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AIRCRAFT OPERATIONS FROM RUNWAYS WITH INCLINED RAMPS (SKI-JUMP)

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FOREWORD

This report was prepared by Elijah W. Turner, Aerospace Engineer in the Loads and Criteria Group, Structural Integrity Branch, Structures Division at Wright-Patterson AFB, Ohio.

The work was accomplished under Project 24010701, which is managed by John T. Riechers, WL/FIBEB, Wright-Patterson AFB, Ohio.

This effort was begun in 1982 to investigate the use of inclined ramps (Ski-Jumps) to launch aircraft from short runways as a possible solution to the runway denial problem in Europe. In 1983, Ski-Jump was briefed to the Airbase Survivability Steering Group and "Phase 1 - Analytical Study" was authorized. Briefings were also presented to Headquarters Tactical Air Command and Headquarters United States Air Force to highlight this application. In 1984, mangement of this effort was transferred to the Fighter Attack Systems Program Office (ASD/TA) at Wright-Patterson AFB. In 1986 the work was terminated due to a lack of funding.

This report covers work done from January 1982 through July 1986. This manuscript was released by the author in May 1991 for publication as a WRDC Technical Memorandum.

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ABSTRACT

The use of inclined ramps to launch aircraft from short runways is proposed as a possible solution to the runway denial problem in Europe. Past efforts to launch aircraft in this manner, including a very successful program conducted by the US Navy to launch the T-2C, F-14, and F-18 aircraft, are reviewed.

An analytical study was conducted for the launch of the F-16, F-15, A-10, A-7D and F-4E from inclined ramps. The takeoff ground roll, stabilizer trim setting, landing gear loads and flight trajectory are reported. The F-15 was selected as a candidate aircraft for a USAF flight test program to be patterned after the Navy program and additional studies were performed. Perturbations in center of gravity, thrust, and ramp exit angle were investigated.

A ramp contour was designed for launch of the F-15, F-16, A-7D and A-10 which minimized the length and height of the ramp while maintaining the landing gear loads below 90 percent of their design limit.

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1. BACKGROUND

1.1 Runway Denial Problem

It has been recognized that the bombing of airbases in Europe could effectively close them to fighter operations for several days. Photographs of airbases that were bombed during the Pakastani war indicate that undamaged segments of the runway will not be large enough for conventional fighter aircraft to takeoff or land. Fighter aircraft require an undamaged strip 50 feet wide and from 2000 to 5000 feet long, depending on the aircraft. The probability that a 5000 foot strip will remain undamaged after an attack is near zero. However, the probability that a 1000 foot strip of undamaged pavement can be located somewhere on the airfield is near a certainty. Therefore, a method of launching aircraft with a ground roll under 1000 feet is a possible solution to the runway denial problem.

The operational concept is to have a moderate number of ramps distributed about the airbase at the ends of taxiways and runways. The number should be large enough so that there is a high probability that several will survive. A post attack damage survey would identify the usable ramps and paths for each aircraft to reach the closest usable ramp. A counter attack could be launched as soon as unexploded ordinance and other debris is cleared from the ramps and selected taxiways.

The ramps could also be used to evacuate an air base in a short period of time in the event of an impending attack. The ramps would provide additional launch sites, many of which would be located closer to the aircraft storage area than the operational runway. This would allow a large number of aircraft to be launched in a short period of time. It would also avoid the vulnerability to attack associated with queuing a large number of aircraft on one or two runways.

1.2 Ski-Jump Launch

The use of inclined ramps for launching aircraft has been recognized for some time. A NACA report in 1952 proposed the use of an inclined ramp on aircraft carrier decks to improve the takeoff performance of aircraft (Ref. 1). The ramp proposed in the 1952 report had a radius of curvature of 50 feet and a rise of 1.73 feet. Whereas fighter aircraft launched from a flat deck normally sink as much as 9 feet below the deck, analysis indicated that the addition of a ramp would eliminate the altitude loss.

In 1974 a British Commander wrote his masters thesis on launching the Harrier aircraft from inclined ramps (Ref. 2). This report started an effort that resulted in launch test of the

Harrier from enclined ramps in 1977.

About the same time, the US Navy was considering a smaller class of aircraft carriers that would not use steam catapults to launch aircraft. This program generated an analytical effort in 1979 followed by a flight test program to launch the T2C, F-14, and F-18 aircraft from inclined ramps. A metal ramp was constructed that could be modified to give ramp exit angles of 3, 6, and 9 degrees. The ramp was 112.1 feet long and 8.58 feet high at the exit when configured for the 9 degree exit angle, measured from the horizontal. A total of 112 launches of the T-2C, 28 of the F-14, and 91 of the F/A-18 were made. The minimum ground roll for the F/A-18 was 385 feet at a gross weight of 32,800 lbs. This ramp effectively reduced the takeoff roll of the F-18 by more than 50 percent.

1.3 Flight Dynamics Directorate Effort

Knowledge of the Navy success in ski-jump launch prompted the Flight Dynamics Directorate to propose the same method of launch for ground based aircraft as a possible solution to the runway denial problem in Europe. Studies were performed to estimate the ski-jump performance of a number of Air Force aircraft. An initial investigation was performed by the Aeromechanics Division in which the pitch of the aircraft was assumed to follow an estimated time history (Ref. 3). A more complete model of each aircraft was used in a study that was performed by the Structures Division. The objective of the Structures Division's study was to investigate the ski-jump performance of a number of Air Force aircraft and select one for further investigation which would lead to a flight test. This study included the design of a ramp contour that would allow each of the aircraft in the study to operate from the same ramp without exceeding limit landing-gear loads. This technical memorandum covers the work performed by the Structures Division of the Flight Dynamics Directorate (FDD).

2. ANALYTICAL INVESTIGATION

A study was performed to estimate the ski-jump launch performance of the F-15, F-16, A-10, A-7D and F-4E aircraft. The study made extensive use of two computer programs, one obtained from the Navy which was a three degree of freedom flight trajectory program, and the other developed in-house at the Flight Dynamics Directorate to determine landing gear loads.

2.1 Flight Trajectory Model

The Navy flight trajectory computer program, JUMP (Ref. 4), modeled the aircraft as a rigid body free to pitch about the center of gravity and translate in two orthogonal directions. The program incorporates non-linear aerodynamics in the form of tables of lift, moment, and drag for various angles of attack. Stabilizer lift and drag is similarly modeled. Thrust is a tabular function of aircraft velocity. A flight control system modeled after the F-14 was used for all of the aircraft. JUMP also has a "pilot" model with built-in reaction delays and limited application rates. The pilot model assumes control of the aircraft after the pitch attitude begins to decrease, and seeks to maintain the maximum angle of attack. This is equivalent to the pilot applying gentle back pressure on the control column so as to maintain a high angle of attack. The program incorporates an oleo-pneumatic landing gear where the air curve and tire deflection curve are tabular functions. Because the structure did not include flexible modes of vibration, the gear-loads capability of the Navy program was not used.

Aerodynamic and inertia modelling of the F-4C, F-4E, F-15, F-16, A-7D, and A-10 was performed under contract with the University of Dayton Research Institute (Ref. 5 - 9). The original JUMP computer program received from the Navy incorporated the F-14 flight control system. This control system model was considered satisfactory for the purpose of this study and was utilized for all of the aircraft.

The JUMP computer program was utilized to determine the length of the takeoff roll, the velocity during the takeoff roll, the velocity leaving the ramp and the flight trajectory. The length of the takeoff roll and the required trim setting were adjusted in a trial-and-error fashion until the trajectory leaving the ramp met the criteria for a successful ski-jump launch. The results from JUMP were input to the USAF landing gear loads computer program, TAXI.

2.2 Landing Gear Loads Model

The FDD computer program TAXI (Ref. 10) was utilized to determine landing gear loads for the aircraft traversing the ski-jump ramp at the velocity determined from the Navy flight trajectory computer program. TAXI modeled the aircraft with three rigid and 6 flexible degrees of freedom. The rigid degrees of freedom were the same as for the aerodynamic program JUMP. The landing gear was modeled with a oleo-pneumatic shock strut with sliding friction and bearing loads due to bending of the strut. The air curve was represented by a poly-tropic compression with a coefficient of 1.0. The tire load stroke curve was a tabular function. The aerodynamics during acceleration for launch was represented by a constant value of lift coefficient. For a given ramp profile, TAXI was used to determine both main and nose gear loads. For the design of optimum ramp profiles, TAXI was used in a trial and error fashion to develop a profile which would minimize the length of the ramp subject to gear loads not exceeding pre-determined values. A computer program was developed to generate ramp profiles for input to TAXI from a series of segments of circular arcs (Ref. 11).

2.3 Ski-Jump Launch Criteria

When the Navy first considered using inclined ramps, the objective was to reduce or eliminate the aircraft sinking below the carrier flight deck after launch. This same criteria could not be applied to testing of the T-2C, F-14 and F-18 because they were launched from a ramp that began at ground level. Sinking below the flight deck would be equivalent to sinking below ground level. The criteria that was finally selected by the Navy were that there should be no loss of altitude. The aircraft leaves the ramp with a vertical velocity imparted by the upward contour of the ramp. The speed, however, is below the minimum level flight speed, so the aircraft is not able to maintain its upward velocity. The vertical velocity decreases as the aircraft accelerates and at some point the degradation is stopped. This results in no loss of altitude, and puts the aircraft in level flight at an altitude of 30 to 50 feet. Thereafter the aircraft accelerates upward. The successful launch criteria that were selected was to allow the aircraft to leave the ramp at the lowest speed for which the vertical velocity would degrade to a value no lower than zero.

The minimum level flight speed depends on what is selected for the maximum allowable angle of attack. Following the precedent set by the Navy, the maximum pitch attitude was required to be equal to the angle of attack that would produce between 80 and 90 percent maximum lift coefficient. For a constant pitch attitude, the angle of attack will approach the pitch attitude from below and become equal when level flight is achieved. The lift characteristics of each aircraft were examined and selection of the maximum angle of attack was made. Table 1 presents the selection used in the analytical investigation.

Table I Angle of Attack

AIRCRAFT	α_{MAX} (deg)	$C_{L\,max}$ (%)
F-15	15	84
F-16	20	87
A-10	16	84
F-4E	24	90

The Navy test program revealed that there is considerable potential to develop undesirable oscillations immediately after launch if the pilot attempts to fly a prescribed trajectory. The pilot induced oscillations were minimized by setting the trim before launch to a value calculated to provide correct trim for flight at the minimum level flight speed. The aircraft leaves the ramp with a pitch velocity that is due to the curvature at the end of the ramp. The pilot holds the stick motionless as the aircraft pitches up, pulling back on the stick after the aircraft reaches its peak attitude. The pilot then applys aft stick to maintain the pitch attitude until the aircraft accelerates to level flight.

The Navy used a tail hook which was hydraulically released by the ground crew after the pilot stabilized the engine power in after-burner. Use of a tail hook was not considered practical by the Air Force. At a heavy gross weight, it is believed that the brakes will be sufficient to hold the aircraft without sliding the tires with the engines in military power. Engine RMP could be stabilized before selecting after-burner and brakes released as soon as the aircraft starts to slide. Additional consideration is needed for a procedure to be used at light gross weights, where the tires will slide with the engine in military power. The simulations in the analytical investigations were performed assuming that 100 percent thrust is applied at time zero.

3. RESULTS - MULTIPLE AIRCRAFT

3.1 Ground Roll for 9 Degree Ramp

This analysis was performed to determine the reduction in ground roll for each aircraft from ski-jump launch and to compare the improvements from one aircraft to another. For each aircraft, three gross weights were selected to cover the practical operational range of each. The lightest gross weight was for a clean aircraft with a moderate fuel load as might be used for evacuating an airbase. The heaviest gross weight was representative of a moderate fuel and bomb load suitable for an attack mission. An intermediate gross weight was also evaluated to better define the trends. The ramp profile was the Navy Ramp at Patuxent River Naval Air Station in the 9 degree configuration. It was 138 feet long and 10.3 feet high at the exit.

The Navy flight trajectory computer program was used in this analysis. The stabilizer trim setting and distance from the aircraft to the ramp exit were input. Plots of the resulting time history analysis were compared to the criteria for a successful ski-jump launch. The stabilizer trim and ground roll were adjusted to meet the criteria for a successful ski-jump launch. The aircraft would pitch to an attitude equal to an angle of attack that would produce between 80 and 90 percent maximum lift coefficient and then tend to decrease. The pilot model would seek to hold pitch attitude. The trajectory of the aircraft leaving the ramp would follow an arc that becomes tangent to the horizontal and thereafter curves upward.

It was determined that the F-4E aircraft can not be launched from a ski-jump using the same criteria as the other aircraft. The aircraft would continue to pitch nose-up past the maximum allowable angle of attack. A successful launch of the F-4E will require the pilot to apply forward stick immediately after leaving the ramp to arrest the pitch velocity, and then apply aft stick to hold pitch attitude. This requirement was taken to indicate that the F-4E would not be a safe aircraft to launch in this manner. No further analysis was performed for the F-4E.

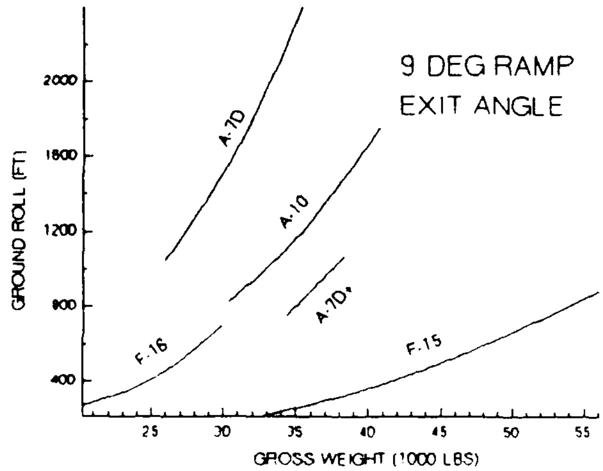

Figure 1 Ground Roll Versus Gross Weight on 9 Degree Ramp

Figure 1 shows the variation in ground roll with gross weight for each of the aircraft except the F-4E. Both the F-16 and F-15 can operate with a ground roll under 1000 feet over the entire gross weight range considered. The A-10 and A-7D with increased thrust require less than 1000 feet at light gross weight.

Figure 2 shows how much the ground roll can be reduced by the use of ski-jump as compared with conventional takeoff at the same gross weight. The curves are fairly flat indicating that the percent reduction is not a strong function of gross weight. The F-16 and F-15 benefitted the most from ski-jump launch. This is due to their higher power to weight ratio. The ground roll for these aircraft was reduced by about 60 percent as compared with a conventional takeoff. The A-10 ground roll was reduced by 40 percent.

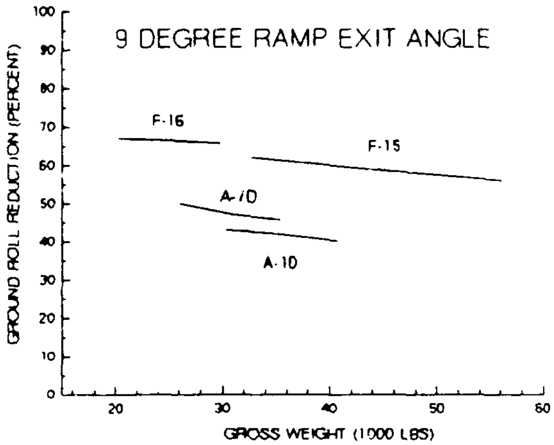

Figure 2 Ground Roll Reduction Versus Gross Weight

Figure 3 shows the velocity of each aircraft as it leaves the ramp. At light gross weight, the F-15 and F-16 could be under 70 knots. This very low speed suggests a need to carefully investigate the controllability of each aircraft, and the sensitivity to out-of-trim conditions. The heavier gross weights are launched at higher velocities and cause the aircraft to reach level flight speed at a higher altitude. Because of the lower altitude and lower speed, the light gross weights will be the most critical.

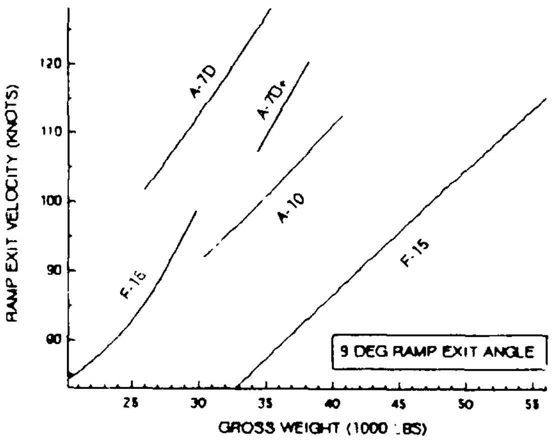

Figure 3 Ramp Exit Speed Versus Gross Weight

3.2 Landing Gear Loads on Modified Navy Ramp

It was determined that the landing gear loads for each of the Air Force aircraft operating from the Navy ramp in the 9 degree configuration would exceed design limit loads for all except the lightest gross weights. This is not surprising considering the difference in the landing gear design load factor between Navy and Air Force aircraft. The possibility of modifying the contour of the Navy ramp was investigated. Through a trial-and-error analysis, it was determined that landing gear loads could be significantly reduced by adding a 6 inch high by 25 feet long wedge in front of the Navy ramp, tilting the first 42 foot unitary section to a lesser angle, and raising the remaining 90 foot section. This new ramp profile, which is designated the Modified Navy Ramp, was investigated because it was physically possible to modify the Navy ramp at Patuxent River Naval Air Station to this new configuration and thus utilize existing government facilities.

Figure 4 shows the landing gear loads for each of the aircraft operating from the Modified Navy Ramp, or Ramp #28. The loads are presented in percent of design limit load. The large of the main or nosegear is shown in the figure as a function of gross weight. Three curves for each aircraft show the possible variation in loads that might result from the aircraft traversing the ramp at higher and lower speed, due to possible variations in thrust. In anticipation of a possible flight test program using the Modified Navy Ramp, figure 4 shows a test limit of 90 percent design limit load. This indicates a probable maximum gross weight that could be tested for each aircraft. The loads are significantly lower than for the unmodified Navy ramp, but not low enough to permit combat weight aircraft to be launched.

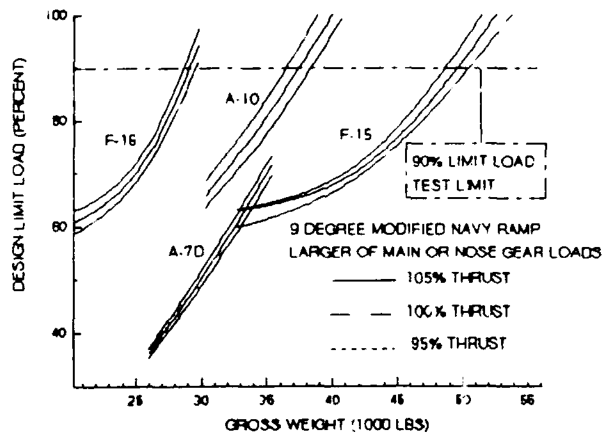

Figure 4 Landing Gear Loads On Modified Navy Ramp

3.3 Design of 9 Degree Optimum Ramp

The objective of this analysis was to determine a ramp contour that would permit the launch of all five Air Force aircraft at a combat gross weight without exceeding 90 percent design limit loads. Ramp length and height were minimized. The result was a ramp 178 feet long and 14.2 feet high at the exit. The ramp is steep at the beginning in order to raise the gear loads rapidly to near the 90 percent limit. The curvature is then decreased to prevent overshoot, followed by an increase to give the aircraft a high pitch rate at the exit. Figure 5 shows the gear loads from all five aircraft plotted against position on the ramp. Using this type of presentation, segments of the ramp were identified where the curvature could be increased (or decreased) in order to maintain the gear loads at a high level without exceeding the limit. The last iteration analyzed was Ramp #44, the results of which are presented in Figures 5 and 6. Figure 6 shows the envelope of the gear loads for all five aircraft. A more fully optimized ramp would show an envelope that follows closer to the 90 percent test limit. Ramp #44 was considered adequate for this investigation.

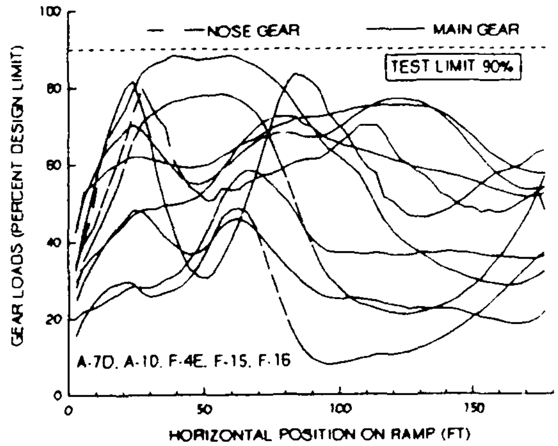

Figure 5 Landing Gear Loads On Optimum Ramp

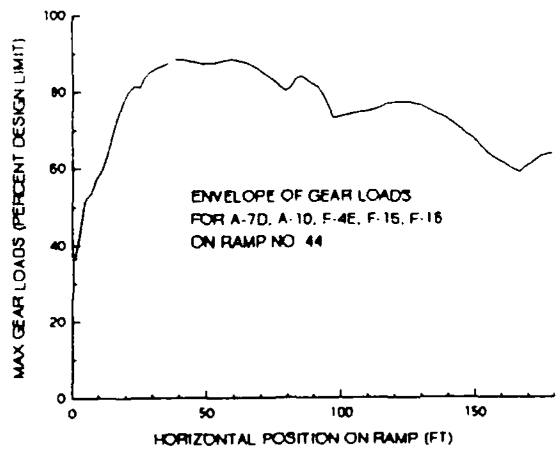

Figure 6 Envelope of Landing Gear Loads on Optimum Ramp

4. RESULTS - F-15 ANALYSIS

Based on the analysis of all five aircraft, the F-15 and F-16 appeared to be the best candidates for demonstrating ski-jump launch of an Air Force aircraft. Because the F-15 had a higher gross weight range, it was selected for consideration as the first Air Force aircraft for testing. It is probable that the F-16 could equally well have been selected.

4.1 Ramp Exit Angle

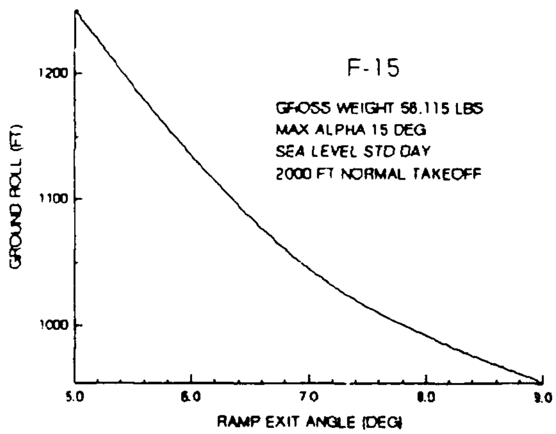

Figure 7 Ground Roll Versus Ramp Exit Angle for F-15

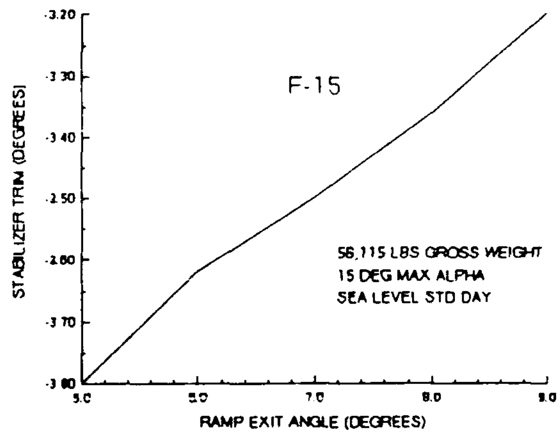

Figure 8 Stabilizer Trim Versus Ramp Exit Angle For F-15

The objective of this analysis was to provide results that could be used to select the exit angle for a ramp to be constructed for testing of the F-15 aircraft. Ramp exit angles less than 5 degrees did not appear to offer improvements significant enough to warrant testing. Exit angles greater than the maximum angle tested by the Navy would significantly increase the danger of the test, and were therefore not considered. Figure 7 shows the takeoff ground roll for the F-15 at a moderately heavy gross weight as a function of the ramp exit angle. The corresponding stabilizer trim settings are presented in Figure 8. The stabilizer trim setting is within a reasonable range, indicating that no control deficiencies are identified by this analysis. This is a necessary but not sufficient indicator for controllability.

4.2 Center of Gravity

Figure 9 indicates that the takeoff ground roll for ski-jump launch of the F-15 is not significantly affected by center of gravity location. Figure 10, however indicates that for forward center of gravity and light gross weights, the aircraft trim setting will be sensitive to gross weight. The effect of probable errors in the trim setting were not investigated.

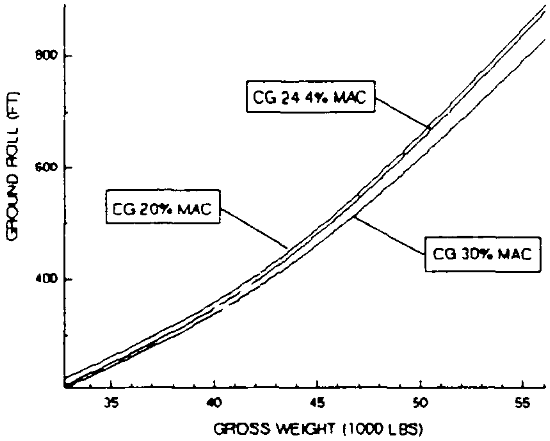

Figure 9 Ground Roll Versus Gross Weight and CG

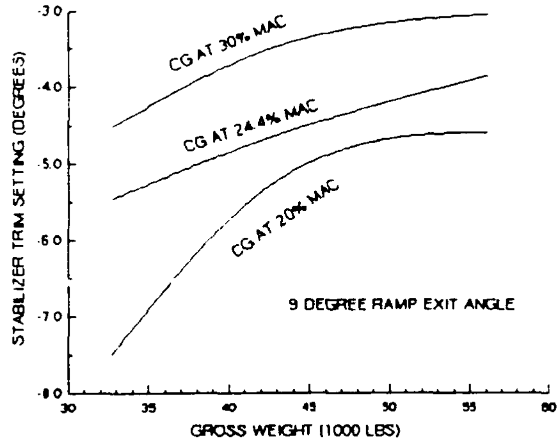

Figure 10 Stabilizer Trim Versus Gross Weight and CG

4.3 Speed Limits

This analysis was performed in anticipation of the first launch of the F-15 from a ski-jump. It provides guidance on selecting the takeoff ground roll that will provide the best margin of safety for the first launch. It is reasonable to initially launch the aircraft at a fairly high speed and then reduce the speed in subsequent test until the minimum speed is reached. Minimum speed means that the flight path becomes horizontal before arcing upward. Increasing the speed is accomplished by positioning the aircraft further from the ramp exit so that the ground roll is longer.

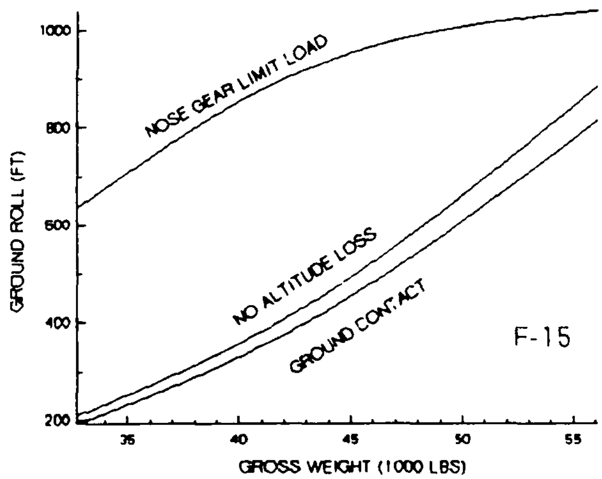

Figure 11 Ground Roll Limits Versus Gross Weight

Figure 11 shows the limits for the ground roll as a function of gross weight. The top curve is the high speed limit where the nose gear loads reach 100 percent of design limit load. The bottom curve is the lower limit where the aircraft dips below the exit height of the ramp and touches the ground. The curve labeled no altitude loss indicates that the flight trajectory becomes horizontal before arcing upwards--this is the minimum ski-jump speed.

4.4 Thrust Variation

Another parameter of considerable importance is that of thrust. The normal variation in thrust is from 97.5 to 100 percent maximum; aircraft producing less than 97.5 are scheduled for maintainence. Variations of plus and minus 5 percent were selected to provide a measure of conservatism and the flight trajectory was examined to see that the lower thrust did not result in the aircraft contacting the ground at its minimum altitude. Figure 12 shows the trajectories for the F-15 at the light gross weight and the combat gross weight.

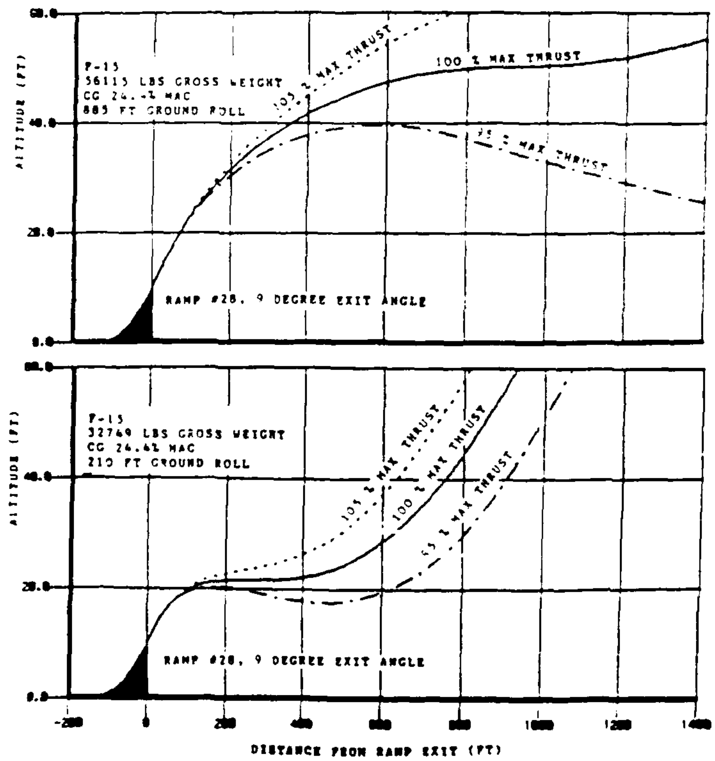

Figure 12 F-15 Flight Trajectories for Thrust Variation

5. CONCLUSIONS

1. The F-16 and F-15 are candidate aircraft for ski-jump launch of Air Force aircraft. Reductions in the ground roll of more than 50 percent can be expected.

2. The F-4E aircraft can not be launched using the same piloting technique as the F-15 and F-16 aircraft. Forward stick will be required to arrest the aircraft pitch at the optimum attitude, thus requiring considerable piloting skills. It is improbable that the F-4E aircraft can be safely launched from a ski-jump.

3. A ski-jump ramp with a 9 degree exit angle, contoured so that the F-16, F-15, and A-7D aircraft at combat gross weights can be launched without exceeding 90 percent of design limit landing-gear loads, will be approximately 180 feet long and 14.4 feet high at the exit.

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