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A UNIQUE DESIGN FOR A DIVERGING FLEXIBLE VERTICAL TAIL

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Summary

A method is developed which allows to use the flexible behaviour of aircraft structures to enhance aerodynamic derivatives. A vertical tail analytical model was used to show these effects and by exploiting the aeroelastic deflections it is possible to reduce the area of this surface up to thirty percent. Numerous applications are possible including fighter and transport airplanes. Since composite structures are involved it is absolutely necessary to use a multidisciplinary optimisation program code such as the US-Airforce ASTROS-code.

1. Introduction

Vertical tails designed for high speed aircraft suffer from reduced stability and control effectiveness at high dynamic pressures due to aeroelasticity. Therefore, adequate tail performance requires large tail area with high aspect ratios, and stiff and heavy structures. These large tails are also subject to burst vortex or shock induced buffet which causes fatigue problems. Their size and structural constraints cause weight, drag, and radar cross section penalties. These penalties can be significantly reduced by the application of divergent flexible technologies to the vertical tail design problem, which results in a lighter structure and potentially smaller size to reduce buffet, drag and observables. In same cases the smaller size requirement could remove the necessity of two vertical tails.

Although active flexible technology is currently being developed for wing structures under other programs [1,2] application of this technology to vertical tails requires a different design process and results in a different design solution due to the different design requirements between the tail and wing.

The vertical tail is a stiffness design because flight loads are much lower than on the wings of fighter airplanes. Therefore there is a wider variation of CFC-layers available than on wings where a lot of the stiffness is defined by strength constraints.

In this work the objective was to demonstrate increased tail effectiveness at high speeds. This could lead to decreased tail size and structural weight that meets or exceeds all tail performance and observables goals.

The reason why it is called „diverging“ is that a surface design with greater efficiency than one must diverge at some speed. Our aim must be that the divergence does not occur in the required speed range of the air vehicle.
The technology applied is called Active Flexible Technology which is a multi-disciplinary, synergistic technology that integrates aerodynamics, controls, and

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structures together to maximize air vehicle performance shapes for optimum performance. This was first described extensively in [3].

For high speed the vertical tail is designed to provide a minimum value of the directional static stability derivative. For low speed the rudder power unit must be adequate to hold a sideslip of $\beta = 11{,}5°$ at the approach speed for a cross wind landing. It also must cover the one engine out case. This low speed requirement may reduce the possibility to cut the fin span and area commensurate with positive high speed aeroelastics.

2. Description of Work

A generic aircraft design was selected and the vertical tail was designed (at the conceptual design level) with conventional and with active flexible technologies. The weight, performance, and observables benefits of DFVT were then determined relative to the conventional design.

A FEM model for a generic fin was available which was used in the Dasa Lagrange optimisation code [4]. This model was modified to serve for the USAF-ASTROS optimisation code. The finite element model could be very useful for future work as a benchmark. Therefore all comparisons with Dasa results are well documented.

Because of the low aspect ratio of the chosen vertical tail design - AR = 1.2 - this is an ideal candidate for applying aeroelastic tailoring for carbon fibre composite structure (Figure I). As can be seen in this figure the higher the aspect ratio is the higher the weight penalties to meet the performance goals.

The design of aircraft and space structures requires the marshalling of large teams of engineers to select a design which satisfies all requirements. Typically this design goes through further refinement or modification as more knowledge is gained about requirements or as new conditions are imposed. Much of this effort presently consists of applying laborious „cut and try“ procedures wherein the design is perturbed and reanalysed many times. This redesign frequently is required because two or more disciplines have conflicting demands that require compromise.

Therefore it is necessary to have an automated design and analysis tool that performs the trade-off and synthesis tasks in a systematic way. The ASTROS (Automated Structural Optimisation System) is such a computer code [5].

3. ASTROS Concepts

ASTROS is a finite element-based software system that has been designed to assist, to the maximum practical extent, in the preliminary design of aerospace structures. A concerted effort has been made to provide the user with a tool that has general capabilities with flexibility in their application.

A vital consideration in software of this type is that the key disciplines that impact the design must be included in the automated design task. This multidisciplinary aspect of the program has been implemented in an integrated way so that all the critical design conditions are considered simultaneously.

In addition to the interaction of several disciplines, ASTROS can treat multiple boundary conditions, and, within each boundary condition, multiple subcases. The system is not arbitrarily restricted by problem size, and it conforms to the current environment for performing structural analysis in the aerospace industry. The practical limitations on problem size are available disk space and data processing time.

Compatibility with the current aerospace environment is addressed because the ASTROS procedures resemble those of NASTRAN in terms of user input and pre- and post-processor interfaces. While the ASTROS program does not contain many of the specialised capabilities available in NASTRAN, the basic structural analysis features have been included. Most importantly, from a user point-of-view, the Bulk Data formats have been taken directly from NASTRAN and modified only if the design considerations required such a modification in the data or, in a few cases, if minor changes result in superior capability. New Bulk Data entries have been created to input design information and data needed to run the steady aerodynamics and other analyses specifics to ASTROS.

3.1 ASTROS Capabilities

This section gives a brief overview of the capabilities that are included in the code. The basic disciplines that are implemented within this code are as follows:

1. Static analysis
2. Modal and flutter analysis
3. Aerodynamic Analysis
4. Dynamic Response Analysis
5. Optimisation

The statics analysis methodology is based on a finite element representation of the structure, as are all the structural analysis disciplines in ASTROS. The static analysis compute responses to statically applied mechanical (e.g. discrete forces and moments), thermal and gravity loadings. Static deformations and their resultant stresses are among the computed responses. An extensive design capability is provided for the static analysis discipline. It provides the capability to analyse- and design linear structures subjected to time invariant loading.

The modal analysis feature in ASTROS provides the capability to analyse and design linear structures for their modal characteristics; i.e., eigenvalues and eigenvectors. The design aspect of ASTROS places limits on the frequencies of the structures. The modal analysis is not only useful in its own right, but also provides the basis for a number of further dynamic analysis. Flutter and blast response analyses in ASTROS are always performed in modal co-ordinates.
Transient and frequency response analyses can be performed in either modal or physical co-ordinates, at the selection of the user.

Steady aerodynamics are used for the computation of external loads an aircraft structures.

The static aeroelastic analysis features in ASTROS provide the capability to analyse and design linear structures in the presence of steady aerodynamic loading. This provides the ASTROS user with a self-contained capability to compute loads experienced by a manoeuvring aircraft and to redesign the structure based on these loads. The capabilities available for steady aerodynamics design include specifying limits on

- allowable stress or strain response due to a specified trimmed manoeuvre,
- flexible to rigid ratio of the aircraft's life curve slope,
- flexible roll control effectiveness of any antisymmetric control surface and
- values of flexible stability derivatives and trim parameters.

Flutter analysis in ASTROS provides the capability to assess the aeroelastic stability characteristics of the designed structure and to correct any deficiencies in a systematic fashion. Both subsonic and supersonic analyses are available and, reflecting the multidisciplinary character of the procedure, the design task can be performed with any number of boundary conditions and flight conditions. In this way, all critical flutter conditions can be analysed and designed for simultaneously.

Dynamic analysis is performed for loadings which are a function of time or frequency.

The final discipline listed above is that of optimisation. If only stress, or strain, constraints are included in the design task, the fully stresses design option may be used. For more general design tasks, a mathematical programming approach has been implemented.

3.2 Structural constraints for Vertical Tail layout

- Strength or strain allowable must not be exceeded. Five load cases were used in our case

- Static aeroelastic efficiencies for vertical tail and rudder were required. These terms are defined as flexible coefficients divided by rigid coefficients.

- Flutter or divergence speed requirements: for this case 530 m/sec, Ma 1,2

In addition there are some specific composite requirements such as minimum ply thickness and maximum amount of one layer.

4. Structural description of Fin and Rudder

The overall geometry of the fin is given in figure 2. The surface area is 5.46 m^2 and the leading edge sweep angle is 45°. The fin box has one shear pick-up in the front and one bending attachment at the rear. The rudder actuator is connected with two rods for control actuation. Fin box and rudder skins are built as carbon fibre laminates. A quasi isotropic glass fibre laminate is used for the tip structure which contains avionic equipment. Fin box and rudder are coupled by three hinges.
These are the four materials which were used: CFC, GFC, Aluminium, Titanium

- Fin Box Skin - Four Layer CFC Laminate
- Rudder Skin - Three Layer CFC Laminate
- Tip Skin - Quasi Isotropic GFC
- Fin Box Rear Spar - Four Layer CFC Laminate
- Rudder Main Spar - Four Layer CFC Laminate
- Remaining Spars - Aluminium

- Fin Box End Rib - Titanium
- Rudder End Ribs - Titanium
- Remaining Ribs - Isotropic CFC

5. Comparison of NASTRAN and ASTROS Results with existing Dasa Data

In order to become familiar with the Dasa model of fin and rudder several NASTRAN and ASTROS analysis were performed and results were compared with existing Dasa data. Correlation was found to be excellent. After that exercise the Dasa-model was changed. To allow different attachment conditions the general stiffness element (GENEL, giving the effect of the fuselage stiffness) was removed and replaced with single attachment springs. These springs were tuned so that the model would give the original Dasa results. ASTROS and NASTRAN results are identical because the ASTROS-code uses the finite element description of NASTRAN.
Results of this comparison can be found in table 1.

6. Results of Optimisation Runs with ASTROS

Several computer runs were performed with

- strength constraints
- flutter speed 530m/sec at Ma 1.2 / S.L.
- areoelastic efficiency

trying to first match the Dasa results for fin efficiency of 0.814 at M 1.8, 102 kPa. The rudder efficiency was fallout at 0.3799.
The ASTROS code reduced the weight for this configuration to

81.1 kg.

The weight of the initial design was 99.4 kg. When all constraints were fulfilled the weight was 95.1 kg for a fin efficiency of 0.814.

Higher fin efficiency was requested and the weights for these designs are plotted in figure 3. Whilst 0.9 can be reached with very little extra weight higher efficiencies need excessive weight penalties. When rudder efficiency was treated as fallout, then the weight reduces considerably and efficiency of 1.0 can be reached when flutter is fallout too. The fallout's are quite reasonable and sufficient for a feasible design.
From figure 3 it can be seen that a fin efficiency of 1.0 can only be achieved with infinite weight.
The picture changes completely when Ma 0.9 subsonic air forces are used (Figure 4). Now we reach higher efficiencies than 1.0. As can be seen with very little additional weight 1.3 can be reached for a high pressure of 102 KPa which is not possible for air. The highest possible q is 57 KPa for Ma 0.9, sea level in air.

This trend is also verified in figure 5 which clearly shows that the wash-in angle increases for higher efficiencies which simulates basically a forward swept fin behaviour (diverging!) and in figure 6 which shows a positive wash-in angle despite that it is a swept back surface.

7. Physical Explanation of the Basic Mechanism of the Diverging Flexible Vertical Tail (DFVT)

In order to understand the elastic behaviour of the fin an equivalent beam is assumed which contains the stiffness of the fin. This beam would be located at the elastic axis which is a spanwise line through the shear centres of each cross section. The shear centre of each cross section is computed by establishing the point in the plane of the section at which a normal load can be applied without twisting the section or whereas torsion moment can be applied to the section without producing a deflection at the shear centre. An effective elastic axis was defined by using the deflection of two points fore and aft on the chord where a moment was applied at the tip assuming small angles and that the deflection vary linearly along the chord. Figure 7 shows the elastic axis location. From this figure one can assess why it is impossible to get a wash-in effect (diverging) for the supersonic Ma 1.8 case. The centre of pressure - at 30% span and 50% chord - just reduces any initial angle attack of the fin, and therefore the best fin efficiency which can be reached with aeroelastic tailoring is 1.0 which is the rigid behaviour and needs a lot of structural weight. At the subsonic case, Ma 0.9, there exists some possibilities for wash-in, because the aeroelastic tailoring also shifts the so called elastic axis. This behaviour is shown in figure 4 and also in figure 8 for an optimised case of Ma 0.9, 102 kPA and fin efficiency of 1.3.

8. Results for shifting the attachments back

The behaviour changes drastically when the fin attachments are shifted back. The x-position for the forward attachment was shifted back from x = 450mm to x = 950mm. The x-position for the rear attachment was shifted from x = 1750mm to x = 2300mm. The new positions can be seen figure 9.
Now the centres of pressure are forward of the elastic axis and wash-in behaviour can be expected for both subsonic and supersonic cases (figure 10). For Ma 0.9, 57 KPa a fin efficiency of 1.3 can be reached with practically no weight increase. Also the rudder efficiency increases from 0.5 to about 0.7. This can be seen in figure 11. For the supersonic case Ma 1.8, 102 kPa the behaviour is similar (Figure 12), and 1.3 can also be reached with an optimised laminate. The rudder efficiency is now reduced to 0.5. The flutter speed is 530m/sec.. As an item of interest an analysis was performed (no optimisation) to find the fin and rudder efficiency at Ma 0.9, 57 kPa for the laminate of Ma 1.8 102 kPa. This shows a fin efficiency of 1.3 and a rudder efficiency of 0.8.
Figures 13 to 16 show the thicknesses of the different CFC layers for Ma 1.8, 102 kPa and an effectiveness of 1.3.

9. Conclusions and Recommendations

A list of possible benefits is presented below:

- The reduced tail size reduces the CD_0 drag.

- The reduced span and area reduces the exposure to upstream induced burst vortex and separated flow unsteady pressure fields which increases tail buffet fatigue life. The increase in life reduces repair and replacement life cycle costs.

- The reduced planform size reduces observable signatures to increase stealth mission capability and reduce detectability.

- Because of the possible size reduction one vertical tail would be sufficient even for Navy airplanes.

- With proper multidisciplinary optimisation a carbon fibre vertical tail can be made 30% more efficient than a rigid surface at the same weight.

- If the low speed requirement is not relevant the area of the vertical tail can be reduced by 30% together with the structural weight.

- An all moveable vertical tail could be the optimum solution for a fighter aircraft because the yaw axis would be brought very far to the rear. It would also be a solution for a subsonic aircraft because moving the whole tail would fulfil the low speed requirement. This was discussed in [6].

- A wind tunnel model should be built and tested to prove the concept experimentally. An analytical method to lay out and fabricate a low cost wind tunnel model is available.

10. References

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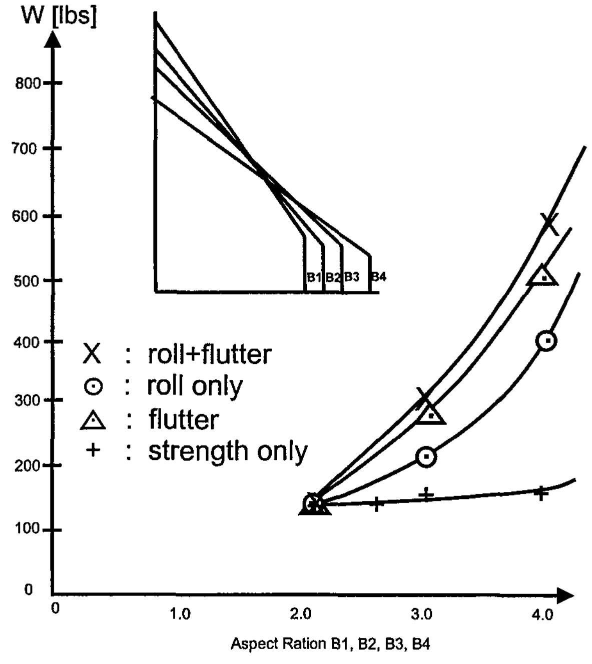

Fig. 1. Structural Weight for Various Constraints vs. Aspect Ratio

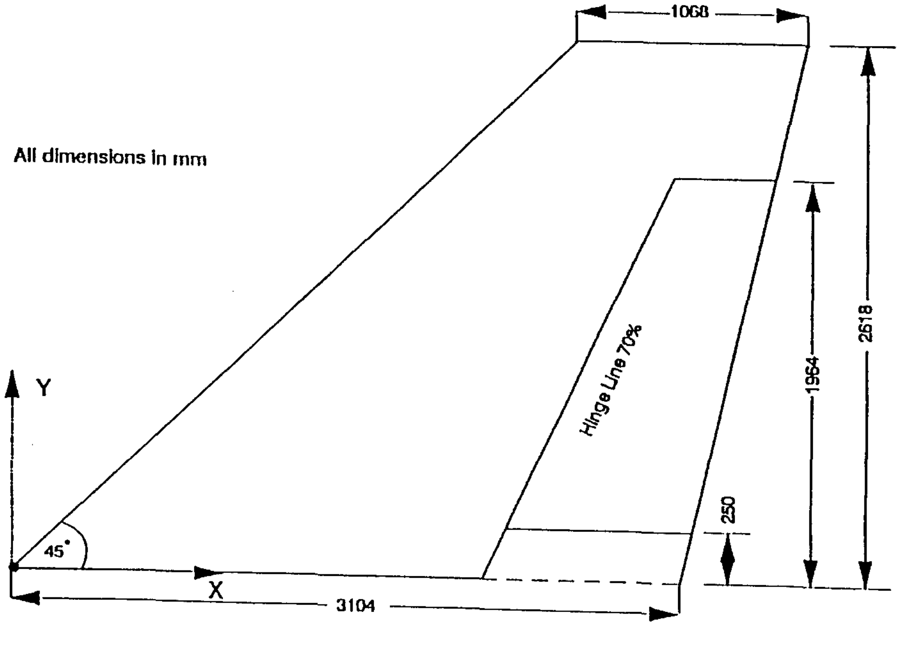

Fig. 2. Fin Geometry

	Initial Design ASTROS	Initial Design Dasa	With Single Springs	Optimum Design	
				ASTROS	Dasa
Weight [kg]					
Structure	99.4	99.4	99.4	95.1	92.9
Non Structure	53.6	53.6	53.6	53.6	53.6
Total	153.0	153.0	153.0	148.7	146.5
Deflections [mm]					
Load Case 1	304	291			
Load Case 2	384	367			
Load Case 3	148	154			
Load Case 4	220	231			
Load Case 5	146	159			
Frequences [Hz]					
f_1	9.1	8.9	9.0	9.0	9.2
f_2	30.5	29.8	30.0	29.1	30.2 (f+a)
f_3	32.5 (fore + aft)	31.2 (f+a)	43.9 (f+a)	42.7 (f+a)	30.6
f_4	41.4	40.0	41.6	41.1	41.08
f_5	55.7	54.9	57.6	60.0	58.31
Ma 1.2, S.L.					
Flutter Frequency – f_F [Hz]	20.2	21.2	20.0		
Speed - v_f [m/s]	493.4	495.0	534.0	530.0	530.0
Ma 1.8, 750 kts – Aeroelastics					
Fin	0.753		0.740	0.814	0.814
Rudder	0.441		0.423	0.500	0.500
Aeroelatic Deflections [mm]					
Fin 1°	65.34	53.7			
Rudder 1°	8.88	8.29			

Table 1: Comparison of DASA-Lagrange and ASTROS Results

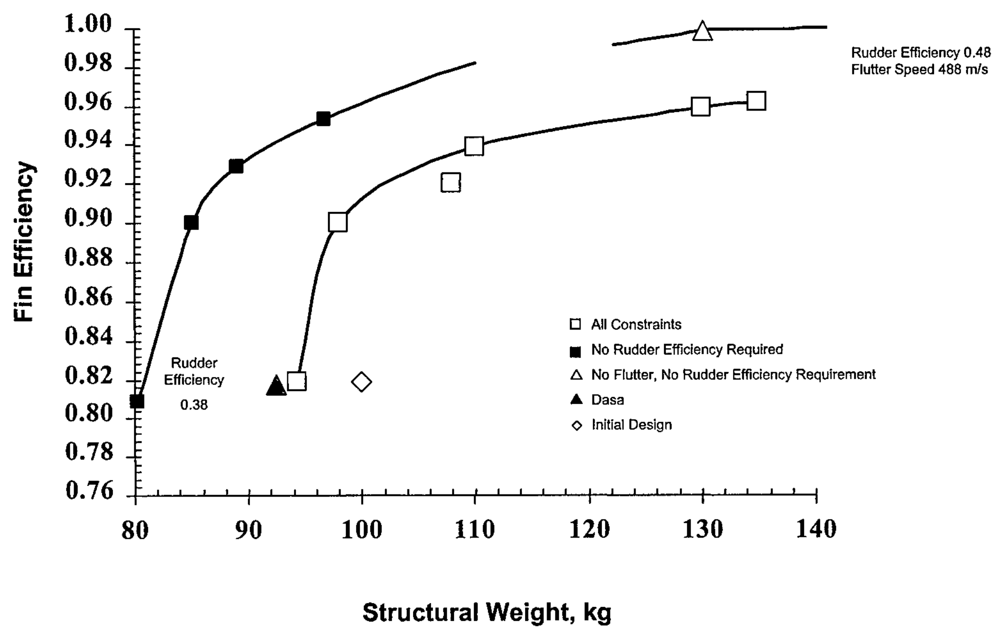

Fig. 3. Fin Efficiency vs. Structural Weight for Ma 1.8, 102 KPa

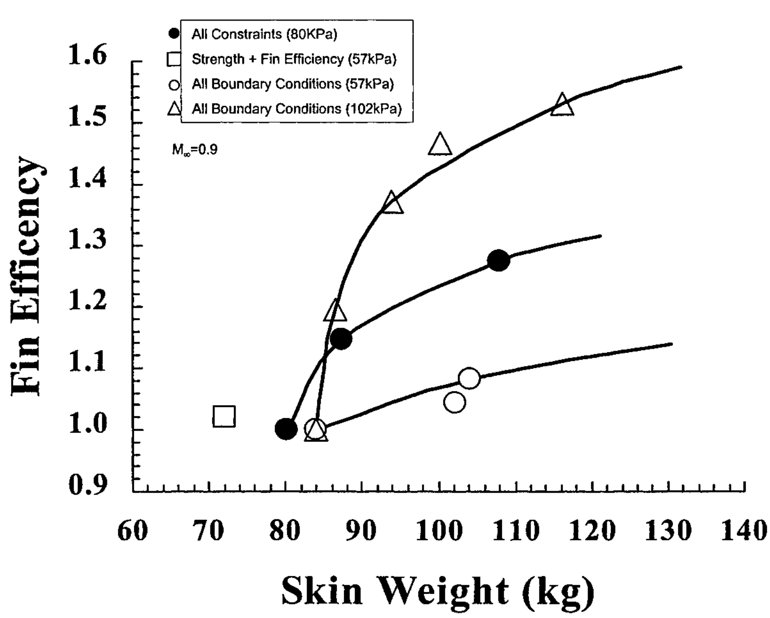

FIG. 4 Fin Efficiency vs. Structural Weight for Ma 0.9

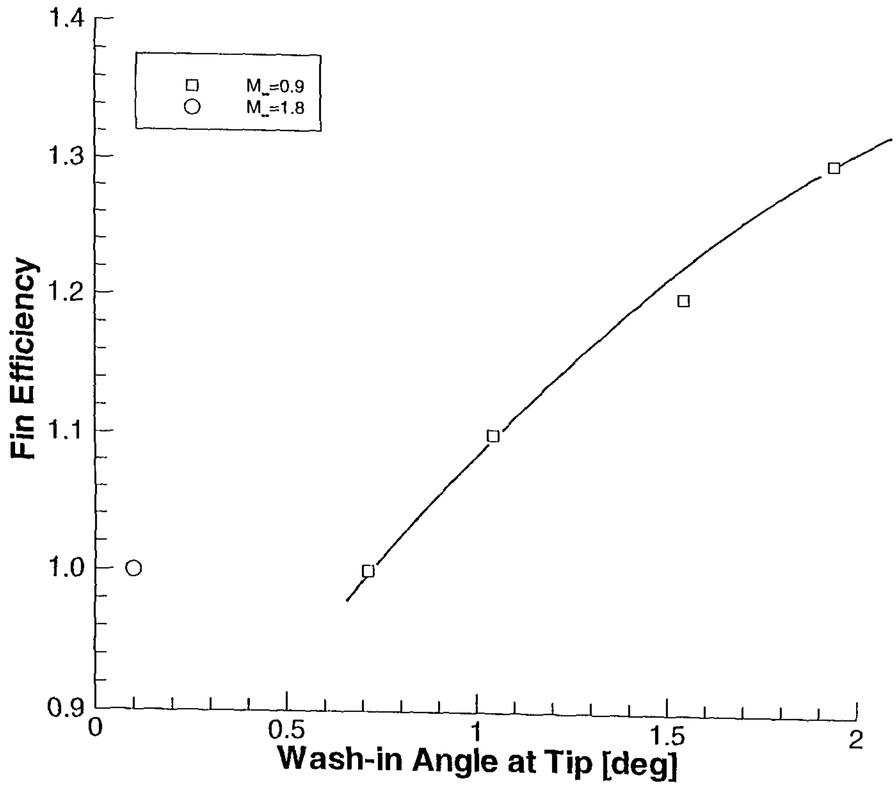

FIG. 5 Fin Efficiency vs. Wash-in angle at Tip

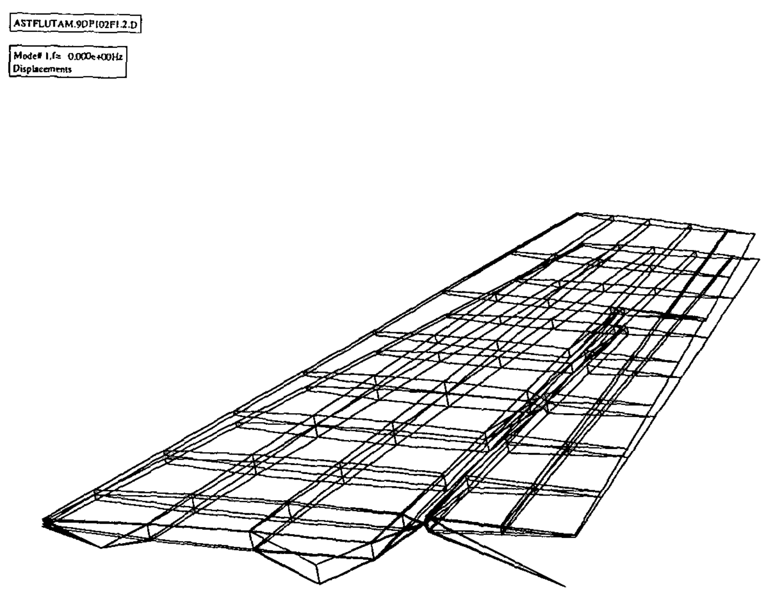

FIG. 6 Displacement in Aeroelastic Case Side Slip for Fin Efficiency 1.2, MA 0.9, 102 kPa

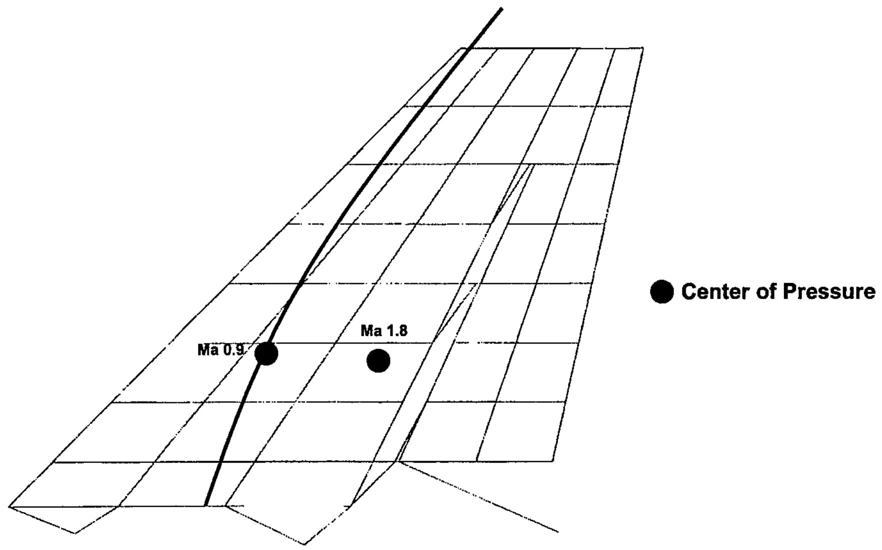

FIG. 7. Elastic Axis Location
(Original Attachments and DASA Skin Thicknesses)

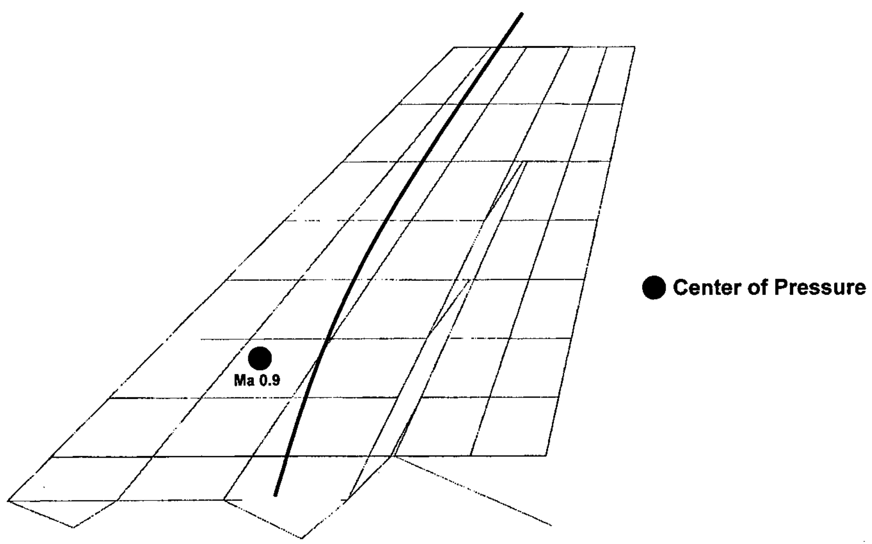

FIG. 8. Elastic Axis Location for Ma 0.9, 102 KPa, Fin Efficiency 1.3

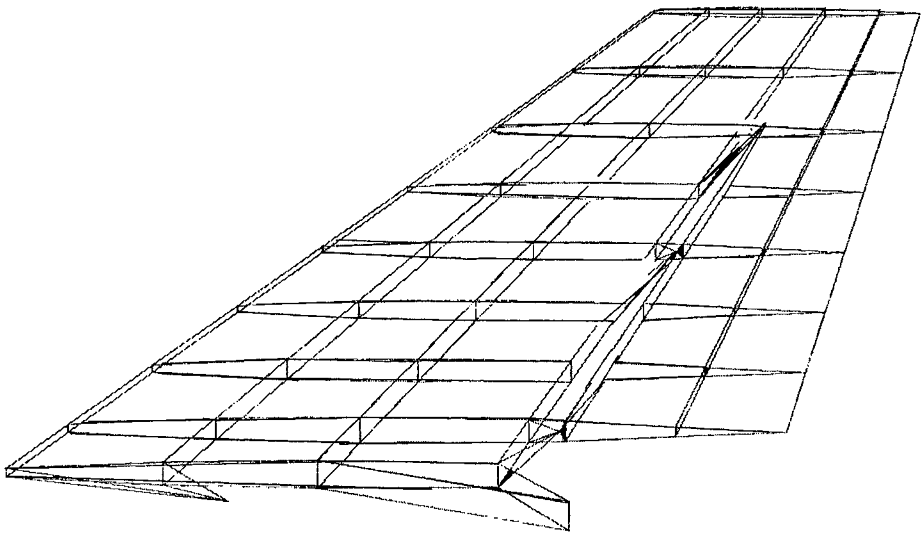

FIG. 9. Rear Attachment Location

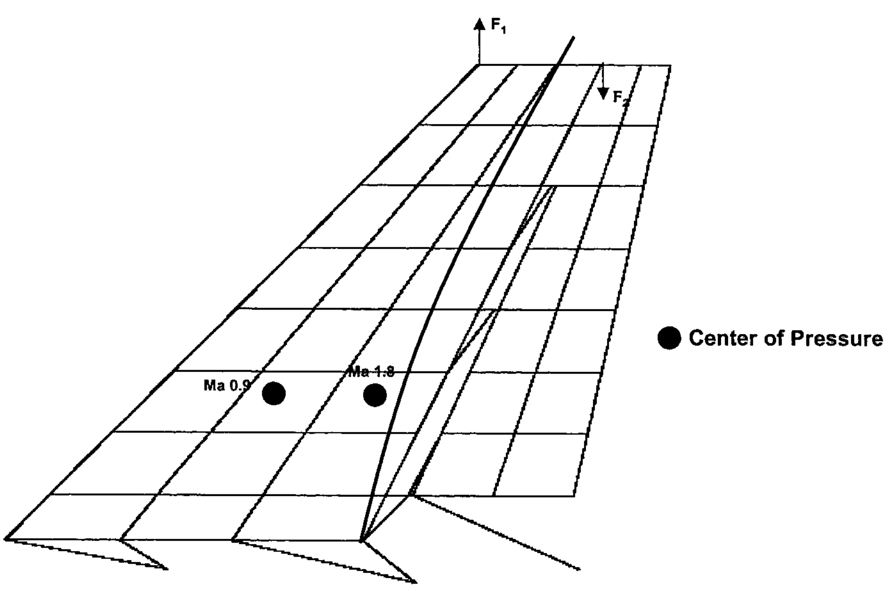

FIG. 10. Elastic Axis Location (Rear Attachments)

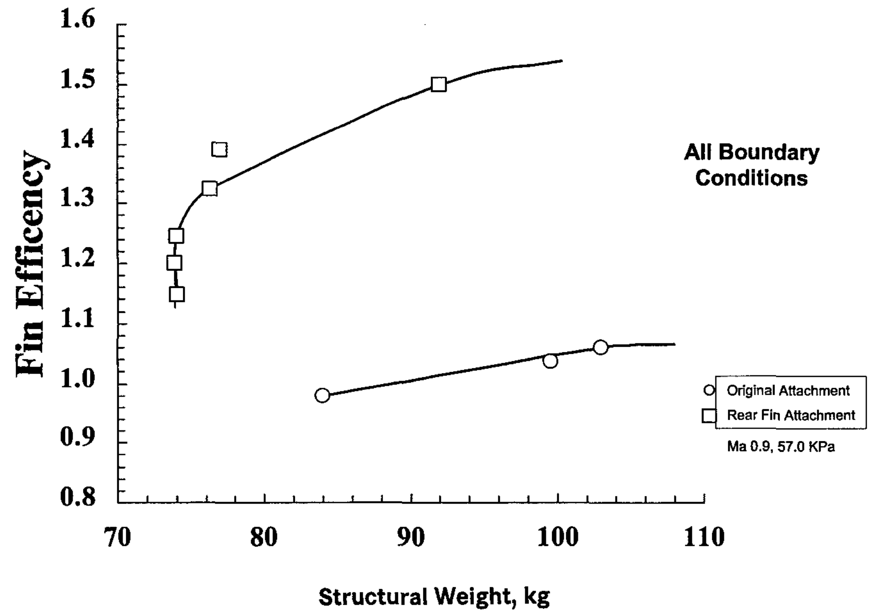

FIG. 11. Fin Efficiency vs Structural Weight for Ma 0.9, 57.0 KPa

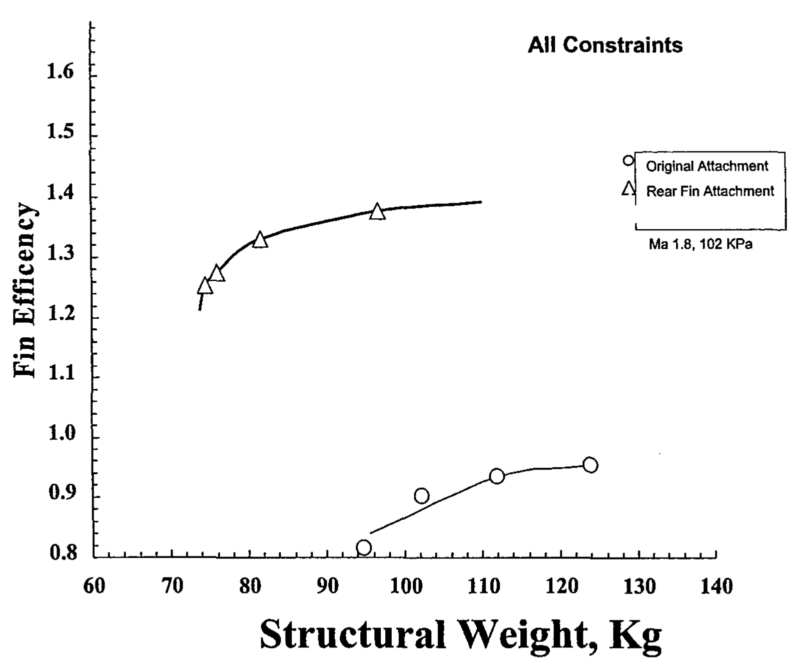

FIG. 12. Fin Efficiency vs. Structural Weight for Ma 1.8, 102 KPa

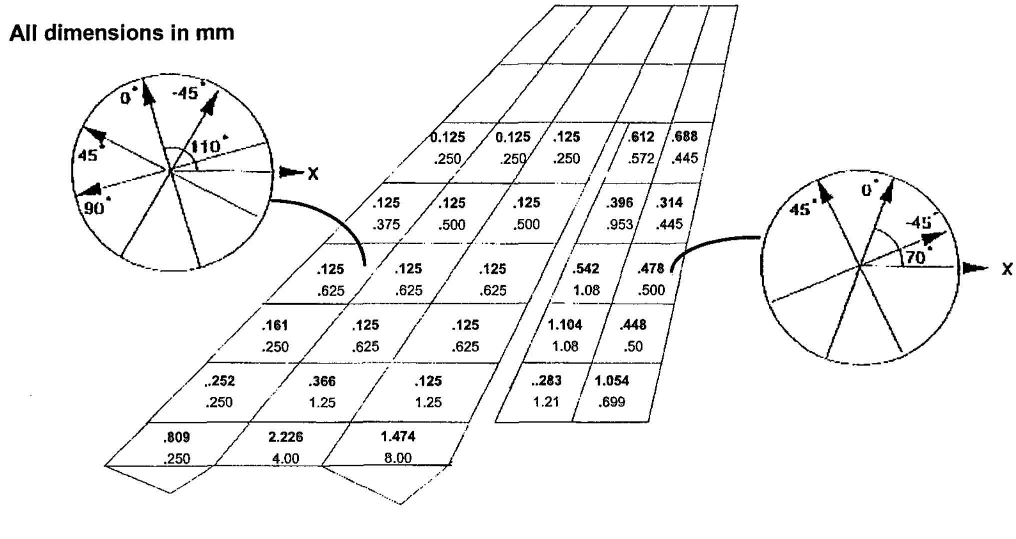

FIG. 13 Thickness of Layer 1 After Optimization (Ma 1.8, 102 Kpa, 1.3 Efficiency)

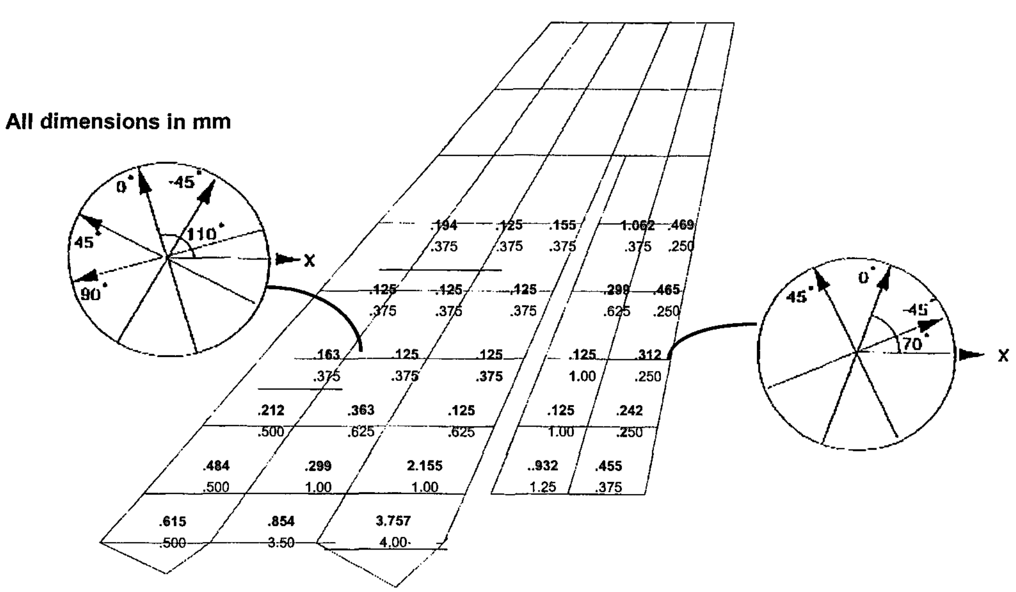

FIG. 14 Thickness of Layer 2 After Optimization (Ma 1.8, 102KPa, 1.3 Efficiency)

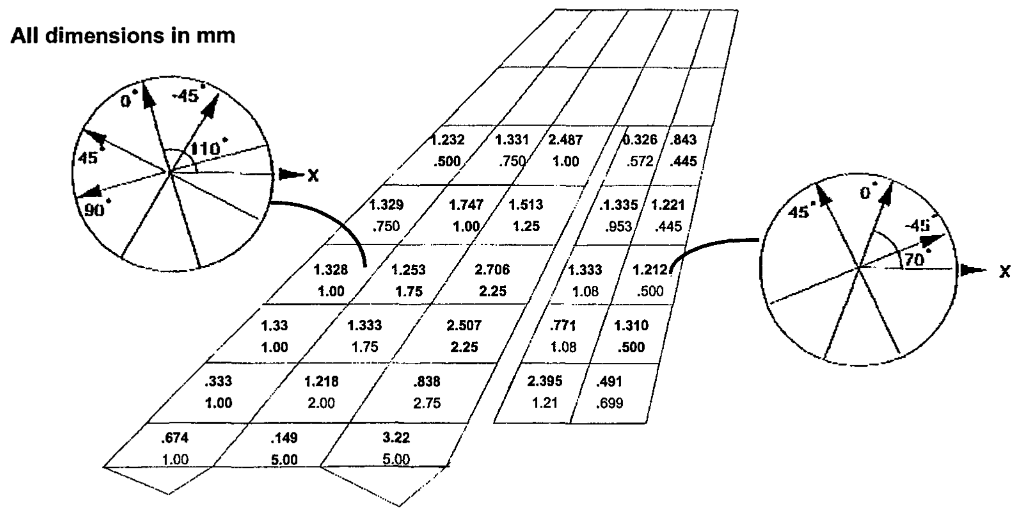

FIG 15. Thickness of Layer 3 After Optimization (Ma 1.8, 102KPa, 1.3 Efficiency)

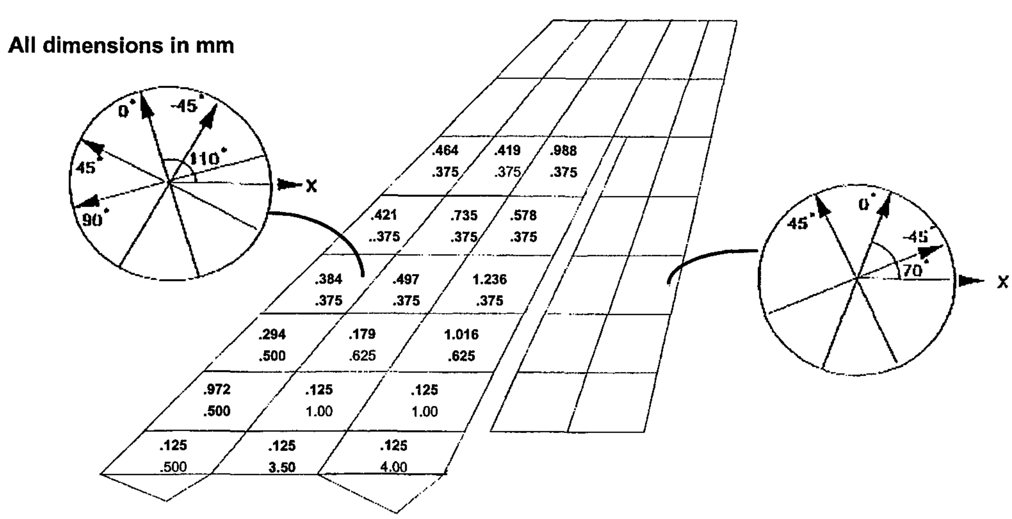

FIG. 16 Thickness of Layer 4 After Optimization (Ma 1.8, 102 Kpa, 1.3 Efficiency)