a girder type DTV was used rather than an actual airframe.

It is usual to do ground or "pit" firings of missiles or guns to measure the loads due to blast or gun recoil. Instrumentation normally includes strain gauges, pressure transducers and thermocouples; accelerometers may also be used. The tests must cover the full range of azimuth and elevation angles for guns and the full range of launch angles for missiles where this can be varied. It is also important to cover the range of environmental temperatures that the weapons may experience in service since this affects the burning rates of propellants and hence the blast pressure and temperature. For guns the effect of firing rate on loads should be investigated to avoid coincidence with airframe structure model frequencies and consequent amplification of loads.

2.1.4 Flight Tests

Flight tests are always done on a new weapon system and must cover the complete flight envelopes for weapon carriage operation, and where applicable, jettison.

Strain gauges are the most common form of instrumentation, but pressure and temperature transducers are used to measure blast effects and accelerometers are often used to measure vibration. Signals are usually tape recorded for subsequent analysis on the ground although critical parameters may be telemetered for real time monitoring.

Loads in weapons, carriers and airframe support structure are usually the prime interest but some weapon installations cause significant increases to overall airframe drag which has to be overcome by increased rotor loads so rotor strain gauging may also be necessary. This in turn introduces the need for slip rings. Rotor strain gauging may also be needed to assess the effects of torque pulses in the transmission caused by engines ingesting missile exhaust gases. Strain gauging of engine mounts is also needed together with torque measurement.

The empennage is an area which may also be subject to high loads generated by weapons. During carriage some weapons can cause wake turbulence which may impinge on the tail and produce high loads (See Case G). The more general effects of missile blast are assessed by airframe strain gauging with the tailplane needing particular attention if it is low set. If rockets are carried, which may be ripple fired, the possibility of the firing frequency exciting a structural mode must be checked, as it does also for guns.

2.1.5 Crash Loads

MIL-STD 1290 (Reference II-4) defines the conditions in a crash against which helicopters may be designed. The conditions are specified in terms of velocity changes accelerations and acceleration pulse widths. The US Army's Crash Survival Design Guide (Reference II-5) amplifies the information and in addition gives guidance on how to design for crashworthiness.

The treatment of external weapons is not, however covered, since there appears to be a difference in philosophy between the various procuring agencies. The question is whether weapons should remain attached to the aircraft or allowed to fall away, hopefully clear of the crash area and any post-crash fire. The US Army prefers a break-away design for their external stores support systems, whereas the US Navy design their aircraft to retain weapons in the event of a crash to avoid them causing damage elsewhere on, for example, the deck of an aircraft carrier.

2.1.6 Current Position

There is considerable dissatisfaction among helicopter designers about the effects of weapon drag on the performance of their aircraft. Few weapons are designed purely for helicopter operation and one major group, the anti-tank missiles, are usually derived from ground launched designs where a drag of the launcher is not a consideration. There seems to be a general feeling that if the faster speeds, which modern rotor technology make feasible, say 200 kts, are to be realized in service, changes will have to be made to the way in which weapons are carried and also the design of the weapons themselves.

For Naval helicopters which may carry a variety of torpedoes, depth charges, missiles etc., there could be advantages in having an internal weapon bay; the Russian Ka-25 "Hormone" and Ka-27 "Helix" designs already are thus equipped. There may however be weight penalties and re-arming may be more awkward.

For anti-tank missiles internal stowage is also a possibility with perhaps an internal magazine with a transport mechanism to a firing station. Again it is necessary to balance extra weight and complexity against the benefits of drag reduction. Air-to-Air missiles often nowadays have semi-internal or conformal mounting on fixed-wing aircraft and this might be applicable to helicopters also if some means of avoiding exhaust gas ingestion by the engines could be devised.

If radical changes are to be made to the way in which helicopters carry weapons, it may be necessary to have weapons designed specifically for the helicopter which is to carry them. The current practice of adapting weapons, such as man portable anti-tank missiles, for use on helicopters is unlikely to be satisfactorily if the full potential of helicopters is to be realized. It needs to be recognized that to maximize operational effectiveness it is necessary to design the helicopter and its weapons as a system.

2.2 VIBRATION AND ACOUSTICS

2.2.1 General

Reduction of vibration and noise is one of the most important but most difficult tasks facing the helicopter designer. Rotor induced vibration produces fatigue in both the airframe and the occupants and is a major cause of equipment defects. Internal noise reduces crew efficiency and external noise is an important means of detecting and identifying helicopters. In general, the vibration environment of a helicopter differs from that of fixed wing aircraft in that it is concentrated in discrete peaks at fixed frequencies related to the rotor speed rather than being essentially random (References II-6, II-7) (See Case H).

Carriage of external weapons may adversely affect the overall helicopter vibration levels and excessive vibration of the weapons themselves is a relatively common problem. Coincidence of structural mode resonance frequencies with rotor order frequencies is the usual cause.

Gun firing and ripple firing of rockets can also excite structural modes as well as generating large amounts of acoustic energy (Reference II-8).

2.2.2 Analytic Methods

The vibration experienced by a weapon will depend on the loads generated by the rotors and transmission, the response of the airframe to these loads, the motion at the weapon carrier attachments to the airframe and the dynamics of the weapon and its carrier. If the weapon is large it may have a significant effect on the whole vibration of the helicopter by changing the overall response of the airframe to the rotor forcing (Reference II-7) (See Case T).

Some vibration is also transmitted to the weapon aerodynamically in the downwash from the rotor. This is usually less significant than the structurally borne excitation and will only occur in the hover and at low speeds. Above about 30 kts there is unlikely to be any wake impingement on weapons.

Techniques for predicting oscillatory rotor loads in steady flight conditions with a generally good degree of confidence are now available (References II-9, II-10) and the response of the airframes to these loads can be modeled using methods such as NASTRAN. Such calculations are normally done on new designs as a check against major coincidences with rotor forcing frequencies but the detailed dynamic behavior of the aircraft is usually established by shake testing as well (Reference II-11).

Once the characteristics of the airframe in terms of mode shapes and frequencies are known the effects of adding weapons can be calculated but accuracy may be limited by the difficulties which are often experienced in defining the stiffnesses of the weapon/carrier interface (Reference II-12). This problem has been made worse by the adoption in some countries of MACE (Minimum Area Crutchless Ejector) weapon release units. In the absence of crutches, restraint is provided by spring loaded wedges and this makes accurate definition of stiffness, particularly in roll and yaw, difficult.

2.2.3 Ground Test

Although the overall dynamic characteristics of a new aircraft are usually determined by means of either single or multi-point sinusoidal excitation, the frequencies of a new weapon system are often found from a simple "bonk" check. An impulse is imparted to the weapon and the response measured, usually by means of accelerometers, and Fourier Transformed to give a frequency spectrum from which resonances can be identified. This process is repeated with impulses in various directions to cover all possibilities of pitch, roll, yaw, etc. The resulting frequencies will then be checked against the aircraft avoid bands. For a helicopter with four main rotor blades these bands would normally be centered on 1R, 2R, 4R and 8R, where 1R is the main rotor rotational frequency, and would normally cover the permitted range of rotor speed. Usually the blade passing frequency, nR, is the dominant excitation.

All loading conditions need to be checked including, for example, those produced by partially depleted weapon dispensers.

If frequency coincidences are found, structural modifications may be made to remove them. However, if there is reason to suppose that the excitation from the rotor will be small or that the store resonance is heavily damped, the decision to modify may be left until the actual flight vibration levels have been measured.

2.2.4 Flight Test

In spite of improving analytic capabilities, flight testing is still an essential part of the vibration assessment program.

Instrumentation is usually the same as for the ground tests i.e., mainly accelerometers (usually piezo-electric) and sometimes strain gauges. These are normally fed via signal conditioning electronics to an airborne tape recorder.

A typical set of transducers might be

Accelerometers:	Weapon nose	-	lateral
	Weapon nose	-	vertical
	Weapon nose	-	fore-and-aft
	Weapon tail	-	lateral
	Weapon tail	-	vertical
	Carrier	-	lateral
	Carrier	-	vertical
	Carrier	-	fore-and-aft
	Pilot's feet	-	vertical
	Co-pilot's feet	-	vertical
	Cabin floor	-	vertical

Cabin floor - lateral

Cabin floor - fore-and-aft

Strain gauges: Carrier

Airframe attachment points.

The whole range of store configurations should be covered, including those produced by abnormal firing sequences to allow for misfires in service. The full range of aircraft speed and flight conditions should be assessed with appropriate aircraft masses and center of gravity positions. Analysis of the records is usually done by means of a spectrum analyzer. Samples of each flight condition are transformed into a frequency spectrum by means of a Fast Fourier Transform algorithm and the response at the various frequencies can then be observed. It is usually found that the spectrum is dominated by the response at the main blade passing frequency.

2.2.5 Current and Future Status

Reduction of overall vibration levels is a high priority objective in most helicopter companies and specifications for new projects are tending to include firm requirements for lower vibration levels than are found in current helicopters. Various techniques are available and others are being developed to reduce vibration and these are well documented elsewhere (Reference II-13). This trend will obviously make for a less damaging environment for external weapons.

In spite of this however, if there is a frequency coincidence between a weapon vibration mode and the blade passing frequency, high vibration is likely to occur. Because of the versatile nature of helicopters they are usually called upon to carry a variety of weapons which will have different masses and inertias and each weapon may be carried on a number of different helicopters. In these circumstances a frequency coincidence is almost inevitable sooner or later.

When this happens various options are open. Introduction of a device such as a bifilar vibration absorber on the rotor head may reduce the rotorloads enough to give acceptable vibration at the weapon in spite of the resonant condition; however, the weight penalty of such a solution would probably only be acceptable if there were other additional reasons for needing to reduce overall vibration.

The most usual solutions are either to add damping to reduce the resonant response or to change the frequency of the mode by altering stiffness or, less commonly, mass. The feasibility of increasing damping will depend on the geometry of the weapon carrier and aircraft and their relative motion; if this is suitable, incorporation of a hydraulic or elastomeric damper may be possible and may be preferable to a change of stiffness which could cause problems then for some other weapon of different inertia.

In general, however changing the stiffness of the carrier or the airframe attachment structure or the weapon/carrier interface seems to be the most common solution to frequency coincidence problems (Reference II-14). Addition or removal of mass in sufficient quantity to make a worthwhile change in frequency is seldom feasible. The decision whether to soften or to stiffen the weapon mounting system will depend on the feasibility of changing the design and on what other weapons are to be carried. If, for example, the weapon experiencing the high vibration was the heaviest that the helicopter carried then it might be preferable to stiffen the mounting thus moving the lighter weapons still further from the frequency coincidence.

An alternative technique which has been used with success in a case where the resonant mode involved the whole airframe and not just the weapon and its carrier, is to soften the carrier enough to place the frequency of the weapon and its carrier well below the blade passing frequency. The airframe is then effectively not aware of the presence of the soft mounted weapon (See Case T).

The chief lesson which seems to come from the numerous vibration problems that have occurred is that it is prudent to design the weapon carrier in such a way that there is scope for modifying the design to tune away from a resonance.

For the future active suspension systems for weapons have been suggested (Reference II-14). A system could be envisaged in which the vertical stiffness of a carrier was provided not by a bracing strut but by a servo controlled hydraulic jack responding to an accelerometer signal off the carrier. The complexity of such a system might be justified if the helicopter was required to carry a range of weapons of diverse characteristics.

2.3 EJECTION PHENOMENA

2.3.1 General

There do not appear to be any great structural problems associated with the release of free fall weapons although the rebound might be considered as a design case as it is on fixed wing aircraft. Rocket boosted weapons that are fired out of a tube tend to cause blast problems due to highly impulsive nature of their short burning launch motors, but these are dealt with in Section 2.4. Other rocket boosted weapons which are fired off rails have somewhat less violent launches but can cause problems to engines and transmissions due to exhaust gas ingestion. Both these types of missiles are often restrained on their launchers by shear pins. Fracture of these pins at launch puts a high impulsive load into the launcher and its mounting, albeit of a well known and controlled magnitude. Ripple firing of rockets can cause high loads if the firing frequency coincides with that of a structural mode. Rocket propelled weapons which are dropped clear of the helicopter before motor ignition avoid such problems, but some of these, such as some of the larger anti-ship missiles, are carried on ejection release units (ERUs) which provide for positive ejection by means of gas powered rams; these can produce reaction loads of the order of hundreds of kN (See Case U).

2.3.2 Analytic Methods

None of the phenomena outlined above appears to be amenable to analytic treatment. The reaction loads from ERUs are well documented and dealt with by conventional stressing. Attention may have to be paid to the stiffness of the carrier and the attachment structure in the helicopter since excessive flexibility may reduce the weapon ejection velocity and may effect aiming accuracy (See Case C).

2.3.3 Ground and Flight Test

ERU launch loads can be measured on the ground using an inert weapon, but in the main loads associated with weapon launch are measured during flight trials. Instrumentation is normally by strain gauging.

The effects of rocket exhaust ingestion on engines and transmission systems require the most complex instrumentation to measure. The frequency response of most standard fit torquemeters is not high enough to measure accurately the sudden torque variations that exhaust gas ingestion can cause. The use of strain gauges and slip rings on rotor masts and drive shafts is likely to be needed.

Ripple firing of weapons needs to be tested to ensure that it does not excite structural resonance of the airframe. Adjustment to the firing rate may have to be made. The instrumentation used to measure weapon carriage vibration would normally suffice for these trials.

2.3.4 Status

The carriage of air-to-air weapons either for self defense or for attacking other helicopters is likely to become more common with attendant risks of exhaust gas ingestion. This should be borne in mind at the design stage of the helicopter if it is envisaged that it will carry such weapons.

2.4 BLAST OVERPRESSURE

2.4.1 General

Blast overpressure effects are caused by the firing of both guns and missiles. The most damaging type of missile is that class of anti-tank weapon developed initially for use by infantry. These are launched from a tube by a booster motor which has to be very short burning to avoid danger to the operator. The impulsive, virtually explosive characteristics of these boost motors can and have caused problems on many helicopters.

2.4.2 Analytic Methods

Validated methods for predicting blast overpressure fields analytically do not appear to be available yet. Usually weapon manufacturer's data derived from previous firing trials are used by helicopter manufacturers to calculate airframe loads (Reference II-15). However, such data have in the past, been found sometimes to underestimate the pressure by a substantial amount. Local areas of high pressure may also be caused by focusing effects caused by the shape of the airframe and analytical methods for predicting these details are also not available.

2.4.3 Ground Test

Ground or pit firing of guns and missiles forms a vital part of the blast overpressure assessment. The possibility of reflection effects from the ground must however be borne in mind.

Instrumentation may utilize pressure transducers, strain gauges, accelerometers (particularly for monitoring the shock effects on internal equipment etc) and temperature transducers to assess the effects of the accompanying thermal pulse. Boards are sometimes erected behind the aircraft to check on the trajectory of debris ejected by missiles and the airframe is always examined for impact damage. High speed cine cameras are normally used as well to record debris trajectories and the effects of blast on access panels etc.

For missile firing, the areas which require particular attention from a structural point of view are the rear fuselage, tailplane and any stub wings, if these are used for weapon carriage. For guns, areas in the vicinity of the muzzle for the full range of azimuth and elevation need checking and, as for recoil, the effects of firing rate need to be examined to check for resonance.

Due to the impulsive, short duration, nature of blast effects instrumentation and recording systems need to cover a bandwidth up to at least 2 kHz. Careful consideration needs to be given to the selection of transducers that will provide reliable data and survive the environment. Burning rates of propellants depend on their temperature and hence extremes of temperature (particularly high) need to be covered during the blast trials. An environmental chamber may be needed to "cook" the weapon prior to firing (See Cases H, S).

2.4.4 Flight Tests

Blast overpressure measurements are made as part of the flight firing trials. The results of the ground tests may be used to select worst case firing configurations (e.g. gun position or missile station) for the flight trials. These should cover relevant flight regimes. The ground test results may also enable the instrumentation fit to be narrowed down to particular critical areas but otherwise a similar coverage will be needed (See Case D).

2.4.5 Current Status

Blast overpressure has caused problems on a number of current helicopters. Impulsive transients in equipment have caused failures and tripping of relays. Access panels have become unlatched and opened. Static failures of airframe structure are unusual but stress levels are often high enough to cause concern about low cycle fatigue failures in perhaps only a few tens or hundreds of missile firings. Low set tailplanes are particularly at risk. Gun firing generates a large range of harmonics of the firing rate thus increasing the number of load cycles and the risk of fatigue failure.

Cures for equipment problems include isolating mounts and repositioning. Improving the integrity of latches and panels is a matter of detailed mechanical engineering. Treatment of structure will depend on the likely consequence of failure. Clearly loss of a tailplane could have serious, perhaps catastrophic effects and local strengthening may be required. However, cracking of skin or even frames by a few hundred missile firings may be seen as an acceptable risk, since the likelihood of any one aircraft doing this, many will probably be small and the flight safety implications not serious. Even if a training aircraft is likely to do large numbers of firings it may be more cost effective to monitor and repair this one aircraft, if necessary, than to modify the whole fleet. On some types, blast deflectors have been introduced to direct the blast into less damaging directions but these do produce undesirable drag loads on the launchers.

It should be noted that the fitting of muzzle brakes or flash guards to guns may altar blast over pressure locally (See Case P).

2.4.6 Future Development

As long as helicopters are required to carry anti-tank missiles primarily designed for launch by men or ground based vehicles, blast is likely to be a problem and this may be so even for purpose built weapons because of the need for rapid acceleration to avoid downwash effects when firing from a low hover. The problem may indeed get worse as demand for heavier warheads, longer stand-off ranges and shorter flight times increases. More powerful guns may also be needed to defeat heavily armored anti-helicopter helicopters.

To combat this, careful placement of the weapons relative to the structure, engine intakes and internal systems will need to be planned. Blast suppressers or diffusers may also help, though with a possible weight penalty. Local blanketing of the structure is another possibility.

2.5 HANG-FIRE

2.5.1 General

The use of shear pins to retain missiles in their launchers is intended to reduce the likelihood of hang-fires. Nevertheless it is usual to assess the results of such an event.

2.5.2 Analytic Methods

The magnitude of the direct loads produced by the firing of a hung-up missile will be accurately known and normal analytical methods of structural analysis can be used to assess the ability of the aircraft structure to withstand them. The major consideration may be the effects on handling and it may be more difficult to predict loads generated by abnormal flight attitudes. Nevertheless, some sort of analysis needs to be done since it is not usual to do flight trails of hand-fires.

2.5.3 Ground and Flight Test

The thrust of missile motors will be well defined so it is not really necessary to measure the hang-fire load on the aircraft. Handling effects may be assessed by means of a ground based flight simulation, and these may be fed into flight mechanics calculations to calculate loads.

Flight tests on hang-fires have not been done in the past for safety reasons but may be contemplated in the future (See Case E).

2.5.4 Current and Future Status

Hang-fires do not appear to be a major problem at the moment. Future developments of longer range, faster or heavier missiles may increase the risk to the helicopter. Provision for emergency jettison may be necessary if it is not already made.

2.6 AEROELASTICS

2.6.1 General

Aeroelastic instabilities on helicopters are usually taken to include ground and air resonance as well as flutter and divergence that apply to fixed wing aircraft. Of these only the former two are likely to be influenced by weapon carriage since flight speeds are not usually high enough to cause concern about fixed surface flutter or divergence and rotor flutter will only be controlled by rotor characteristics (Reference II-16).

2.6.2 Analytical Methods

Methods for predicting ground and air resonance are widely documented (References II-19, II-20) and universally used. Since both involve a coupling between rotor and airframe motions, the full range of airframe inertias needs to be considered. Ground resonance is also very dependent on the damping of airframe motions which is largely due to undercarriage damping. Some aircraft have a system for locking oleos to maintain ride height during weapon loading and this clearly changes both undercarriage stiffness and damping so that the ground resonance calculations need to cover this to allow for rotors running weapon loading.

2.6.3 Ground Tests

Ground resonance testing has in the past been done by provisioning a restraint rig capable of checking the motion of the aircraft should a resonant condition be encountered during ground running. Such systems were not without problems and in some cases were potentially capable of making the instability worse rather than stopping it. The current trend seems to be to dispense with restraint rigs and to use modern methods of vibration analysis (e.g. Fast Fourier Transform Analysis) to monitor the vibration in the damping of the aircraft motions as rotor speed is progressively increased; rotor behavior may also be monitored via lead-lag stresses. This information is used to check the trends predicted by the theoretical analysis (Reference II-20).

Critical configurations, including weapon fits, will be checked during these ground running tests.

2.6.4 Flight Tests

Air resonance (Reference II-20) which is of more significance on helicopters with nonarticulated rotors, is checked by monitoring rotor stresses and the damping of aircraft motions during flight testing. If there was some predicted problem involving a weapon configuration, then this would be checked by progressive flight trials and provision for emergency jettison would probably be made.

2.6.5 Current and Future Status

From a weapon integration point of view aeroelasticity does not appear to present special current or predicted problems for helicopters.

2.7 STRUCTURAL INTEGRITY

2.7.1 General

Structural integrity is a measure of the structure's performance in its ability to withstand the various loading actions imposed by the weapons systems.

2.7.2 Analytic Methods

Widespread use of finite element structural analysis techniques such as NASTRAN or ASAS is made in the design of all aircraft components. The same methods are sometimes used in the strength substantiation process but care must be taken to ensure that a valid stress check is actually being made; putting the same input into the design model with the same finite element program will clearly not prove anything.

2.7.3 Ground Tests

Strength substantiation, both static and fatigue, of components such as weapon carriers is usually done by testing.

Strength testing is a well documented technology in its own right and it is not intended to go into detail here. The philosophy and methods for testing the static strength of components or structures are much the same in all countries with a requirement to demonstrate an ultimate load factor of 1.5 on limit loads being almost universal. Requirements for the proof load factor vary from 1.0 to 1.2 but with modern materials the proof to ultimate strength ratio is such that the proof requirement is usually subsidiary to the ultimate.

Fatigue testing is a much less standardized technology, although there have been international collaborative efforts to produce standard loading spectra such as Helix and Felix for use in fatigue testing (Reference II-21). In some countries such as UK the national airworthiness requirements spell out in detail what factors should be used, or at least how they should be derived. In the USA, although there are fatigue requirements (References II-22, II-23) different helicopter manufacturers have their own systems for fatigue substantiation with their own factors, S-N curves, etc. (References II-24, II-25). In practice the factors used for calculating safe fatigue lives vary from about 1.5 to 2 on stress for the high frequency loads and from about 3 to 5 on life for the low cycle loads such as landings. Methods for defining the flight loads during a particular flight regime also vary and introduce different degrees of conservatism.

Fatigue testing practice also varies from one manufacturer to another with some doing only constant amplitude loading while others make an attempt to simulate flight loading more closely by doing more variable amplitude loading (See Case B).

2.7.4 Current and Future Status

The somewhat indeterminate implications of the details of the fatigue substantiation process make it impossible to define accurately the levels of safety from failure that it produces. However, most fatigue failures that occur in service seem to stem from deficiencies in the input data, e.g. the flight loads were different from those measured during flight trials or from material or manufacturing defects whose influence was not taken into account during the substantiation process. Failures purely due to inadequate factors seem to be very rare.

There are moves to abandon the safe life philosophy because principally of its inability to deal with defects and to adopt the damage tolerant approach (References II-26, II-27, II-28). The USAF are doing this for their fixed wing aircraft, but to use damage tolerance in its MIL-A-83444 form (Reference II-29) presents formidable difficulties for helicopters. Times for crack growth from specified defects have to be demonstrated either by fracture mechanics calculations or by crack propagation test. Because of the rapid accumulation of loading cycles in a helicopter crack propagation may be very rapid leading to unacceptably short inspection periods.

Some features of the damage tolerant approach, such as the emphasis it throws on the need for materials exhibiting slow crack growth and the need to design for easy inspectability, are obviously desirable and can be implemented immediately on helicopters. Such things apply as much to weapon carriers and attachments as to any other part of the helicopter and should help to improve their structural reliability.

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3.0 SPECIAL EFFECTS

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3.1 GENERAL

Armament on modern helicopters tends to fall into one of four basic categories; droppable stores such as bombs, torpedoes, and sensors, forward firing ordnance such as unguided rockets, guided missiles, and fixed guns, articulated weapons such as turreted and crew served guns, and airframe mounted dispersers for items such as chaff, sonobouys, and flares. Each of these categories has its own set of compatibility conflicts with the host helicopter that must be quantified and integrated during design, test and evaluation, and operational assessment.

3.1.1 DROPPABLE STORES

Droppable stores are typically carried on some type of external bomb rack that utilizes either gravity release or ejected jettison to separate the store from the helicopter. These stores can range from practice bombs or sensors of only a few pounds mass to 500 pound class bombs or greater. Typically these droppable stores have been designed for fixed wing aircraft and adapted for use on helicopters. Structural problems associated with these stores included those caused by cantilevering the stores out away from the helicopter fuselage (accentuated by any maneuvering flight), potential sympathetic vibration frequencies between the load (or load combination) and helicopter, and any reaction load caused by the store jettison. Effects on aircraft performance can also be dramatic with large decreases possible, due to the extra weight and drag of the external stores. Flying qualities can also be detrimentally affected (especially by the larger stores) due to lateral load imbalances caused by asymmetric jettison or release of stores, aircraft center of gravity shifts, or potential blanking of aerodynamic surfaces. Other effects of droppable stores tend to be limited to potential airframe damage caused by flailing of loose arming wires and operational incompatibilities between the stores fragmentation pattern and the host helicopter's speed and altitude range.

3.1.2 FORWARD FIRING ORDNANCE

Fixed forward firing ordnance can usually be carried on the same weapon stations as used for droppable stores but also includes airframe mounted launchers and guns. This category of ordnance typically includes unguided rockets (pods), guided missiles (air-to-air and air-to-ground), gun pods, and airframe mounted, fixed forward firing guns of the World War II fighter genre. Generally, all of the considerations for droppable stores apply to fixed forward firing ordnance as these launchers and pods are often carried on the same stations and can usually be jettisoned. Additionally, recoil or reaction loads imposed during firing can impart severe stress into the aircraft support structure and result in structural failure or reduced fatigue lives. Rocket and gun blast pressures can also overstress and cause significant damage to aircraft skin (see cases D, H, P and S). Rocket exhaust and residual gun gases create their own set of compatibility problems including engine ingestion and erosion of the aircraft skin/components where impingement occurs. Thermal effects from these hot gases must also be considered along with potential debris damage from arming lanyards, boost motors, spent cartridges, etc.. Finally, human factors (visibility losses caused by smoke, muzzle flash, etc.), operational restrictions caused by store characteristics, and detrimental effects on possible adjacent stores must be considered.

3.1.3 ARTICULATED WEAPONS

Articulated weaponry has historically consisted of turreted and crew served gun systems. These gun systems allow off-axis fields of fire and present the same basic design and testing concerns as fixed forward firing guns in addition to unique flying quality effects created by the off-axis recoil loads (typically yawing or pitching moments) and travel stop requirements to avoid shooting part of the helicopter structure or rotor disc. Special effect considerations also mirror those for fixed guns with the additional requirement to fully test for detrimental effects upon aircraft utility systems (hydraulics, electrical, pneumatic, etc.) when operating turreted systems at peak demands (maximum slew rates plus firing for example).

3.1.4 DISPENSERS

Airframe mounted dispensers for sonobouys, chaff, flares, etc. tend to impose less severe loadings on structure and fewer problems from ejection blasts (if present) than forward firing or droppable stores due to the typically smaller ejection charges used. These areas must still be investigated as fatigue stresses may be a concern, particularly on light mounting structure, but the major area of compatibility concern is in separation characteristics and potential debris damage to tail rotors, aft fuselage skin, etc.

3.1.5 SPECIAL EFFECTS CONSIDERATIONS

Special effects caused by weaponization of helicopters mainly involve debris damage, exhaust plume erosion, potential thermal problems created by hot gases, propulsion system effects, operational limitations inflicted by store operating characteristics, and aircrew effects. It should be noted that the same basic tests and evaluation processes will satisfy most of the special effects concerns detailed in the following paragraphs (as well as store separation and structural concerns) and should obviously be conducted concurrently with sufficient data collected to satisfy all aspects of special effects testing.

3.2 DEBRIS DAMAGE

A major compatibility problem found with all categories of stores employed on armed helicopters is potential debris damage. This is typically caused by spent boost motors, cartridge brass, protective store fairings, arming/fin lanyards, and other "disposable" pieces of ordnance hardware that do not stay with the store after it is fired/launched/dropped. These objects can produce substantial damage from impacting against aircraft surfaces, entanglement/strikes with the main or tail rotor, potential jamming of flight controls, or flailing against weapon station fairings. This last item is becoming more of a concern with the increased use of composite materials in the weapon station structure.

3.2.1 ANALYTIC METHODS

The first, most basic analytic method is to study the store/weapon system in question and identify if it has any components that will be detached or pulled loose during launch/operation. Once these components have been identified they should be prioritized according to the potential damage threat they pose. For example, the small pieces from a frangible, fiberglass rocket pod fairing would not generally pose the threat of airframe damage that a several pound, hard cased, spent missile booster would. A review of literature and/or films that document previous tests of similar systems gives valuable information to help with this prioritization. A detailed study of expected weapon/debris trajectory should be made and overlaid onto scale drawings of the host helicopter to determine if any potential impingement exists. Manual methods can certainly be used, but computer modeling would be quicker and more repeatable if scale representations of the helicopter and stores are available. If these analytic methods show that debris damage is possible, then a review of the store/helicopter interface should be conducted to determine if any modifications could be made to remove or reduce the chance of damage. Typical modifications may include having arming wires or fin lanyards remain with the store after launch instead of staying on the aircraft, incorporating a chuting arrangement to direct spent ammunition cases away from the helicopter, redesigning mounting provisions to increase separation distances, or providing protective shielding for vulnerable components (this last option is most often used for sensors or adjacent stores). If no adequate modifications can be practically incorporated, stores that pose a signficant threat to flight safety should be discarded from consideration.

3.2.2 GROUND TESTS

Ground testing is typically useful for providing more information to either substantiate or fine tune analytic results. The first tests would be to "fit check" the weapon system in question onto the host helicopter. This is done with preliminary mock-ups of new equipment and repeated as the design develops. For incorporation of existing weapons systems onto new platforms (more often the case), dummy or training units should be mounted/installed onto the host helicopter and any areas of potential debris damage assessed. This full scale, three dimensional check often shows up potential conflicts that were overlooked in the earlier analytic drawing overlays as scale representations of the helicopter/store are often not totally accurate or representative of operational units. This is a good time for evaluating "try it and see" solutions to problems identified in the analytic assessment such as devising arming wire routings. Any potential conflicts or proposed modifications (as well as the overall fit check) should be documented with still photography. Further ground tests will typically include actual firings of ordnance with the helicopter securely tied down and the engines and rotors not operating. For this phase of tests (intended to verify safety of flight and basic weapon integration), inert ordnance should be used as much as possible. For example, dummy warheads and boost motors with dummy sustainer and guidance units should be used as only the initial phase of weapon operation/trajectory is being investigated. High speed photography or video coverage should be used to document and analyze this work. Two-hundred to four-hundred frames per second (fps) is normally adequate for this coverage. In depth analysis of high speed gun systems would need special cameras and much higher frame rates, but this is not typically a requirement for assessment of separation, debris damage, or other special effects. The final phase of ground testing is to conduct launches/firings with the helicopter's rotors and engine turning, and all possible flight sytems on. These firings should represent as close as possible actual in-flight operation without the added danger and risk of flight. This phase of firings should also be photographically documented with high speed cameras. For all ground tests, it is suggested that initial firings be conducted from the side of the helicopter away from the tail rotor (if applicable) to minimize the possibility of damage. After each phase of ground testing, the results should be incorporated back into the analytical assessment. This keeps the assessment up to date and allows a basis for continuation/cancellation of the weapon integration process.

3.2.3 FLIGHT TESTS

Once the ground tests have been completed and the results incorporated into the analytic assessment, flight testing may be fully planned out and conducted. A non-firing, captive carriage flight to whatever limits (aerodynamic and structural) that have been defined for the store/helicopter combination should constitute the initial flight. This is conducted primarily for reasons other than debris damage (structural, aerodynamic, and weapon system interoperability) but onboard cameras (24 fps is adequate) and post flight inspection can identify possible problems from loose or flailing arming wires or connections. Firing flights, as in the ground tests, should initially be conducted from the side of the helicopter away from the tail rotor to minimize damage potential. These firings/releases should be conducted in a buildup fashion, starting at the analytically predicted most benign flight condition, and progressing on to more critical conditions, as a review of the flight data is conducted and predictions verified. Flight testing should be conducted over a range that provides adequate safe distances to accommodate weapon launch/release footprints as well as provide a clear area below the helicopter for landing sites if needed. Safe landing sites are not always practical (overwater torpedo drops, for example) but every precaution to ensure aircrew safety should be taken, such as having search and rescue standing by. Onboard, high speed camera coverage (200 to 400 fps) remains the most desired instrumentation for documentation and analysis of weapon separation and debris damage assessment, augmented by chase aircraft or ground based film/video coverage if available. The onboard cameras should be mounted so as to provide both forward and aft facing view of the weapon in question (if possible) in order to fully view any impingement on the rear fuselage or tail rotor as well as of the immediate area around the weapon location. Adjacent weapon stations, aircraft landing skids, or fuselage mounting are often used as camera locations. A detailed post flight aircraft inspection should be conducted to determine whether any debris damage occurred on that flight. Old damage should be marked and monitored so as not to be counted twice. Onboard film must be reviewed prior to the next build up flight along with the post flight aircraft inspection to verify debris trajectories or damage amounts. In general, any object that could cause significant damage to the host helicopter must constantly increase its separation distance away from the helicopter during the launch/weapon release event to be considered acceptable. In other words, spent boost motors or ammunition cases must fall away from the helicopter instead of being drawn in towards it. Minimum separation distances from critical components such as main and tail rotors should be established and the films analyzed to verify that this separation is maintained throughout the flight envelope. Close attention must be paid in trying to establish trends for debris trajectories and weapons separation characteristics during these build up flights and the analytic model continually updated in order to accurately predict the next event and avoid potentially disasterous debris damage. If significant debris damage occurs, if separation distance criteria are not met, or debris trajectory trends indicate that debris strikes are about to occur, flight testing should be terminated. The weapon release envelope should be limited to that where satisfactory results were obtained. It should be kept in mind that some minor debris damage may be tolerated and must be prioritized with the helicopter/weapon's mission to determine acceptable limits. For example, minor debris damage to the weapon station fairings experienced while firing rocket pods from an attack helicopter may be acceptable and only result in increased maintenance costs (see Case Q).

3.2.4 OPERATIONAL EVALUATION

The operational evaluation of a weapon system for debris damage should not differ drastically from that described for the last stage of flight tests except that onboard cameras will probably not be utilized. A close post flight inspection should still be conducted after each weapon firing flight. There is the possibility that actual mission representative maneuvers conducted during an operational evaluation may uncover a portion of the flight/launch envelope missed during the initial flight testing. Any damage or anomalies observed should be tracked and incorporated back into the analytical assessment and developmental test results along with any further envelope restrictions required. It is important that communication exists between the developmental testers and the operational evaluaters and users, so that results of each test are incorporated together and the full picture of the weapon integration achieved.

3.2.5 STATE OF THE ART ASSESSMENT

Potential debris damage will remain a major consideration for incorporation of weapon systems into helicopters for the forseeable future. This is based on continued adaptation of ground based missile systems (due to their wide spread availability and slow launch speed requirements) which often incorporate jettisonable launch motors. Ever increasing rotorcraft speed capabilities may dictate use of new types of gun systems, as found in the fixed wing world, where spent cartridges are not ejected overboard but are retained onboard the aircraft and downloaded at the completion of the flight in order to eliminate the potential of strikes and damage from this source.

3.3 EXHAUST PLUME EROSION

Erosion of helicopter skin and components due to impingement of hot rocket and missile exhaust gases (or gun gases) is another significant compatibility problem for armed rotorcraft. This erosion is usually caused by abrasive particles in the exhaust plume and accentuated due to the corrosive nature of many exhaust/gun gases. Exhaust plume erosion tends to manifest itself as long term maintenance or corrosion control problems, rather than as catastrophic component failures.

3.3.1 ANALYTIC METHODS

Analytic methods used to assess potential exhaust plume/gun gas erosion problems are not vastly different from those followed for debris damage assessment. Many solid rocket motor propellants contain large amounts of metals which often are not burned completely or which form abrasive oxides once burned. These metal particles form hot projectiles that strike helicopter components and skin within the weapon exhaust plume profile and can cause severe abrasion. Imbedded particles of these potentially dissimilar metals will eventually create corrosion concerns of affected helicopter components. Because of this, it is important to know what the composition and profile (length, shape, and duration) of the weapon exhaust plume may be, in order to assess the severity of any exhaust plume impingement and identify potential erosion/corrosion problems. The plume profiles should be overlaid onto scale representations of the host helicopter (as for debris damage assessment) and vulnerable helicopter components identified. Based upon exhaust gas composition and previous tests performed on similar systems, a decision can be made as to whether a serious enough potential exists to warrant modifying or protecting these components. Typical modifications can involve plume deflectors, abrasion strips, or protective applications of paint-like substances to these components. Transparencies and sensors should receive particular attention as these items tend to be more susceptible to abrasion/erosion damage than composite or metal components. A method sometimes used to protect store opti al sensors from exhaust plume erosion by adjacent stores is to incorporate a disposable protective cover over the op .. This cover is then jettisoned or broken off prior to launch of that store. Gun gases can also cause erosion problems s their composition includes unburnt particles and corrosive gases as well as bits of gun barrel and projectile pieces. The latter items become more of a concern as the gun system becomes well used and the barrel rifling begins to wear.

3.3.2 GROUND TESTS

Ground tests mirror those described for debris damage assessment with high speed cameras (200 to 400 fps) and post launch inspections utilized to document exhaust plume profile and erosion effects. Proposed modifications should be tried at this time and the results compared to determine their effectiveness. It should be remembered that ground tests do not simulate actual airflow patterns or attitudes experienced in flight and resulting exhaust plume profiles and impingement areas may be somewhat different from actual inflight firings. Sample pieces of material may be placed in the weapon exhaust plume during these tests to verify erosion concerns without jeopardizing an airframe component.

3.3.3 FLIGHT TESTS

Exhaust plume/gun gas erosion problems can be documented in flight testing by verifying plume profiles and impingement areas through onboard, chase aircraft, or ground based high speed cameras (200 to 400 fps). This film coverage will not only verify analytic results and ground tests, but can give an idea as to plume composition, as any large pieces of hot material contained in the exhaust will be seen. Detailed post flight inspections must be conducted, with any erosion damage documented by still photography. Measurements of surface roughness or depth of penetration should be taken in severe cases. Again, old damage should be marked so that future growth can be monitored and accurate data recorded. Potential adjacent store combinations should be flight tested to determine possible erosion effects on these stores and establish compatibility. Modifications to limit the exhaust plume erosion damage problem should be evaluated at this time and a recommendation made as to their effectiveness and overall worth. As with debris damage, if the maintenance costs associated with correcting the erosion problems or operational limits imposed by these problems outweigh the benefits of incorporating that weapon system, it should be dropped from consideration.

3.3.4 OPERATIONAL EVALUATION

Often, a complete assessment of the real cost associated with an erosion problem cannot be determined until the operational evaluation. This is because of the operator representative environment and generally larger number of stores expended during this phase of testing. Gun problems based on barrel deterioration may also begin to show at this point. Again, results of the operational evaluation must be incorporated into the developmental data base in order to achieve a full assessment of the weapon system integration. This also helps to establish a better foundation for future testing of any similar systems.

3.3.5 STATE OF ART ASSESSMENT

Development of cleaner burning rocket motors will help reduce the erosion problem as would future aircraft designs that could reduce the number of aircraft components subjected to the exhaust plume. The increased use of composite material (though they may be less resistant to abrasion than metal) will reduce or eliminate the corrosion aspects of this problem which are responsible for the majority of the maintenance actions associated with weapon exhaust plume erosion.

3.4 TEMPERATURE EFFECTS

The temperature effects of a hot exhaust plume/gas on aircraft structure and components can result in structural damage and mission aborts due to burned wires or damaged sensors. These effects tend to be worse than those associated with exhaust plume erosion due to their more immediate nature. Temperature effects are becoming more critical with the increased use of digital electronics and composite materials due to the rapid breakdown of these items at relatively low temperatures. Unfortunately composite materials will be more vulnerable to temperature effects than metallic structures.

3.4.1 ANALYTIC METHOD

An analytic assessment of temperature effects of hot exhaust plumes would begin with an overlay of the plume onto a representation of the host helicopter, as done for exhaust plume erosion, with the additional requirement to include plume temperature profiles. This information should be available from the ordnance manufacturers and should not only provide temperatures but duration of exposure as well. From this profile, critical airframe components may be identified. Most likely, any items subjected to plume erosion effects will also be subjected to the highest temperatures. Material specifications of any critical items should be reviewed to establish maximum allowable temperatures and exposure times. Computer modeling can be very effective at this point to accurately assess temperature profiles and effects for multiple launches (ripple firing of a rocket pod or a sustained gun burst, for example) where maximum duration of exposure and highest component temperatures are likely. If it is determined that material specification temperature limits will be exceeded, then the same types of system modifications employed for erosion effects should be considered. If these do not appear to be practical or effective, then the weapon should be relocated on the aircraft, its release envelope be restricted, or the weapon not be incorporated onto the aircraft.

3.4.2 GROUND TESTS

A close inspection of weapon fit checks should reveal any potential problems with burn through or melting of any unshielded wiring in the weapon stations. Vulnerable wiring harnesses or cables should be relocated or shielded to protect them from weapon exhaust plume or hot gun gas temperature effects. As discussed earlier, these fit checks provide a three-dimensional perspective and may show up additional problem areas not noticed in the analytical study. Ground firing tests should also be conducted, building up to ripple firings or sustained bursts. Instrumentation should include thermocouples mounted at critical locations as well as the high speed cameras described for other special effect tests. It should be remembered that thermocouple response time may be too long to react to short duration exposures but should provide component surface or skin temperatures, which are the critical concern. For example, a high temperature, short exposure, "flash" exposure may not cause any significant component temperature rise and cause no material damage while a longer exposure to a lesser temperature could effect enough of a component temperature rise to cause severe damage. Thermocouples should be augmented with applications of temperature sensitive tapes. These tapes are available in a wide range of temperature zones, and are very inexpensive, and provide data on maximum temperature exposure. These tapes provide no time history data and are not reusable, but can be easily applied and are often used to verify analytical results.

3.4.3 FLIGHT TESTS

Flight testing for weapon temperature effects is conducted in the same manner as that for exhaust plume erosion with the additional instrumentation requirements of thermocouples (if available or practical to use) and temperature tapes on critical components or areas. It should be remembered that the possibility of burned wiring and/or a fire exists with this type of testing and appropriate emergency procedures should be reviewed prior to the flights. Some appropriate item to be reviewed might be emergency store jettison envelopes and procedures, "hung" ordnance practices (proper procedures for returning to base with unexpended ordnance), and emergency ordnance shut-down procedures such as turning off the master arm switch in the event of a gun runaway caused by wiring damage. The flight test matrix snould build up to worst case conditions, as done in the ground tests. A detailed inspection and reading of temperature tape results should be conducted after each flight. Thermocouple data may be monitored real-time during the flight through telemetry systems if this equipment is available and analytical study and ground testing showed a high degree of concern for temperature effects.

3.4.4 OPERATIONAL EVALUATION

No specific testing for temperature effects is usually conducted during an operational evaluation as these effects are normally discovered in developmental testing. The durability or practicality of any thermally protective coatings may be assessed but most temperature effects are of an immediate nature and should be documented during early firing evolutions. Post flight inspections should be sufficient to track known problem areas or monitor for new ones.

3.4.5 STATE OF ART ASSESSMENT

Aside from further development of some of the modifications outlined earlier, such as protective coatings, little is being done on combating weapon thermal effects other than trying to design around them through weapon station location. The increased use of composite materials and digital electronics with their more limited temperature resistance may drive more development in this area.

3.5 PROPULSION SYSTEM EFFECTS

Effects of weapon firing on rotorcraft propulsion systems have historically been of minor concern due to the normally large physical separation between any missile or rocket exhaust plume (or gun gases) and the engine inlets combined with the normally small size of helicopter ordnance. The increased weight carrying ability of modern helicopters, along with the new emphasis on air-to-air weapons, has changed this and propulsion system effects such as engine surges, torque overspikes, and degraded engine life must be considered. These effects are most likely to be experienced when launching large items of forward firing ordnance, such as five inch rockets or air-to-air missiles, that put out a large volume of hot exhaust gases as compared to smaller items of ordnance and guns.

3.5.1 ANALYTIC METHODS

Analytic methods of determining helicopter propulsion system susceptibility to effects from weapon launches may begin by studying the weapon exhaust plume profile (temperatures, pressures, and physical distribution in relation to the host helicopter) to determine if an appreciable plume influence is possible on the engine inlets. A detailed study of previous testing of any similar weapon/helicopter integration efforts will help to establish the severity of any possible plume influence. The engine performance data should also be reviewed to determine its susceptibility to surge throughout its operating envelope. This review should include the engine fuel control system. New electronic units may be much quicker to react to observed changes to inlet temperatures than hydro-mechanical units and could exaggerate potential interface problems. If the engine does not have an adequate surge margin at some power settings or a significant control mismatch is identified, ordnance firing envelopes may need to be restricted to avoid these areas. Aircraft operating limits will also affect the severity of ingestion problems. For example, a helicopter with very generous torque limits may be able to tolerate large torque overspikes (typically caused by the engine surging and recovering where drive train torque is rapidly removed and then reapplied and any backlash present in the drive system is suddenly taken up with a resulting torque overspike) and reduce the severity of any potential problem.

3.5.2 GROUND TESTS

There are not many ground tests that can be performed to assess weapon interaction with the helicopter propulsion system as the engines must be operating at flight representative power settings to adequately simulate inflight conditions. A review of weapon exhaust plume profiles collected for erosion and temperature effects should help validate analytic results. It should be brought up at this time that instrumentation requirements for propulsion system effects testing can be quite extensive, expensive, and time consuming to install. Typical requirements could include compressor inlet temperature, and pressure, compressor discharge pressure, turbine inlet temperature, outside air temperature, engine power lever positions, main rotor RPM, and main and tail rotor torques. Due to the complexity and expense of these instrumentation systems, every effort must be made to determine analytically the need for ground or flight tests to avoid incurring unnecessary expense.

3.5.3 FLIGHT TESTS

Flight testing should include the instrumentation listed above with critical parameters either telemetered and monitored real time (such as torques, RPM, compressor discharge pressure, and turbine inlet temperature) or reviewed after each single event flight prior to the next data point. Flight testing should be conducted in a build up manner (as always) starting at the analytically predicted most benign point and progressing to the most critical condition. In exhaust plume/propulsion system effect testing, this can usually mean starting with single launches in high speed flight. Slower speeds and multiple weapon launches can be approached from these high speed points to whatever endpoint is desired (such as a hover, ripple firing) or until a problem is encountered. On twin engined helicopters with individual inlets, launches should be conducted from a single side of the aircraft so as to only affect one engine, and then built up to launches from both sides of the helicopter at once. Slow speed and hover launches should be the worst cases as the engines will be producing high power and, due to the lack of relative airflow, the inlet will be most vulnerable to exhaust plume influences. Always have a suitable emergency landing site available during these tests as a complete and unrecoverable loss of engine power is possible. For this same reason, all testing should be conducted from flight conditions and altitudes where a successful autorotation can be performed. A flight test investigation into AH-1T engine torque overspikes caused by firing 5 in. zuni rockets is contained in the Compendium of Case Histories (Case U). Propulsion system effects other than engine surges and drive system torque spikes can include erosion or coating of the compressor blades, which will decrease surge margin and performance, and potiential decreased engine component life as a result of compressor blade fatigue caused by surges.

3.5.4 OPERATIONAL EVALUATION

Engine surge and drive system overtorque effects should be discovered during developmental testing and, due to the extensive instrumentation required to adequately assess them, would not be evaluated in operational testing. The long term effects of blade erosion or coating buildup should be monitored through engine inspections, to include periodic borescoping. An increased schedule of engine washings, including the compressor section, may be necessary to combat coating buildup and the associated loss of performance and surge margin.

3.5.5 STATE OF ART ASSESSMENT

The use of electronic engine controls may make it easier to schedule preventative measures into the engine fuel controls, such as turning on the ignitors during weapon firing or adjusting the fuel control schedule during launches to compensate for exhaust plume effects. Fixed wing aircraft have had exhaust plume problems for years due to the proximity of their inlets to the weapon stations and have developed some "work around" methods to avoid problems, like the two listed in the first sentence. The helicopter world should study these solutions and incorporate those considered appropriate into future rotorcraft designs.

3.6 MISCELLANEOUS

Several unrelated, miscellaneous effects caused by integration of weapons systems on helicopters including aircrew effects, utility system compatibility, weapon operation/helicopter compatibility, adjacent store effects, and internal gun gas concentrations should also be considered when designing or testing weapon systems for helicopters.

3.6.1 WEAPON CHARACTERISTICS

Weapon operational envelopes and characteristics must be taken into account when considering incorporation of a weapon system onto a rotorcraft platform. Items such as minimum weapon launch speed and safe separation distances can be determining factors in deciding if a weapon system/helicopter integration is feasible. For example, even though some attack helicopters are capable of carrying general purpose bombs, the altitudes required to drop these stores and remain clear of the weapon's fragmentation pattern at the relatively slow speeds that the helicopter is capable of makes them realistically unusable in anything but the most low threat environment. The low altitudes and slow speeds required to survive in today's tactical environment can also severely limit the release envelope of numerous missile systems. These missiles may be relatively unstable during the initial, slow speed portion of launch and could fly into the ground immediately ahead of the launch helicopter. Also, any warhead equipped with a proximity fuse could potentially explode immediately upon arming when fired at these low altitudes. These factors should be researched during the analytical study and the results verified during operational testing. As more weapon systems are developed specifically for helicopter use, these mismatches should diminish.

3.6.2 ADJACENT STORES

Effects of weapon firing upon any potential adjacent store or store combination should also be investigated. All of the major special effects detailed previously (except perhaps propulsion system effects) along with separation and structural concerns should be considered. Potential electromagnetic interference should also be evaluated (if appropriate) before clearing adjacent store combinations for use. This requirement is growing more important as weapon systems increase in complexity and cost.

3.6.3 AIRCREW EFFECTS

The possibility of detrimental effects of weapon firing upon the aircrew should also be evaluated. These could consist of loss of visibility due to excessive smoke trails left by forward firing ordnance, gun firing residue coating the windscreen, or loss of "night vision" caused by rocket motor or muzzle flash encountered while firing at night. Flash effects are potentially a serious problem also when night vision enhancement systems are in use. Potential loss of eyesight due to laser energy must also be considered on today's battlefield with the increased use of laser guided and ranged weaponry. Little can be done to test for these effects other than to consider them during developmental flight testing and to investigate them further during the operational assessment. It is worth noting that gases produced by the firing of guns and missiles can also be a direct health hazard to the occupants of the helicopter (references III-1 and III-2). The operational assessment is where these effects will be "mission related" and the true scope of their importance evaluated.

3.6.4 UTILITY SYSTEM COMPATIBLITY

Compatibility between the helicopter utility systems and powered weapons must be accounted for during design and testing. Analytic studies should guarantee that adequate flow rates and power are available from aircraft utility systems at their maximum rates throughout their operational envelope. These should be verified in ground and flight testing by conducting peak demand tests (for example, firing a hydraulically powered turret while translating it at full rate). Any incompatibility or reduced capability should be noted and fixed or included into the formulation of the weapon's operational envelope restrictions. In no case should a mismatch between the helicopter system and the weapon system or a failure of the weapon system endanger the host helicopter.

3.6.5 GUN GAS CONCENTRATIONS

Concentrations of explosive gun gases inside a restricted compartment can pose a major problem for fuselage mounted and some turreted gun systems. These concentrations can be quantified during ground and flight testing by instrumentation ("sniffer") installed in the suspect bay that can either collect samples of or analyze the gas content or concentration. An excess concentration can be accommodated by either modifying the system or bay to reduce the gas level (pop open vents for example) or by limiting the burst length so that large concentrations of gases are not allowed to build up. This problem has been largely avoided in rotorcraft for many years as their restricted speed capabilities have allowed the use of unfaired gun systems that operate in free airflow. This may change as higher speeds become attainable and designers are forced to reduce gun system drag by fairing these systems.

3.7 REFERENCES

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APPENDIX I

EFFECTS OF AIRBORNE WEAPONS ON HELICOPTERS

Appendix I is a set of a synoptic tables which relates each particular undesirable weapon deployment characteristic to various effects and results and suggests some solutions. These tables should serve as a guideline for any new helicopter weapons integration venture at the design stage.

TABLE 1 - GUNS (TURRETED, PINTLE AND FIXED)

CHARACTERISTICS	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
GUN RECOIL	COMPLEX TRANSIENT AND REPEATED EXCITATION CHARACTERIZED BY A LARGE NUMBER (20 TO 30) HARMONICS OF THE FIRING RATE WITH DIRECTIVITY PARALLEL TO GUN AXIS. TYPICAL AZIMUTH ELEVATION LIMITS: AZIMUTH: +110° -110° ELEVATION: +15° -60°	o EXCESSIVE DYNAMIC LOADING OF STRUCTURE RESULTING IN REDUCED SERVICE LIFE DUE TO FATIGUE o EXCESSIVE COMPONENT VIBRATION - BLACK BOXES - SIGHTING DEVICES - TRANSPARENCIES o EXCESSIVE CREW VIBRATION o FLIGHT STABILITY MAY BE DEGRADED	o SELECT GUN FIRING RATE TO COINCIDE WITH MINIMUM RESPONSE LEVELS OF AIRFRAME o PROVIDE RECOIL ATTENUATION (ACT VE OR PASSIVE) o BENCH TEST QUALIFICATION OF COMPONENTS AND SIGHTING DEVICES o LIMIT TURRET ANGLES o ENHANCED STABILITY AUMENTATION	o CONDUCT AIRVEHICLE DYNAMIC RESPONSE TO SIMULATED RECOIL IN 3-AXES: A_Z E_Z 0° 0° 0° -60° 90° 0° o CONDUCT SHAKE TEST WITH SIMULATED RECOIL (3 AXES) o CONDUCT NON-FIRING AND FIRING FLIGHT TESTS
BLAST PRESSURE	HIGH INTENSITY, BROAD BAND, IMPULSIVE EXCITATION	o DAMAGES STRUCTURE DAMAGES ELECTRONICS	o PLACEMENT OF WEAPON RELATIVE TO STRUCTURE o BLAST DIFFUSERS o BLAST SUPPRESSOR o BLANKET STRUCTURE	o CONDUCT PIT FIRING TESTS WITH INSTRUMENTATION TO DEFINE FINAL CONFIGURATION
FLASH	HIGH INTENSITY SHORT DURATION FLASH	o MOMENTARILY "BLINDS" CREW o MOMENTARILY MAKES SIGHTING DEVICES INEFFECTIVE	o PLACEMENT OF WEAPON RELATIVE TO CREW AND SIGHTING DEVICES	o IN-FLIGHT FIRING TESTS
		o NIGHT VISION SYSTEMS AFFECTED	o OPTICAL FILTERING	o GROUND AND FLIGHT TESTS

GUNS (CONT)

CHARACTERISTICS	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
BREACH GASES AND SMOKE	o ACRID FUMES, COLORED SMOKE, RESIDUE o HIGH TEMPERATURES IN VICINITY OF GUN	o OBSCURES VISION OF CREW, OBSCURES VISION THRU SIGHTING DEVICES o FUMES CHOKE CREW o FUMES INGESTED BY ENGINE CAN CAUSE ENGINE SURGE WHICH CAN RESULT IN HIGH DRIVE SYSTEM TRANSIENT LOADING o RESIDUE MAY COAT SIGHT GLASS o IGNITION OF FLAMMABLE MATERIALS	o PLACEMENT OF WEAPON RELATIVE TO CREW, SIGHTING DEVICES, ENGINE INTAKE o ENHANCED GAS DIVERSION AND PURGING	o IN-FLIGHT FIRING TESTS
EJECTION OF CARTRIDGES	o CARTRIDGES MAY EJECT INTO SLIP STREAM AND HIT HORIZONTAL STABILIZER OR TAIL ROTOR	o DAMAGE TO ELEVATOR STRUCTURE OR TAIL ROTOR	o PROVIDE EJECTION CHUTE, INDUCE AERODYNAMIC FLOW	o FLIGHT TEST
BARREL TUNING	o NATURAL FREQUENCY OF GUN BARREL CAN BE EXCITED BY MAIN ROTOR HARMONICS OR GUN RECOIL	o EXCESSIVE BARREL RESPONSE WILL INDUCE DISPERSION OF ROUNDS THUS AFFECTING FIRING ACCURACY	o CONDUCT ANALYSIS AND TEST OF GUN BARREL	o ANALYSIS, BENCH TEST, NON-FIRING FLIGHT TEST, FIRING FLIGHT TEST
FIRING TRAJECTORY (TURRETED & PINTLE ONLY)	o ROTOR CLEARANCE	o POTENTIAL DAMAGE TO MAIN ROTOR	o MAINTAIN 3° CLEARANCE CONE	o ANALYSIS, FIRING TESTS
CARTRIDGE TRANSPORT	o HIGH FEED RATES COUPLED WITH LARGE AZIMUTH & ELEVATION ANGLES CAN CAUSE JAMMING	o INOPERATIVE GUN	o DECREASE FIRING RATE o LIMIT TURRET ANGLES o INCREASE FEED CHUTE RADII	o GROUND AND FLIGHT TESTS

TABLE II - EXTERNAL STORES

TYPE	CHARACTERISTIC	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
GUNS (POD MOUNTED)	JETTISON AND CAPTIVE CARRIAGE	(TYPICAL OF STORES OF SIMILAR MASS CHARACTERISTICS)			
ROCKETS	LAUNCH TRANSIENT	o SINGLE ROUND INSIGNIFICANT: RIPPLE-FIRE MAY EXCITE STRUCTURAL RESPONSE	o ROCKET POD MAY VIBRATE, INDUCING TIP-OFF ERRORS	o CONTROL FIRING RATE, DETUNE ROCKET POD SUPPORT STRUCTURE	
	INITIAL TRAJECTORY	o ERRATIC TRAJECTORY UPON LAUNCH	o POTENTIAL DAMAGE TO MAIN ROTOR	o PROVIDE 3° HALF-ANGLE CLEARANCE CONE	o STATIC FIRE, FIRING FLIGHT TESTS
	BLAST	o USUALLY INSIGNIFICANT			
	FLASH	o SEE GUNS			
	SMOKE/RESIDUE	o SEE TURRETED GUNS WORST CASE IS FULL SALVO			

EXTERNAL STORES (CONT)

TYPE	CHARACTERISTIC	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
ROCKETS	DEBRIS	o USUALLY INSIGNIFICANT			
	DISPENSING	o VARYING MASS CHANGES SUPPORT STRUCTURE NATURAL FREQUENCIES	o RESPONSE TO MAIN ROTOR INDUCED EXCITATIONS MAY BECOME EXCESSIVE IF AMPLITUDE BECOMES EXCESSIVE, DAMAGING LOADS IN SUPPORT STRUCTURE AND AIRFRAME COMPONENTS AND EXCESSIVE CREW, ENGINE AND COMPONENT VIBRATION MAY OCCUR.	o DETUNE SUPPORT STRUCTURE FROM ROTOR HARMONICS	o ANALYSIS, SHAKE TEST, NON-FIRING FLIGHT TEST, FIRING FLIGHT TEST
	CAPTIVE/CARRIAGE	o STRUCTURAL MODES MAY BE EXCITED BY AND AMPLIFY ROTOR HARMONIC EXCITATION OR GUN RECOIL EXCITATION	o HIGH VIBRATIONS MAY EXCEED MISSILE QUALIFICATION LEVELS; CAUSE DAMAGING LOADS TO SUPPORT STRUCTURE OR TO AIRFRAME COMPONENTS; CAUSE EXCESSIVE VIBRATIONS ON CREW, ENGINE, SIGHTING DEVICES	o DETUNE STRUCTURE FROM ROTOR INDUCED HARMONICS	o ANALYSIS, SHAKE TEST, NON-FIRING FLIGHT TEST
	HANG-FIRE	o ONE OR MORE MISSILES HANG IN POD	o PRIMARILY A HANDLING QUALITIES CONCERN o HIGH STRUCTURAL LOAD TRANSIENTS o THERMAL EFFECTS	o DESIGN FOR LOADS AND THERMAL PROBLEMS	o DESIGN, ANALYSIS

EXTERNAL STORES (CONT)

TYPE	CHARACTERISTIC	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
MISSILES	CAPTIVE/CARRIAGE	o STRUCTURAL MODES MAY BE EXCITED BY AND AMPLIFY ROTOR HARMONIC EXCITATION OR GUN RECOIL EXCITATION	o HIGH VIBRATIONS MAY EXCEED MISSILE QUALIFICATION LEVELS; CAUSE DAMAGING LOADS TO SUPPORT STRUCTURE OR TO AIRFRAME COMPONENTS; CAUSE EXCESSIVE VIBRATIONS ON CREW, ENGINE, SIGHTING DEVICES	o DETUNE STRUCTURE FROM ROTOR INDUCED HARMONICS	o ANALYSIS, SHAKE TEST, NON-FIRING FLIGHT TEST
	LAUNCH TRANSIENT	o RELEASE OF RETENTION MECHANISM (SHEAR OF PIN) CAUSES IMPULSIVE LOADING	o HIGH TRANSIENT LOADS AND VIBRATIONS RESULT WHICH MAY INDUCE SIGNIFICANT TIP-OFF ERRORS	o DESIGN SUPPORT STRUCTURE TO MINIMIZE MOTIONS AND ACCOMMODATE LOADS	o DESIGN, ANALYSIS FIRING TESTS
	INITIAL TRAJECTORY	o ROTOR CLEARANCE o GROUND CLEARANCE	o SAME AS GUNS o EARLY MISSILE IMPACE	o SAME AS GUNS o OPERATIONAL LIMITATIONS	o SAME AS GUNS
	BLAST PRESSURE	o HIGH INTENSITY, BROAD BAND, IMPULSIVE EXCITATION TRAVELING ALONG THE STRUCTURE	o DAMAGING LOADS ON STRUCTURE; UNLATCHING OF COWLS & DOORS; EXCESSIVE DEFORMATION OF STRUCTURE; EXCESSIVE VIBRATIONS WHICH MAY EXCEED QUAL LEVELS OF ELECTRONIC GEAR	o DESIGN FOR ESTIMATED OVERPRESSURES; CONDUCT PIT FIRING TESTS	o DESIGN, PIT TEST FIRING TESTS

EXTERNAL STORES (CONT)

TYPE	CHARACTERISTIC	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
	FLASH	o SEE GUNS			
	SMOKE/RESIDUE	o SEE GUNS	o DUE TO VOLUME OF SMOKE, ENGINE INGESTION IS OF HIGH POTENTIAL; HOT GASES PASSING OVER ELEVATOR AND TAIL ROTOR MAY AFFECT HANDLING QUALITIES AND INDUCE OSCILLATIONS INTO DRIVE SYSTEM		
	HANG FIRE	o SEE ROCKETS			
BOMBS, TORPEDOS, DEPTH CHARGES	HEAVY WEIGHT	o	o HIGH FATIGUE LOADS IN SUPPORTING STRUCTURES	o DETUNING o REDUCED LOAD-OUT	o DESIGN, ANALYSIS & FLIGHT TESTS
ALL	JETTISON	o ACTIVE JETTISON o COLLISONS o LATERAL C.G. MIGRATION	o LOAD TRANSIENTS o DAMAGE TO A/C o STABILITY & CONTROL PROBLEMS	o DESIGN FOR LOADS o SPECIFIED JETTISON SEQUENCE INTERVAL & FLIGHT REGIME o SYMMETRIC JETTISON o ENHANCED DIRECTIONAL AND LATERAL CONTROL	o DESIGN, ANALYSIS, GROUND & FLIGHT TEST o ANALYSIS AND WING TUNNEL AND FLIGHT TESTS o ANALYSIS AND FLIGHT TESTS

APPENDIX II

WEAPONS SYSTEMS QUALIFICATION PROGRAMS

TABLE 1 -- GUNS

WEAPON SYSTEM TYPE	WEAPON SYSTEM NAME	HELICOPTER MODEL	YEAR	PRIMARY MISSION	STATUS Q=Qualified E=Experimental
Turretted MG	XM-28	AH-1G	1969	Attack	Q
Gun pod	SUU-11	AH-1G	1969	Attack	Q
Gun 20 mm	AME-621	SA 316/ 315	1970		E
Gun 20 mm	MG 151	SA 330	1970		Q
Pintle mounted MG, cal 7.62 mm	RO GPMG L7A2	Sea King	1970	Area suppression	Q
Gun 20 mm	AME 693	SA 316/ 315	1971		Q
Door mounted MG cal 0.50"		AH-1N	1972	Utility/Assault	Q
MG 7.62 mm	GAU-2/A	AH-1N	1973	Utility/Assault	Q
2MG gun pods cal 7.62mm	MATRA MYT 29	SA 316/ 315	1973		Q
2 MG cal 7.62mm	MG-3A	AB 206	1973	Scout	Q
Turret gun system		AH-1J	1974	Attack	Q
1 MG 7.62 mm Gatling type	MINI-TAT EMERSON	AB 206	1974	Scout	Q
Gun 20 mm	AME 20M621	SA 330	1974		Q
Gun 20 mm	AME 693	SA 330	1974		E
1 MG 7.62 mm Gatling type	MINI-TAT EMERSON	SA 341/ 342	1975		E
MG 7.62 mm	NF1 MAG-FG	SA 316/ 315	1975		E
1 MG 7.62 mm Gatling type	MINI-TAT EMERSON	CH-136 Kiowa	1976	Self-defence	Q
1 MG 0.50"		CH-135 Twin Huey	1976	Area suppression	Q
2 MG gun pods cal 7.62	A.E.I. ltd	SA 341/ 342	1977		E
2 MG gun pods cal 7.62 mm	MYT29 or FN TWINMAG	SA 341/ 342	1978		Q
2 MG gun pods cal 7.62 mm	MATRA MYT29	BO 105	1978	Area suppression	Q
2 MG 7.62 mm	NF1	SA 360/ 361	1978		E
Gun 20 mm	MG-151	SA 360/ 361	1978		E
Turret gun system 20 mm	M197	AH-1S	1978	Attack	Q
MG pod 7.62 mm		AH1S	1978	Target acquisition	Q
Chain gun 1200 rds		AH-64	1978	Covering force	Q

TABLE 1 -- GUNS (Continued)

WEAPON SYSTEM TYPE	NAME	HELICOPTER MODEL	YEAR	PRIMARY MISSION	STATUS Q=Qualified E=Experimental
2XCannon pods cal 20 mm	Oerlikon KAO	Lynx AH1	1978	Area suppression	Q
2 MG gun pods cal 7.62 mm	FN TMP	BO 105	1979	Area suppression	Q
Fixed fwd firing cannon	FPFC Mk20 RH202	BO 105	1979	Area suppression	Q
Turret Gun 20 mm	AME 693 CASSIOPEE	SA 330	1980		E
2 MG 7.62 mm	NF1 or FN MAG	SA 330	1980		E
Fixed fwd firing cannon	FPFC II KAO B12	BO 105	1981	Area suppression	Q
Gun 20 mm	20 M 621	SA 341/ 342	1981		Q
Pintle mounted MG. cal 7.62mm	RO GPMG L7A2	Lynx HAS2	1982	Area suppression	Q
2 fixed fwd firing cannons 25mm	GBH-A01 (KBA-C04)	AB 412	1983	Anti-light armoured vehicle	Q
MG 12.7 mm pod	FFV	BO 105	1983	Area suppression	Q
2xtwin MG pods cal 7.62mm	FN	Lynx AH1	1983	Area suppression	Q
2xHeavy MG pods cal 0.50in	FN	Lynx AH1	1983	Area suppression	Q
MG 7.62 mm	M-60	UH-1N	1984-86	Utility/Assault	Q
MG 7.62 mm	GAU-2/B	UH-1N	1984-86	Utility/Assault	Q
MG 0.50"	XM-218	UH-1N	1984-86	Utility/Assault	Q
MG 0.50"	GECALSO	UH-1N	1984-86	Utility/Assault	Q
Gun 20 mm	20 M 621	AS 350/ 355	1984-86		Q
Turretted MG cal. 20 mm	M-196	AH-1J	1985	Attack	Q
MG 12.7 mm pod	FN HMP127	BO 105	1986	Area suppression	Q
MG 7.62 mm	FN-MAG	AS 350/ 355	1986		Q
Gun 20 mm	MG 151	AS 365 F	1986		Q
2 Guns 20 mm	NC20 M621	AS 365 M	1986		Q

TABLE 2 -- GUNS & ROCKETS

WEAPON SYSTEM TYPE	WEAPON SYSTEM NAME	HELICOPTER MODEL	YEAR	PRIMARY MISSION	STATUS Q=Qualified E=Experimental
2 MG cal. 7.62mm 2 rocket pods 2.75"	M 21	AB 205	1971	Area suppression	Q
2 MG cal. 7.62mm 2 rocket pods 2.75"		CH-135 Twin Huey	1977	Area suppression	E
1 MG cal. 7.62 mm 2 rocket 70 mm twin pod	SF 260W + XM 157	A 109	1979	Area suppression	Q
2 MG cal. 7.62mm 2 rocket pods 81 mm	SNORA	AB 205	1980	Area suppression	Q
2 MG MAG58 7.62mm 2 rocket pods 2.75"	XM 156	AB 412	1983	Area suppression	Q
Machine-gun pod/rockets	HMP/ MRL 70	BO 105	1986	Area suppression	Q

TABLE 3 -- ROCKETS

WEAPON SYSTEM TYPE	WEAPON SYSTEM NAME	HELICOPTER MODEL	YEAR	PRIMARY MISSION	STATUS Q=Qualified E=Experimental
5" rocket pod	LAU-10	AH-1G	1969	Attack	Q
2.75" rocket pod	LAU-61	AH-1G	1969	Attack	Q
2.75" rocket pod	LAU-68	AH-1G	1969	Attack	Q
2x6 rockets cal. 68 mm	MATRA F22	SA 316/ 315	1976		Q
4 rockets cal. 68 mm	SARHEL	SA 341/ 342	1976		E
2x18 rockets cal 68 mm	MATRA SNEB	Lynx AH1	1976	Area suppression	Q
2x7 rockets cal. 2.75"	FZ M157C FZ68	SA 341/ 342	1977		E
2.75" rocket	SURA D-81	BO 105	1977	Area suppression	Q
2.75" rocket	CRV 7 or Mk4	CH-136 Kiowa	1977	Target marking	Q
2.75" rocket	CRV 7 /Mk40-3	CH-135 Twin Huey	1977	Area suppression	E
2x12 rockets cal 81 mm	Oerlikon SURA-D	Lynx AH1	1977	Area suppression	Q
2x19 rockets cal 2.75"	FZ FFAR M159C	Lynx AH1	1977	Area suppression	Q
2.75" rocket pod		AH-1S	1978	Area suppression	Q
76 rockets pod	FFAR	AH-64	1978	Airmobile escort	Q
2.75" rocket	FFAR	BO 105	1978	Area suppression	Q
50 mm rocket	SNIA	BO 105	1978	Area suppression	Q
2x7 rockets cal. 2.75"	FZ M157C Mk40	SA 341/ 342	1978		Q
2x12 rockets cal. 68 mm	TH-BT F1	SA 341/ 342	1978		Q

TABLE 3 -- ROCKETS (Continued)

WEAPON SYSTEM TYPE	WEAPON SYSTEM NAME	HELICOPTER MODEL	YEAR	PRIMARY MISSION	STATUS Q=Qualified E=Experimental
2x10 rockets cal. 68 mm	F1-A MATRA	SA 341/ 342	1978		Q
2x22 rockets cal. 68 mm	TH-BT F1	SA 360/ 361	1978		E
2x19 rockets cal. 2.75"	FZ M159C Mk 40	SA 360/ 361	1978		E
2x22 rockets cal. 68 mm	TH-BT F1	SA 330	1980		Q
2x19 rockets cal. 2.75"	FZ Mk 40	SA 330	1980		Q
2x6 rockets cal. 68 mm	MATRA F 22	SA 341/ 342	1981		E
68 mm rocket	SNEB	BO 105	1981	Area suppression	Q
2x12 rockets cal 81 mm	Oerlikon SNORA	Lynx AH1	1982	Area suppression	Q
2x6 rockets cal. 68 mm	MATRA SNEB F.2	Gazelle	1982	Area suppression	Q
70 mm rocket	CRV 7	BO 105	1983	Area suppression	Q
2x36 rockets cal. 68 mm	TH-BT F1	AS 332	1983		Q
2x18 rockets cal. 68 mm	MATRA SNEB	Sea King	1983	Area suppression	Q
2.75" rocket pod	LAU-61	UH-1N	1984-86	Utility/Assault	Q
2.75" rocket pod	LAU-68	UN-1N	1984-86	Utility/Assault	Q
2x12 rockets cal. 68mm	TH-BT M 157C	AS 350/ 355	1984-86		Q
2x7 rockets cal. 2.75"	FZ M 157C	AS 350 355	1984-86		Q
2 rocket pods 50 mm	SO-HIA29	AB 412	1985	Area suppression	Q
2 rocket pods 81 mm	81-HLA12	AB 412	1985	Area suppression	Q
2.75" rocket pod	LAU-61	AH-1W	1985	Attack	Q
2.75" rocket pod	LAU-68	AH-1W	1985	Attack	Q
5" rocket pod	LAU-10	AH-1W	1985	Attack	Q
5" rock pod	LAU-10 ZUNI	AH-1T	1986	Attack	Q
2 rocket pods 81 mm	MEDUSA	A 129	1986	Area suppression	Q
2x12 rockets cal. 68 mm	TH-BT F1	AS 350/ 355	1986	Q	
2x7 rockets cal. 2.75"	FZ 68	AS 350/ 355	1986		Q
2x19 rockets cal. 2.75"	FZ 68	AS 365 M	1986		E
2x22 rockets cal. 68mm	TH-BT F1	AS 365 M	1986		E
2 rockets pods 2.75"	CRV7 B.A.C.	AS 350/ 355	1987		E

TABLE 4 -- MISSILES

WEAPON SYSTEM TYPE	NAME	HELICOPTER MODEL	YEAR	PRIMARY MISSION	STATUS Q=Qualified E=Experimental
2 wire-guided missiles	AS 12	AB 204	1968/69	Anti-Vessel	Q
2 wire-guided missiles	AS 12	AB 205	1970	Anti-Vessel	Q
2 wire-guided missiles	AS 11	AB 206	1973	Scout	Q
2x2 wire-guided missiles	HOT	SA 341/ 342	1973		Q
4 wire-guided missiles	AS 12	AS 61	1973/74	Anti-Vessel	Q
4 or 2 wire guided missiles	AS 11/ AS 12	SA 341/ 342	1974/75		E
2 wire-guided missiles	AS 12	AB 212	1974	Anti-Vessel	Q
2 wire-guided missiles	AS 11	SA 316/ 315	1975		Q
2 anti-ship missiles	AM 39 EXOCET	SA 321	1975		Q
2x2 wire-guided missiles	AS 12	WG 13	1975		Q
4 wire-guided missiles	TOW	A 109	1977	Anti-Tank	Q
8 wire-guided missiles	Hughes/BAe TOW	Lynx AH1	1977	Anti-Tank	Q
8 wire-guided missiles	Euromissile HOT	Lynx AH1	1977	Anti-Tank	Q
8 wire-guided missiles	BAe Hawkswing	Lynx AH1	1977	Anti-Tank	Q
2 anti-ship missiles	MARTE Mk1	AS 61	1976/78	Anti-Vessel	Q
Wire-guided missiles	TOW	AH-1T	1978	Anti-armour	Q
Wire-guided missiles	TOW	AH-1S	1978	Anti-armour	Q
16 missiles	HELLFIRE	AH-64	1978	Anti-armour	Q
2x3 wire-guided missiles	HOT	BO-105 (PAH1)	1978	Anti-Tank	Q
2x3 wire-guided missiles	HOT	SA 341/ 342	1978		E
2x4 wire-guided missiles	HOT	SA 360/ 361	1978		E
2 anti-ship missiles EXOCET	AM 39	AS 61	1980	Anti-Vessel	Q
4 anti-ship missiles	AS12	Lynx HAS4	1980	Anti-ship	Q
2 guided missiles	Aerospat Exocet AM39	Sea King		Anti-ship	Q
Air-to-air missiles	AIM-9	AH-1T	1982	Attack	Q

TABLE 4 -- MISSILES (Continued)

WEAPON SYSTEM TYPE	NAME	HELICOPTER MODEL	YEAR	PRIMARY MISSION	STATUS Q=Qualified E=Experimental
2x2 anti-ship missiles	AS-15	AS 365N	1982		Q
2 anti-ship missiles	AM 39 EXOCET	AS 332	1982		E
16 missiles	HELLFIRE	UH-60	1982	Anti-armour	Q
4 Anti-ship missiles	BAe Sea Skua	Lynx HAS2	1982	Anti-ship	Q
Wire-guided missiles	TOW	BO 105	1983	Anti-tank	Q
2 Air-to-air missiles	Stinger	Lynx HAS2	1983	Anti-aircraft	Q
8 guided missiles	Rockwell Hellfire	Lynx AH1	1983	Anti-armour	Q
A/A missiles	STINGER	BO 105 (VBH)	1984	Anti-air self defence	E
Air-to-air missiles	AIM-9	AH-1J/T	1984-85	Attack	Q
Missiles	HELLFIRE	AH-1J	1984-85	Anti-armour	Q
Missiles	HELLFIRE	AH-1W	1985	Anti-armour	Q
Air-to-air missiles	AIM-9	AH-1W	1985	Attack	Q
2 anti-ship missiles	MARTE Mk2	AS 61	1985/86	Anti-vessel	Q
8 wire-guided missiles	TOW	A 129	1986	Anti-tank	Q
2 anti-ship missiles	Sea Skua	AB 212	1985/87	Anti-vessel	Q
Anti-ship missiles	Sea Skua	Sea-King Mk-41	1987	Anti-vessel	Q
Wire-guided missiles	HELITOW	BO 105	1987	Anti-tank	Q
2 guided missiles	BAe Sea Eagle	Sea King	1987	Anti-ship	Q

TABLE 5 -- MISCELLANEOUS

WEAPON SYSTEM TYPE	NAME	HELICOPTER MODEL	YEAR	PRIMARY MISSION	STATUS Q=Qualified E=Experimental
2x2 Torpedoes	MK 44 or MK 46	SA 321	1966		Q
500 lb bomb	Rockeye	AH-1G	1969	Attack	Q
500 lb bomb	Mk-77 Firebomb	AH-1G	1969	Attack	Q
500 lb bomb	FAE I	AH-1G	1969	Attack	Q

TABLE 5 -- MISCELLANEOUS (Continued)

WEAPON SYSTEM TYPE	WEAPON SYSTEM NAME	HELICOPTER MODEL	YEAR	PRIMARY MISSION	STATUS Q=Qualified E=Experimental
Practice bombs		AH-1G	1969	Attack	Q
2 Torpedoes	Mk 44	AB 204	1969/70	Anti-submarine	Q
4 Depth charges	BAe MK11	Sea King	1970	Anti-submarine	Q
Improved wing armament system		AH-1J	1971	Attack	Q
2 torpedoes	Mk 44 or Mk 46	AB 212	1972/72	Anti-submarine	Q
4 torpedoes	Mk 44 or Mk 46	Sea King	1974	Anti-submarine	Q
4 torpedoes	A244/S	Sea King	1974	Anti-submarine	Q
4 torpedoes	Marconi Sting Ray	Sea King	1974	Anti-submarine	Q
2 torpedoes or Depth charges	Mk 46 or Mk 52	WG 13	1975		Q
Remote Piloted Vehicle	MIRACH Mk 100	A 109	1980/82	Battlefield surveillance	Q
Parachute Retarded Sonobuoys	PRS	CH-124 Sea King	1980	Anti-submarine	Q
2 torpedoes	Mk 44 or Mk 46	Lynx HAS2	1980	Anti-submarine	Q
2 torpedoes	Sting Ray	Lynx HAS2	1980	Anti-submarine	Q
2 depth charge	BAe MK III	Lynx HAS2	1980	Anti-submarine	Q
Mine dispenser 128 AT or 1536 AP mines	Tecnovar Italiana DAT	Lynx AH1	1981	Anti-tank/personnel	Q
40 mines	Mk 56	UH-60	1982		Q
2 torpedoes	Mk 46	AS 365N	1982		Q
2 torpedoes	A244/S	Lynx HAS2	1983-84	Anti-submarine	Q
40 mm grenade launcher	Mk 19	UH-1N	1984-86	Utility/Assault	Q
Chaff and flare dispenser	ALE-39	SH-2	1985	Anti-submarine	Q
TACTS pod		CH-46	1986	Utility/Assault	Q
TACTS pod		CH-53	1986	Utility/Assault	Q

APPENDIX III

LESSONS LEARNED

This appendix describes several case histories of helicopter weapons systems integration problems and solutions. These case histories serve to substantiate the recommended procedures in the report.

CASE A - STRUCTURAL DESIGN, DEVELOPMENT AND QUALIFICATION OF THE UH-60 EXTERNAL STORES SUPPORT SYSTEM (ESSS)

Background

In 1976, at the completion of the Utility Tactical Transport Aircraft System (UTTAS) competition, source selection, and subsequent contract award to Sikorsky Aircraft, the Army conducted feasibility studies of an Armed UTTAS. These showed that a winged* design was practical from a weight/performance/structural standpoint. Because funds were not then available to pursue this configuration, the plans laid follow through final development, qualification and initial production of the aircraft. By 1980, the emphasis had shifted from a purely armed configuration to an equal need for self-deployment, giving impetus to implementation of an aircraft with alar members for carriage of multiple external stores. A contract was awarded to Sikorsky to initiate design, development and qualification of a "winged" BLACKHAWK in 1981.

Operational Concept

The primary utility mission role remained paramount. The capability to perform anti-armor, mine dispensing and self-deployment missions greatly enhanced and expanded aircraft flexibility and utility. The initial design was predicated on the use of the Hellfire Missile System, MK 56 mine system and two 230 gallon and two 450 gallon external tanks to accomplish self-deployment. Soon, thereafter, the Army recognized that use of the 230's for all missions would significantly increase total mission response. Sikorsky was directed to focus on this configuration and determine the maximum performance available within the existing airframe and drive system capability. As a result, when the 230 gallon tank was procured in 1983, it was specified as a crashworthy and ballistically tolerant design to be compatible with the aircraft. Time and money was saved by using a modified F-101 centerline 450 gallon tank since several thousand were available from long term storage. The tank is used only for ferry missions and is not crashworthy nor ballistically tolerant.

General Description

The External Stores Support System (ESSS) is comprised of fixed airframe structure and an External Stores Subsystem (ESS) designed for rapid installation and removal from the aircraft. See Figure A1.

The primary fuselage structure consists of two upper and two lower fittings per side. These attach to the main landing gear frames at FS 295.0 and FS 308.0. The upper fittings support the Horizontal Stores Support (HSS) and are machined 7075-T73 aluminum alloy. High interference fit steel bushings are installed in the lugs to provide unlimited service life. The lower fittings support the strut assemblies and are 17-4 PH stainless steel. Spherical rod end bearings are installed in the lugs to ensure that only axial loads are applied to the fuselage. Fairings are provided to cover the fittings when the HSS and support struts are removed. The fixed provisions include fuel and air lines with a self-sealing breakaway feature. Electrical harnesses for the fuel system, jettison system, Hellfire Missile System and navigation lights complete the installation. The stores fitting was designed to accommodate different types of ejector racks as well as provide interface space to add other ordnance on both fixed and removable provisions.

ESS

The structural elements of the ESS consist of two Horizontal Store Supports (HSS), four support strut assemblies, four vertical stores pylons, four identical ejection rack fittings, adjustable links which permit the incidence angle of the rack fitting to be varied, and adapter fittings which allow the rack fittings to be used with either 14 inch or 30 inch ejector racks. See Figure A2. The HSS is a two cell, three spar, constant cross section (but tapered in laminate construction) beam of graphite/epoxy construction. Three spars are used for ballistic damage redundancy. A 6 degree incidence angle and a 7.7 degree anhedral are maintained relative to the fuselage. Three internal ribs, also of graphite/epoxy construction, are located at the tip, and just inboard and outboard of the BL80 pylon. Attachment to the fuselage is accomplished through two sets of lugs located at the forward and aft sides of the box. Each set has three lugs to provide redundancy for ballistic damage. High interference, stainless steel, bushings are installed in the lugs to reduce vibratory loads and provide an unlimited service life. The fuselage attachment bolts are 1" dia, quick release, expandable fasteners similar to those utilized in the main rotor blade cuff to hub attachment.

The inboard stores attachment fitting, located at BL80.0 is machined 7075-T73 aluminum alloy. Lugs, in which spherical rod end bearings are installed, extend down from the fitting to provide the upper connection for the support strut assemblies. The outboard stores attachment fitting is located at BL112.0. The configuration is similar to the inboard fitting except that the support strut attachment lugs are omitted.

The strut assemblies support each HSS. The struts are identical and interchangeable. They are connected to the front and rear spars of the HSS at BL80.0. The strut tubes are of graphite/epoxy construction. End fittings are bonded and bolted to the tube. At the lower ends, the stainless steel fittings are threaded to allow adjustment of the strut length. This is a one time adjustment.

The rack fitting is machined 7075-T73 aluminum alloy designed to accommodate the MAU-40/A ejector rack. The ejector rack fitting fastens below the store attachment fitting at a pivot point located above the

* Although the term "wing" is descriptive, great care was taken to insure that the member did not generate lift which might have affected stability, control and performance of the aircraft.

store c.g. The forward end of the rack fitting is attached through a set of adjustable links. This feature allows a variable incidence angle to obtain an optimum store configuration for minimum drag and optimum firing attitude for ordnance.

Fuel lines are routed along the trailing edge to each stores pylcn with appropriate valves and sensing elements. Electrical harnesses were run along the leading edge or in the middle to provide the maximum separation from the fuel lines as possible for safety. Fairings are provided for the HSS leading edge, trailing edge and tip to minimize drag. Easily removable fairings enclose the store attachment and rack fittings. This completes the wing installation.

Structural Design Criteria

The ESSS, without stores, is capable of operating within the basic structural design envelope with a useful life greater than 20,000 hours. The fuselage attachment structure does not require overhaul/removal in less than 8000 hours-the airframe design life. For carriage of stores, the strength and stiffness requirements of the ESSS installation were determined from the following considerations.

With the 230 gallon external fuel tanks on the outboard store stations only, the limit maneuver load factor is 3.5 G. This is compatible with the basic aircraft design. However, the inherent strength capability of the fuselage is reduced to 3.0 G due to the increase in gross weight. For simultaneous carriage of four (4) external fuel tanks (450 gallon tanks inboard and 230 gallon tanks outboard) in the ferry mission configuration, the limit load factor is 2.0 G.

The aircraft limit landing capability is a ten (10) foot-per-second (FPS) sink speed at level land contact with a forward velocity of zero (0) to sixty (60) knots. For contact on any 12 degree slope, the sink speed is six (6) FPS at zero forward velocity. This is retained for carriage of the Hellfire Missile or M56 Mine Dispenser. With the external fuel tanks, the sink speed for level contact is reduced to six (6) FPS while the 12 degree slope capability is unchanged.
Primary jettison of a store from any store station or emergency jettison of all stores being carried was required. Positive separation, of the 230 gallon tanks and Hellfire Missile System, was achieved in level flight from hover to V_H, with 10 degree and 5 degree sideslip angles at 80 and 120 knots respectively and in partial power descents of 1000 and 500 feet-per-minute also at 80 and 120 knots. Released stores did not come in contact with any portion of the aircraft nor with each other.

Torsional stiffness of the using and fittings were driven by the Hellfire Missile requirement for an acceptable tip-off (pitching) rate. Positive bending (up) was dictated by jettison of the mine dispenser. The missile hangfire requirement of 2500 pounds thrust for two seconds also influenced torsional and chord bending strength. Blast pressures, temperatures and debris from missile firing were investigated, but no damage resulted either to the aircraft structure or adjacent stores.

The ESS and fuselage attachment were designed to accept ballistic damage and be capable of supporting limit loads and repeated loads, while carrying the critical store configuration, without separation from the aircraft, for at least thirty (30) minutes. This included complete loss of one support strut. This was accomplished by "fail-safe" design of the wing and is discussed further in the NASTRAN analysis.

For the forward crash condition, it was desired that the wing or stores separate from the fuselage prior to structural failure of the supporting frames at Stations 295 and 308. This was a safety consideration to try and prevent the stores from impacting the fuselage or causing damage to the cabin which would impede safe exit. It could not be achieved because the stiffness requirements overrode static strength design.

The elevation angle of the store installation is manually adjustable to allow for minimization of drag in the extended range configuration and to optimize Hellfire Missile performance. A half-angle clearance cone of not less than five (5) degrees was maintained between the Hellfire Missile trajectory and the aircraft structure/rotor positions throughout the firing flight envelope. A revised usage spectrum was provided by the Army based on the original BLACKHAWK spectrum and modified by projected mission usage in the ESSS configuration supplied by the user command. The utility missions were expanded, additional missions defined and the ferry mission included.

Development and Qualification

The UH-60A airframe structure was analyzed using a NASTRAN finite element computer model. It is divided into three parts. Parts one and two represent the basic airframe and such items as the main and tail rotor gearboxes. Part three contains those mass items which make up the different weight configurations modified to include the detailed finite element model of the ESSS and the various stores to be used. In addition, ballistic damage was imposed to eliminate various load paths. The analyses were performed for a total of nine different shots through the HSS and the support strut assemblies. For each component, a stress analysis was performed, and margins of safety calculated at critical sections. A fatigue analysis was carried out for all critical areas, and service lives calculated. This was also done to demonstrate that the structure remaining after ballistic damage could sustain the vibratory loads associated with thirty minutes of restricted flight.

Static, fatigue, functional and environmental ground tests were conducted. Because the original UTTAS static test vehicle was essentially destroyed by the qualification tests completed prior to production, it was not available for ESSS development. The static test was accomplished on the instrumented flight test aircraft prior to first flight. It consisted of applied loads to 100% design limit (proof) load.

Deflection data was obtained for individual load directions and then used concurrently with the combined limit loads to determine the stiffness characteristics of the system including any significant slop and/or hysteresis.

For the fatigue test, a specimen of the fuselage was constructed by duplicating the support structure between the forward and aft frames at Stations 295 and 308. This was mounted from the typical structural steel framework. The objective was to expose all possible fracture modes, determine the fatigue strength of the ESS components and evaluate the fail-safe characteristics of the system. With just one test installation available, fatigue load test levels were moderate. Because the ESS design is driven by ballistic tolerance and weapons platform stiffness requirements, the load levels did not produce non-representative modes of cracking. Crack propagation tests were conducted to evaluate fail-safety.

Functional and environmental (hot/cold) tests completed the ground test qualification.

A shakedown flight load survey was conducted to develop the flight envelope in a build-up fashion and identify problem areas in the appropriate configurations. The effects of the various stores on flight characteristics and structural parameters was determined. Vibration and handling qualities data were acquired simultaneously prior to formal qualification flight testing. Total flight time was approximately 35 hours. Full instrumentation involved 377 parameters. Flight test aircraft 77-22714 was used. A comprehensive Flight Loads Survey was conducted based on the ESSS usage spectrum. It was flown with various combinations of the 450 gallon and 230 gallon external fuel tanks including tanks full, partially full and empty. The data was combined with laboratory demonstrated fatigue strengths to determine component replacement times for the ESSS and all the aircraft rotor system components. Approximately one third of the rotor system components showed a decrease in life. Additional survey work was accomplished with the Hellfire Missile System and M56 Mine System involving both captive flight and firing maneuvers and their associated loads. No adverse problems were uncovered that required major redesign or rework of the ESSS Systems or the aircraft.

Operational Evaluation

The final phase of the development and qualification effort was formal demonstrations of system compliance with stated requirements. These covered the areas of aerodynamics and performance, handling qualities, dynamic stability and vibration, store jettison and separation, electromagnetic interference and armament and fire control. This operational evaluation culminated in the structural demonstration flight test. The purpose was to define the maximum safe operating limits of the aircraft consistent with the structural design envelope and define the critical conditions of helicopter strength and rigidity. The aerodynamic boundary limits were also established. Results are shown in Figures 3 and 4. The Army Engineering Flight Activity at Edwards Air Force Base conducted their airworthiness and performance evaluation prior to final acceptance of the ESSS system.

FIGURE A1

UH-60 With External Stores Support System Mounting 16 Hellfire Missiles.

FIGURE A2

ESSS STRUCTURAL INSTALLATION

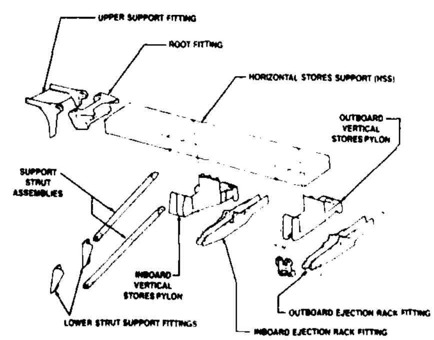


FIGURE A3

UH-60A/ESSS LIMIT V-N DIAGRAM
ESSS WITH 230 GALLON FUEL TANKS
ON OUTBOARD STORE POINTS

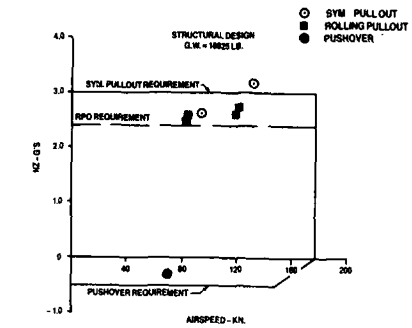
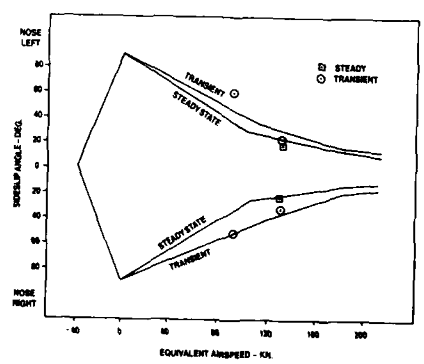


FIGURE A4

UH-60A ESSS SIDESLIP ANGLE ENVELOPE



CASE B - AH-64 Chain Gun Support

The AH-64 APACHE has a 30 mm chain gun mounted on intercostal beams on the belly of the fuselage. The beams are supported by heavy fuselage frame members. The structure was initially designed to react repeated loads from gun recoil indefinitely, substantiated by conventional fatigue analytical methods. Strain data on the gun support structure was acquired during the aircraft flight strain survey. A full scale laboratory fatigue test of the gun support structure was conducted. Comparison of test failure loads and cycles and measured applied laods and frequencies indicated that structural reinforcement would be required at the intersection of the intercostal and forward frame to insure adequate system life. The reinforcement and down stream redesign were substantiated by conventional fatigue analytical methods. Subsequent ground and flight firing programs have not uncovered additional problems.

CASE C - UH-60 Externally Supported Stores System

The UH-60 has an Externally Supported Stores System (ESSS). The system is made up of a stub wing, lift struts and two pylons for weapons attachment. During Hellfire firings it was found that reactive forces were sufficient to torsionally wind the stub wings and reduce the aiming accuracy of the missiles. A finite element analytical model was developed and used to establish acceptable deflections and required beam stiffness of the wing spar. Spar design became stiffness critical and resulted in a heavy graphite box section. (See Case A for a detailed discussion of the ESSS design development)

CASE D - AH-1 TOW Missile Blast Pressure

The AH-1Q which was the original TOW equipped AH-1 is an AH-1G with a nose mounted sight and TOW missiles with special pylons attached to the outboard wing store stations. TOW blast pressures are higher than the 2.75 rocket pressures which the AH-1G had previously experienced: therefore, a TOW firing ground test was proposed. This ground test was performed and passed with the AH-1 mounted on a flat bed semi trailer in order to reduce the ground nearness effects. Subsequently the TOW Missile was fired from a flying AH-1; this resulted in some unanticipated fuselage stringer buckling. As a result, the stringers and longerons were strengthened to about the present configuration. Analyses indicated that the initial failure was caused by the combined effect of flight loads and overpressure which caused the stringers to fail in a continuous beam column mode.

CASE E - Model 500K Hangfire Solutions

Recent investigations of a universal mount design for the Model 530K helicopter indicate that if a 2.75 in. rocket experiences a hang fire in the outermost mount, the aircraft will rotate 360° whether the pilot does or does not input corrective action instantaneously. If the hang ire occurs below 100 kt the aircraft will be capable of reacting the resultant structural loads without damage. It is not known whether the pilot can safely recover from this sudden gyration. The manufacturer asserts that the condition is safely recoverable.

Several alternatives are being considered:

(a) Develop an automatic jettison system which would sense hangfire.

(b) Include a shear pin type mounting that releases the rocket pod at a predetermined level of hangfire load.

(c) Demonstrate by flight test that an aircraft can recover from an actual hangfire.

(d) Accept risk of extremely remote hangfire.

CASE F - Model 500F External Store Separation

An external stores separation trajectory analysis for the Model 530F helicopter indicates that the M-261 Rocket Launcher and the HMP .50 Cal heavy machine gun pod will contact the skid landing gear. It is anticipated that the stores will be deflected by the skid tubes and then continue to drop down and away from the helicopter. No additional flight problems are anticipated by the manufacturer. To minimize the probability of store/skid gear contact, stores jettison should be conducted at zero or minimum sideslip angle of the helicopter. Also, when empty HMP .50 cal. pod is jettisoned, opposite side slip angle should be maintained. The U.S. Army is considering this evaluation and the manufacturer's recommendations.

CASE G - UH-60 Volcano Turbulence

The Volcano system consists of 160 mines mounted in racks on the sides of the UH-60 helicopter; 80 on each side. The system is in the final stages of engineering development. The racks mount to the same hard points provided for the ESSS. As noted in Figure G1, the racks present a large flat plate area. A complete flight loads survey was conducted and concluded that the racks did not adversely affect the vibratory loads in the rotor system of the aircraft. However, vibratory loads on the stabilator doubled due to wake turbulence impingement. The fatigue and durability implications of these amplified loads are under investigation.

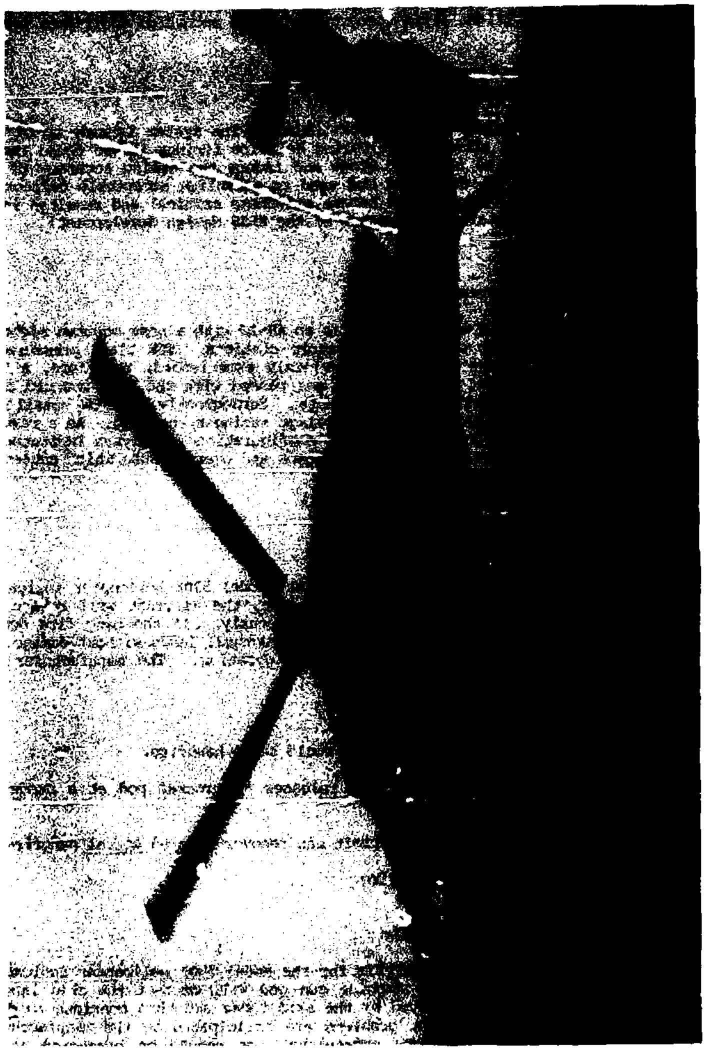


FIGURE G1

CASE H - Integration of TOW Wire Guided Missiles on Agusta A 109 Helicopter

Analysis made during the development phase and flight tests prior to the firing tests did not show significant trouble. The problem emerged during the ground firing tests. The helicopter was tied to the ground and in front of it was a facility to stop the rockets after short travel. The rockets were shot after being heated to their specification temperature limit. After a few shots damage was observed on the fuselage near the rear of the launchers and on the stabilizer. The damage was due to blast (buckled panels, access panels opened) and to the debris on the stabilizer. In order to solve the problem, local reinforcements were designed and installed, the access panel locks were changed and the stabilizer trailing edge was reinforced. Ground firing tests were resumed after these modifications and the results were satisfoactory. (See Figure H1)

CASE J - Integration of MARTE Anti-Ship Missiles on Agusta-Sikorsky AS-61 Helicopter

The MARTE booster engine ignites 1 second after the missile being dropped from the support. During the flight dropping test it was observed that the missile rotated nose down and that its attitude at time = 1 sec. was out of the allowable range for the guidance system. Preliminary aerodynamic analysis on the rotor down-wash effects and dynamic analysis on the behavior of the support structure during the dropping sequence had not shown evidence of this problem. So further analyses were made on the geometry of the attachment system and on the mass, C.G. position and inertia moments of the missile. These characteristics were then found to be responsible for the problem, but their modification was not possible. So a radical solution was designed by the weapon manufacturer and two micro rocket engines were installed on the upper and rear section of each missile to produce a rotating moment to counteract the nose down rotation. The required thrust, the ignition time and the duration of the ignition were calculated by the results of fully instrumented dropping tests. (See Figure J1)

CASE K - Integration of Sea Skua Anti-Vessel Missiles on Agusta-Bell AB 212 Helicopter

These missiles have been already installed on another helicopter of the same weight class and, for this reason, no preliminary aerodynamic analysis was done. During dropping tests from the hovering helicopter, both right and left missiles showed nose up attitudes beyond the allowable range. The aerodynamic analysis, supported by wake instruments, proved that the problem was due to the effect of the rotordown-wash on the missile wings. As a consequence, shields were designed and placed normally to the down-wash, just above the missile wings. (See Figure K1)

CASE L - Anti Ship Missile on Sea King

Missile separation trajectory flight trials have been done with direct data link via light-cable to the helicopter. The telemetry warhead was modified to transmit data via fiber optic and not via radio link. Three off-the-shelf micro gyros from an anti tank missile have been integrated and their attitude data have been transferred via the 30 m long fiber optic cable. Separation flight testing was done with only ten drops, all of those fully successful.

CASE M - Anti Tank Missile on Light Attack Helicopter (2.4 to)

Emergency jettison drop separation of a dual launcher for anti tank missiles has been done. The helicopter was equipped with snow skids. After release the launcher hit the snow skid. When hitting the snow skid, the launcher turned at approximately 600 deg/sec around its longitudinal axis. The behavior of the helicopter did not change. Only very little damage was discovered on the skids. The rotation of the launcher, induced by hitting the snow skids at the inner side of the launcher, was discovered to be an advantage because of lower risk of a pop up and lift reaction of the empty launcher. (See Figure M1)

CASE N - Fixed Gun on Light Helicopter

A 20mm gun was integrated on a 2.4to helicopter. The gun control was limited to 10 deg azimuth and ±10 deg elevation. Without modification the first shot hit the target; all other rounds were located below. A short delay between trigger-press and gun-fire, as well as a pull up signal given to the flight control system was implemented. The result was a controlled movement of the hits over the target. The first hit was in the target, the next few hits slightly below the target and then the hits moved up over the target. In a similar case, when using this method, the performance of the weapon system was even more improved. A time delay of approximately .1 sec was given by the hydraulic initialization of the weapon fire. The down motion was compensated by a pitch up flight control signal followed by a pitch down signal.

CASE P - Pod Gun on Light Helicopter

After having extensive damage on doors and windows by the blast of the gun, flight testing was stopped. A series of ground tests (trial and error) led to a flash hider configuration which deflected the blast up and down splitting it through several holes. Weapon performance coincidentally improved. (See Figures P1 and P2)

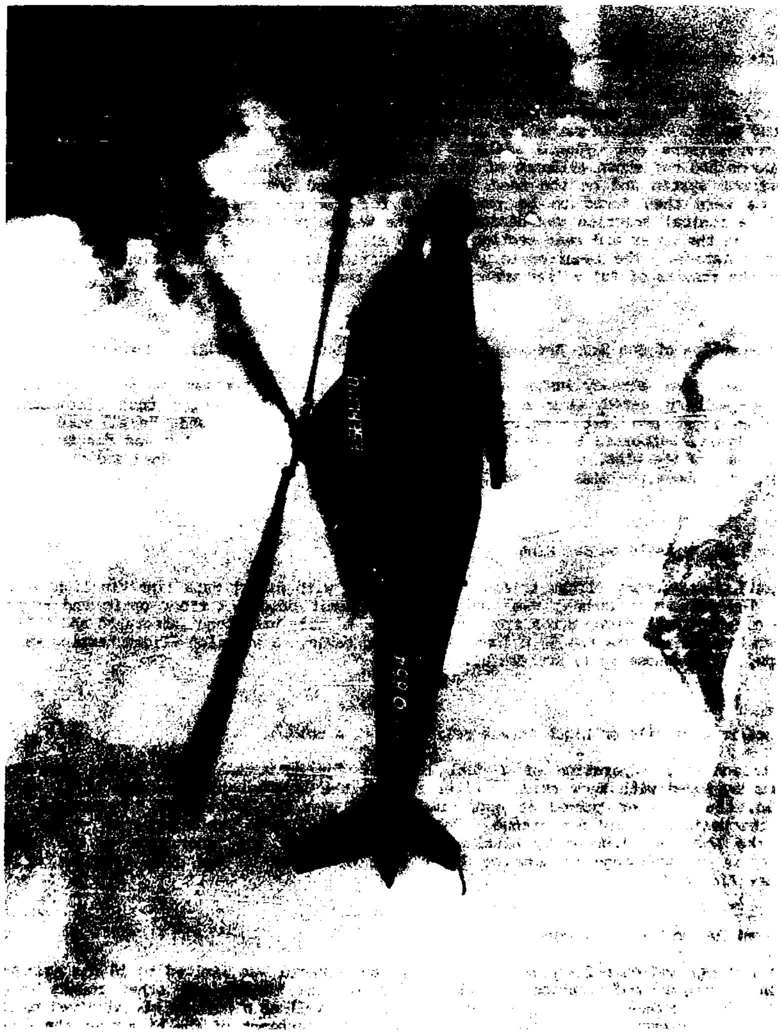


FIGURE H1

FIGURE J1

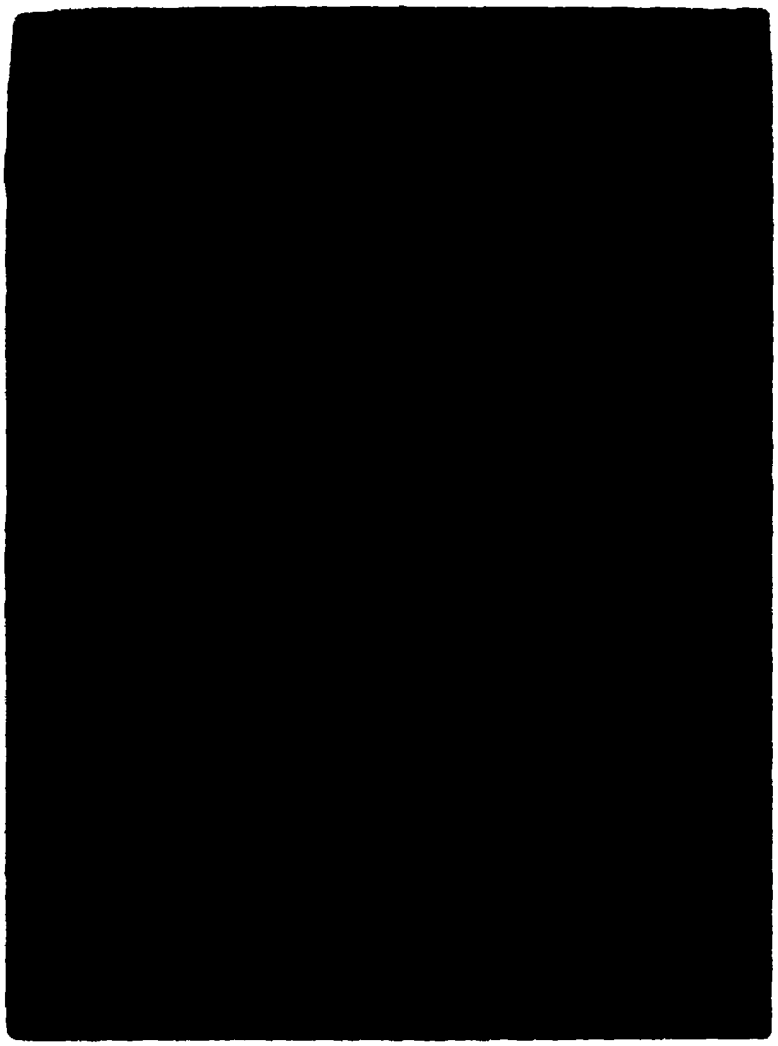


FIGURE H1

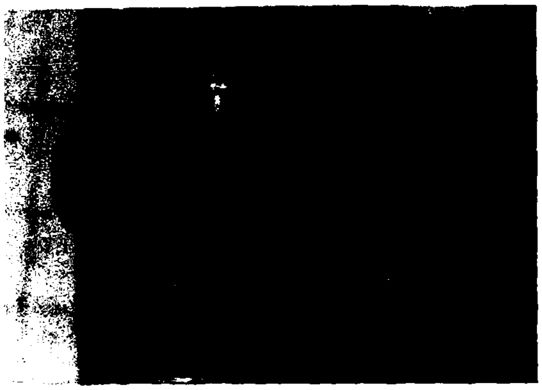


FIGURE P1

FIGURE P2

CASE Q - Door Gun in Helicopter

The ejection of cartridges led to uncontrolled interference with skids and reflection to fuselage and tail area. A tradeoff between good gun function with aforementioned interference and safe cartridge ejection with occasional inherent cartridge jamming was performed. The solution was a knee form channel with deflection plate to reduce impulse of the cartridge and safe trajectory between skids and fuselage.

CASE R - Sights for Weapon Systems/Anti Tank Missile on Light Helicopter

Fixed mounted sights usually have unacceptable vibration in the 4 omega rotor frequency. Mounting the sight on shock mounts reduced the vibration for the sight to an acceptable level, but caused unacceptable vibrations of the image and gunners eyepiece and missile line of sight mismatch. The solution was a pendulum type mount (a two pronged fork) where the rear end was fixed approximately 2 ft behind the sight and the two forward ends left and right of the sight. The acceleration in the critical axis was kept within acceptable level and the image vibration was reduced to an operationally acceptable level. In addition, coupling of the sight's line of sight into the AFCS yaw axis showed the performance of the weapon could be improved and the crew workload reduced.

CASE S - TOW Missile on Westland Lynx

The Westland Lynx AH-1 is armed with eight TOW missiles. These are carried on protruding weapon carriers either side of the aircraft roughly on a level with the cabin floor. Firing trials were carried out on the ground using an instrumented airframe to determine the effects of the boost motor blast. The measurements showed that some areas were subject to high transient stress levels. The worst of these were the inner flanges of some of the frames in the fuselage forward of the joint with the tailboom, where it appeared that fatigue cracking might start after a few hundred firings. Reinforcement was considered but it was obvious that the fastener holes that would have to be drilled to join on extra material would themselves act as stress raisers and might make the problem worse rather than better unless large amounts of material were added.

It was finally agreed that reinforcement of the whole fleet was unnecessary since it was unlikely that any aircraft would do sufficient firings to cause damage unless it was dedicated to TOW training. If there was such an aircraft it would be protected by regular inspection and repaired when necessary.

CASE T - Heavy Weapon on Westland Lynx

The naval version of the Westland Lynx is equipped to carry two heavy weapons such as torpedoes and depth charges. The carriers from which these are suspended each consist of a pair of curved members joined fore and aft by a box beam incorporating the ejector unit. Each carrier is attached to the aircraft by two pairs of lugs. The upper pair connect directly to corresponding lugs on the aircraft but the lower ones connect via a pair of links to avoid any preloading or transfer of vertical shear loads to these lugs. (See Figure T1a)

When weapon carriage flight trials commenced it became apparent that there were vibration problems. Not only did the weapons themselves experience high levels of vibration at the blade passing frequency (4R = 21.6Hz), such that their carriage fatigue life was measured in minutes at the aircraft's top speed, but the levels increased markedly throughout the airframe giving concern about crew comfort and airframe fatigue.

Flight measurements and ground shake testing revealed that there was a vibration mode involving torsional motion of the fuselage, with a natural frequency somewhat higher than 4R for the clean aircraft. When weapons were added their inertia caused the frequency of this mode to drop to near reasonance with the 4R rotor forcing.

Since the motion of the weapons was already in phase with the airframe, there was clearly nothing to be gained from trying to stiffen the carriers. The problem was solved by replacing the links which joined the bottom ends of the carrier to the airframe by springs which took the form of scissor linkages joined by torsion bars running fore and aft inside a torque tube (Figure T1b). This soft mounted the weapons in a vertical direction with a natural frequency well below 4R and decoupled their motion from that of the airframe mode which was causing the problem. The inertia of the weapons therefore no longer affected this mode whose frequency remained well separated from 4R. Unlimited carriage lives are now achieved.

CASE U - AH-1 Engine/ZUNI Rocket Compatibility

Background

The ZUNI rocket is a 5 in. diameter, solid fuel rocket that is carried in pods of four on most U.S. attack helicopters. Weapon firing tests of these rockets from the AH-1W aircraft showed that previously documented engine surges also caused potentially damaging torque overspikes in the helicopter's drive system. A test program was initiated to determine if similar torque overspikes were caused in other AH-1 series helicopters and what their magnitude may be.

CASE U (continued)

Test Description

An AH-1T helicopter was instrumented for sensitive engine, main rotor, and tail rotor torques as well as for engine parameters such as inlet temperature and pressure, compressor discharge pressure, interturbine temperatures, and fuel flows. Rockets were then fired from this aircraft, starting at the most benign flight conditions (outboard mounted pods, single firings, 60 KIAS airspeed), with all critical parameters monitored on the ground by real time telemetry. Engineers had established "knock-off" values of 90 percent of drive system limit torques for these tests and would stop the flight if these limits were approached. All flights were conducted over a suitable landing site in case of a drive system failure or loss of engine power and accompanied by a chase helicopter to provide photographic coverage as well as aid in clearing the target area. An example of the progressive type of flight test matrix followed is presented in Table I. An attempt was made to establish a pattern for any drive system torque reactions observed and suggest methods to minimize their effect upon the mission of the aircraft.

Table I

Flight Run	Airspeed	Altitude	Store Position and Release Mode
1/1	60 KIAS	1,000 FT	outboard station, single shot
1/2	30 KIAS	1,000 FT	outboard station, single shot
1/3	60 KIAS	1,000 FT	inboard station, single shot
1/4	30 KIAS	1,000 FT	inboard station, single shot
2/1	HOVER	10 FT	outboard station, single shot
2/2	HOVER	10 FT	inboard station, single shot

*Matrix continued to include multiple rocket shots conducted in a similar progressive fashion until a drive system limit was reached.

Results

Rocket firing tests identified helicopter drive system overtorques caused by engine surges and recoveries. These surges were attributed to the effects of the high temperature rocket exhaust gasses and were worst at the low speed, multiple firing conditions. Recommended changes to the operating envelope and procedures for firing 5 in. rockets from the AH-1T helicopter (including maintenance practices) resulted from these tests. Future designs should also benefit from the knowledge gained in these tests as changes in engine fuel controls, intake design and placement, and drive system design can reduce the detrimental effects of rocket exhaust gasses upon the attack helicopter.

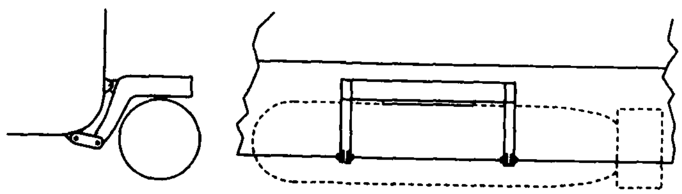


FIGURE T1a

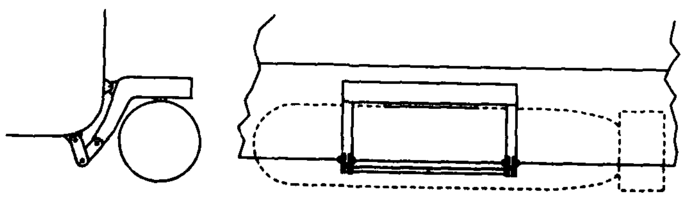


FIGURE T1b

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14. Abstract

This report contains detailed discussions of the aero-mechanical aspects of helicopter weapons integration. Particular emphasis is placed on flying qualities and performance with externally mounted weapons systems as well as weapons separation characteristics. In addition, structural mechanics topics, operational issues, and special problems are discussed. Each technical area is discussed in terms of analytic methodology, ground testing and flight testing procedures, instrumentation, and an assessment of the state-of-the-art, where possible. The text material is supplemented by three appendices. Appendix I is a synoptic table which relates each particular undesirable characteristic to various effects and results and further suggests solutions. Appendix I should serve as a guideline for any new helicopter weapons integration venture at the design stage. Appendix II is a listing of known helicopter weapons certification programs completed to date that have either produced experimental results or a fully qualified system. Thus, Appendix II should indicate a source of weapons or helicopter manufacturers which the reader could query directly. Appendix III is a compendium of case histories which are referred to by the text and which will serve to explain more fully the phenomena discussed therein.

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