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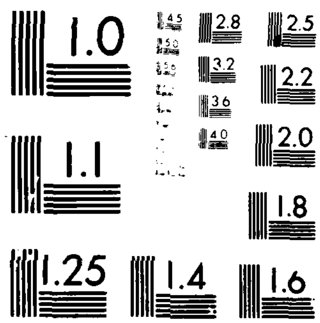

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Aircraft Dynamic Response to Damaged Runways

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AGARD Report No.685

(6) # AIRCRAFT DYNAMIC RESPONSE TO DAMAGED RUNWAYS.

Papers presented at the 49th Meeting of the Structures and Materials Panel, Porz-Wahn, Germany, October 1979.

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PREFACE

At its Spring 1979 meeting in Williamsburg, Virginia, USA, the AGARD Structures and Materials Panel (SMP) formed a group to study the potential problems of aircraft structural dynamic response to damaged and repaired runways. At its subsequent Fall 1979 meeting, the group received pilot papers from the Federal Republic of Germany, the United Kingdom and the United States.

Those three papers, which comprise this volume, arrived at the following general conclusions. For small aircraft with relatively simple landing gear, the operation over nominal repairs was dominated by rigid body motions of the aircraft. The prediction of those motions was possible and compared reasonably well with experimental data. For larger aircraft or aircraft with large external stores, the prediction of detailed loads in critical areas has met with limited success so far. Since landing gear equations are highly nonlinear, the prediction of aircraft dynamic response has required time-consuming numerical integrations. Also, the behaviour of large external stores can be affected by nonlinear effects (such as rigging loads), and both landing gear and external stores nonlinearities are affected by aircraft servicing procedures and by the ambient environment.

At the same Fall 1979 SMP meeting the group heard a presentation from the NATO Military Interservice Working Party for Airfield Repair. That presentation gave the following guidance. The SMP could assist in assuring that all of the necessary NATO aircraft are capable of operating safely from repaired runways, considering local repair procedures, in all of the host NATO nations. To implement that assistance local military commanders need simple, fast, approximate methods to determine if taxi, take off and landing operations are safe on damaged and repaired runways. Also, future NATO aircraft must be assessed with respect to their capability to operate in the presence of expected threats. To that end the military authorities and aircraft and landing gear designers need guidance for future developments.

As a result of the information and guidance, the SMP agreed to form a subcommittee to develop a future Specialists' Meeting on "Aircraft Dynamic Response to Damaged Runways." That future Specialists' Meeting will bring together experts in the fields of military operations, airfield construction and repair, landing gear design and operation, aircraft dynamic response analyses, and aircraft dynamic testing to explore several areas of concern:

(1) The requirements of the military commander in the field, the aircraft landing gear/structure designer, and the certifying authorities.

(2) The development of mathematical modeling techniques for aircraft tires, landing gear oleos, primary structure, and store attachments.

(3) The variability among NATO nations of existing runways, threats, damage, repair procedures, and expected post-repair profiles. The influence of repair time on expected roughness and safety of operations.

(4) Compression of cost and time expended in the validation of mathematical models by laboratory and flight test. New methods to simplify the mathematical solutions or to reduce the time, hazard, and cost of testing.

(5) The development of simple rules (e.g. Pilots' Handbooks) to assess the safety of runway operations.

(6) Recommendations for the ingredients of Military Specifications and Standards.

Nearly every NATO nation has expressed a strong interest in the subcommittee's work. It is the hope of the SMP that this volume will stimulate further participation and cooperation among technical managers and specialists.

JAMES J.OLSEN
Chairman, Subcommittee on Aircraft Dynamic
Response to Damaged and Repaired Runways

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SUMMARY

This paper reports on the technique used for analysis of the effects of Runway Surface Roughness on an F-4 aircraft. Computer simulations, and their results are discussed. These results are compared to test data measured from operation of an F-4 over simulated bomb damage repair. Techniques are presented for preparation of Surface Roughness Criteria that can be used in repairing an airfield after an attack.

I. INTRODUCTION

The rapid repair of bomb damaged runways, often called Bomb Damage Repair (BDR), has been a concern of tactical air commanders since the advent of the aircraft and its use in warfare. The extensive use of aerial warfare in World War II brought the subject into sharp focus. Since most recent warfare has had air superiority as a dominant factor, and destruction of our airfields was not anticipated, the subject of BDR became, for a time, dormant.

Recent events and situations demand renewed attention in the BDR area. Because of the improved performance of modern combat aircraft, forward tactical air bases throughout the world are now within easy reach of, and are therefore vulnerable to, attack by enemy aircraft. The hardening of aircraft shelters, and the consequent increased costs an aggressor must pay to destroy aircraft on the ground, has created a renewed interest in the alternative of directly attacking the airfield pavement system.

The rebirth of interest in attacking the runway, brought by the Israeli-Arab conflicts, leaves little doubt as to the consequences of not being able to rapidly recover the use of airfield pavements. Therefore, upgrading of the BDR capability is urgently required.

In order to rapidly repair bomb damaged runways it is necessary to determine how rough the aircraft launch and recovery surface can be without resulting in structural damage to the aircraft or causing it to lose its external stores (i.e., weapons, fuel tanks). The rougher the allowable aircraft operational surface, the less time it takes to repair the surface and the quicker the surface can be used by aircraft.

II. CURRENT REPAIR TECHNIQUES

An example of a typical repair is shown in Figure 1. The debris from the crater is pushed back into the crater, covered with select fill, and an AM-2 mat is positioned on top of the filled crater and secured to the original pavement at both the leading and trailing edges of the mat. A detailed drawing of an AM-2 mat is shown in Figure 2. The standard mat size, as provided in a crater repair kit, is 1½ inches high, 54 feet wide and 77 feet 6 inches long including a 3 foot 9 inch long ramp on the leading and trailing edges of the mat. This current US Air Force bomb damage repair technique is discussed in detail in Reference 2.

Referring to the simplified example of a repaired crater in Figure 1 the following parameters are defined:

(a) Upheaval: The height above the original pavement of the material that has been heaved up by the explosion around the edge of the crater. Upheaval could also be caused by over fill at the edge of the crater during repair operation. Upheaval does not include the 1½ inch thickness of the AM-2 mat.

(b) Sag: The depth that the top of the AM-2 mat sags beneath its maximum height. Sag will increase with aircraft traffic as the fill consolidates.

(c) Crater Length: The distance from the start of the upheaval on one side of the crater to the end of the upheaval on the far side of the crater, measured along the axis parallel to the direction of traffic.

(d) Mat Length: Total length of the repair mat, including the ramps.

(e) Percent Change in Gradient: Deviation of the repair slope from the original pavement grade. For example, since the AM-2 mat ramp rises 1½ inches above the original grade in 3.75 feet, the ramp represents a gradient change of: $(1.5) \div (3.75 \times 12) = .033$ or 3.3 percent.

III THE SURFACE ROUGHNESS PROBLEM

The effect of surface roughness upon the dynamic response of the aircraft is evaluated as a part of a larger R&D program to improve the current Rapid Runway Repair (RRR) capability. The technical approach for this evaluation (HAVE BOUNCE), is to develop and validate simulation models of selected mission aircraft and to use these computer models as tools for developing detailed surface roughness criteria for each mission aircraft.

This paper presents the approach and initial results from surface roughness testing to date for F-4 aircraft. Only general results are included.

IV COMPUTER MODELING

Computer simulation of aircraft response to rough runways has been a part of the industry since the 1960s. The mathematical models vary from simple single degree of freedom linear systems to very sophisticated highly nonlinear multi-degree of freedom models with aircraft structural flexibilities included. Generally speaking, the results of the nonlinear simulation models have been verified by and compare favorably to certain test data. However, the applications of this technology for tactical and logistic aircraft operating over rapidly repaired bomb damaged runways (HAVE BOUNCE) requires further investigation. The surface roughness may be severe with hundreds of spalls, multiple bomb damage repairs of varying sizes and spacing, upheaved pavement and sags caused by settling.

Computer simulation of aircraft response to operations on rough surfaces is a required tool in solving the damaged runway problem. The cost of instrumenting and testing each mission aircraft over the many combinations of aircraft and runway profile parameters would be prohibitive. In addition, aircraft testing can be hazardous, and should be limited to validation of computer programs and demonstration of aircraft capabilities, after these capabilities have been analytically determined. The validated computer simulations can then be used to economically and safely analyze many possible aircraft and profile combinations.

The surface roughness problem is of course a vibrations problem and aircraft response is a function of:

(a) Repair upheaval or sag amplitude

(b) Spacing between the repairs

(c) Aircraft velocity

(d) Natural frequencies of vibration of the aircraft

The aircraft frequencies are a function of nonlinear tire and strut parameters, aircraft gross weight, center of gravity, inertias, gear spacing, structural flexibility, lift, thrust and drag.

The formulation of and solution to the resulting nonlinear coupled differential equations of motion can be routinely handled with various types of solution techniques on a digital computer. Reference 1 contains a thorough discussion of the development of the equations of motion and one solution technique.

The output of a computer program of this type is normally a time history of a force or acceleration (see Figure 3) at some point of interest on the aircraft. Figure 3 also shows a comparison of computed versus measured data for an RF-4C light gross weight aircraft traversing a 16 foot AM-2 repair mat.

Computer programs, such as TAXI (Reference 1), although not fully verified for the BDR application, are very useful in providing guidance in the aircraft testing that is required for final computer model verification. Parametric studies can eliminate unnecessary testing and expose potentially hazardous test conditions.

One convenient method for evaluating a particular aircraft/runway configuration is to plot calculated peak loads for the entire velocity spectrum from near zero to takeoff speed. This will point out the velocities at which the aircraft's modes of vibration are in tune with the surface frequency. These may be velocities to be avoided during testing because of potential structural overload conditions. Figure 4 illustrates the method used by the AFFDL in plotting peak load versus velocity. The basic approach was to put a "DO LOOP" around the program "TAXI", and store and plot peak values for each aircraft velocity. Figure 5 is an example of a velocity plot showing the results for an F-4E aircraft at 57,500 pounds gross weight traversing two 78 foot AM-2 repair mats on a flat surface spaced 70 feet apart. The aircraft is responding in vertical translation, and the tuned impact of the second mat for the first, second, third and fourth cycles of motion is evident. Figure 6 illustrates that response. If the second mat encounter occurs just after a rebound on the strut and tire, the aircraft experiences a compounded loading effect. First you have the static load plus the dynamic load from the first mat and then the second ramp is encountered which has an equivalent "sink speed" effect. Traversing a 1.5" height in four feet (AM-2 Ramp) at 100 knots is equivalent to a five foot per second sink speed, however, at 100 knots the F-4 is in a nonrotated attitude and therefore very little lift is being generated. Coupling the dynamic loading condition with the no lift sink speed effect is the condition that could induce overloading in the aircraft structure. The same effect can happen on a single repair mat with settling in the center of the repair.

Examination of Figure 3 shows that the F-4 is very lightly damped at the main landing gear. In fact, most of the aircraft dynamic reponse is caused by tire deflection rather than strut deflection. The design of the F-4 dual chambered main landing gear strut is inherently very stiff during taxi. All but approximately 0.5 inches of stroke is used up, and therefore very little remains for shock absorption. During taxi, the aircraft rides on a small high pressure chamber in the lower portion of the strut as shown in Figure 7.

Knowing that the F-4 main landing gear is a very stiff, lightly damped system during taxi, several ideas were devised to "soften" the system.

Computer modeling was an excellent method for evaluating the merit of these ideas. One idea was to increase the pressure in the upper chamber of the main landing gear strut, raising the aircraft so that a significant amount of strut stroking could occur. The increased pressure resulted in "softening" the strut as can be seen on the load stroke curves shown in Figure 8. Simulation and subsequent testing of the idea has proven to be a very worthwhile approach in reducing loads in the F-4 aircraft structure as shown in Figure 9.

Similarly, it was found that by properly designing repair mats, the length and/or spacing can be adjusted to "de-tune" the system. Mathematical modeling of the aircraft/rough surface problem is essential for developing and evaluating ideas such as these as well as numerous other parametric studies.

For the F-4 HAVE BOUNCE effort, three independent computer programs were used to predict loads and accelerations during the tests at Edwards AFB, California. Results thus far have indicated that main and nose landing gear vertical forces, center of gravity, pilot station vertical acceleration and rigid body resonant conditions can be predicted with reasonable accuracies. However, we have been unsuccessful thus far in predicting loads or response frequencies at store locations. It is conceivable that at the end of the F-4 HAVE BOUNCE program, accurate pylon loads will not have been predicted. This would be important to learn because follow-on efforts could use less complex, and therefore more efficient mathematical models from the onset of each program.

V FLIGHT TESTS

The Air Force has had rapid runway repair programs for many years, but with the introduction of Warsaw Pact aircraft with improved range and payload, the problem became more serious, and the computer simulations of F-4 dynamic response to multiple runway repairs indicated high structural loads could be expected.

A variety of runway repair methods have been tested - tests on new methods are going on today. But the most successful repair method to date continues to be the AM-2 Mat shown in Figure 2. The expected problem was resonant response of the aircraft to multiple mat installations, but it was also necessary to recognize that repairs under the mat are liable to be less than smooth in any real world situation.

In structuring the test program at Edwards it was necessary to meet the following objectives:

(a) Develop test methods: Only limited testing of this type had been done in the past and the quantity and quality of data needed was far greater than in past programs. In addition, since testing of other types of aircraft is planned in the future it will be necessary to simplify and improve those test programs based upon the F-4 experience.

(b) Realistic Testing: Since TAC, PACAF, and USAFE are highly interested parties, and since they are less interested in hearing about computer simulations than they are in seeing real airplanes going across real runway repairs, it was necessary to perform tests in a manner that would demonstrate a realistic operational capability.

(c) Validate Simulations: Primarily the tests were responding to questions raised by computer simulations. It was necessary to collect enough data so that, at the end of the program, the rough runway simulation could be validated. Additional data would be required to make corrections and improvements to the simulations before final validation. Once simulations are validated, new repair techniques can be analyzed with little or no further testing. The validated simulation can also be used to expand and improve runway repair guidance for the using commands.

One important consideration in the testing was that each event is necessarily conducted without control of the loads. Consequently, test procedures had to deal with unexpected high loads, and the test conditions where loads are the highest are the ones of most interest. Control of the risk inherent to this situation depends upon having sufficient instrumentation to evaluate the accuracy of the analytical simulations as the test progresses from lower load conditions towards higher expected load conditions.

The basic test method developed was to respectfully assume that the simulation was erroneous and would only lead us into trouble. Consequently, the airplane was instrumented thoroughly for structural loads - gear, wing, pylon and tail loads. A detailed attempt was not made to decide what the exact point of failure might be but rather loads were measured corresponding to normal structural design limits. Among the important quantities measured were wing shear, gear compression and pylon hook tension. Other parameters were also measured for comparison to simulations and for instrumentation development.

Finally, that time-honored technique was used of doing a lot of testing in the areas thought to be safe and only occasionally sneaking up on test points thought to result in high loads.

The F-4 itself has some peculiar properties that impact its rough runway capability. As mentioned earlier, the strut has two chambers in series - one with a long stroke that only absorbs landing loads and one with a short stroke that primarily absorbs taxi loads. A heavy F-4 has about .5 inch of main gear suspension travel available for taxi operation. The gear is a straight-forward cantilever arrangement but is mounted to the wing. This results in wing shear and bending inputs from the gear loads.

The airplane has been tested over various simulated runway repairs. One example is Figure 5. This installation of two mats is spaced so as to excite a resonant response and represents one kind of worst case. Another kind of worst case is where the repair under the mat deviates significantly from the grade of the runway and testing is being reformed over repair mat installations that simulate this case.

One of the most significant results of testing to date is that the F-4 responds mostly as a rigid body. Originally it was expected that a lot of higher frequency response correlating to wing and pylon structural modes, would occur. While these modes are present, they are not nearly as significant as had been expected. The rigid body response of the F-4, characterized by bouncing up and down on the main gear struts, seems to be consistent at about a 2Hz frequency. It's this mode of response, when compared to the wave-length of the mats at a given aircraft speed, that appear to be of the most importance in determining loads.

Figure 10 shows how aircraft response changes as a resonant speed of 32 knots is approached and passed with the aircraft operating over a single mat. The significant response is the one that corresponds to the aircraft coming off the back side of the mat. Coming off the mat can cancel or reinforce the resonant response. Notice that for a 77 foot mat, reinforcement could occur after about 3/4 of a cycle or after 3/4 of a cycle plus any number of full cycles.

For a 54,000 pound F-4E, reinforcement on a single mat occurs at about 32, 55 and 135 knots. Of these, the 55 knot point is the one leading to the highest loads. Impact energy is high because of the relatively high speed but aerodynamic lift is not yet reducing main gear loads. Loads do continue to increase somewhat after the resonant peak because of increasing impact loads at the leading edge of the mat but reinforcement at the trailing edge does not occur.

The pylon hook load had been expected to be one of the limiting parameters for the F-4. However, as shown in Figure 11 the simulation was predicting loads a lot higher than those actually measured. As mentioned earlier, test results show that the F-4, even with heavy stores on the pylons, responds as a rigid body. No really significant loads are associated with the bending or torsion modes of the wings or any of the pylon's six degrees of freedom. This is another classic example of the requirement to test in order to verify analysis.

Earlier it was mentioned that the test F-4 was heavily instrumented. The instrumentation and calibration process took a year and a half and cost about a million dollars. It's certainly an objective to learn how to run this kind of a test cheaper, faster, and better. Current plans call for testing the F-16, F-111, A-10, F-15, C-130, C-141, C-5, DC-10 and Boeing 747 to verify that they can be operated from rapidly repaired runways. If each of these aircraft were to require the same lengthy, expensive and difficult program, advantage would not have been taken of all the opportunities the F-4 program has presented.

There are various ideas about what kind of instrumentation can and should be used in rough runway testing. Since one of the test objectives was to determine test methods for future use, it was decided to use a relatively elaborate instrumentation setup. From the beginning it was known that some of our instrumented parameters would be of little value but it was not sure which ones.

One approach that can be taken is to use the simulation to predict easily measured parameters, like acceleration at the center of gravity, as well as critical parameters like gear loads. If you can assume the simulation is equally successful in predicting both parameters, measuring c.g. acceleration could go a long way toward evaluating the simulation. Of course doing this violates the first rule of instrumentation - measure whatever it is that you want to know. Secondly - we have already discovered how our initial simulation was successful in predicting gear loads but unsuccessful in predicting pylon loads. So if this approach is used, it must be used with extreme caution.

Our counterparts in the UK have been conducting similar tests on their F-4 and on other aircraft. Instead of instrumenting their gear for loads, they measured the air pressure in the oleo strut chamber and multiplied it by the cross-section area. The initial concern was that this method would be inaccurate because of friction and would have poor dynamic response. However, as shown in Figure 12, the output from the pressure transducer closely matches the output from the strain gauges. Notice also how well c.g. acceleration matches gear load.

The power spectral density scan of the same three parameters, also confirm their similarity. Even at 10Hz, the frequency response is virtually identical. Probably in future tests of any aircraft with cantilever gear, like the F-15 or A-10, strain gauges will not be required on the gear. In future programs where the object is simply to qualify an aircraft for operations on rough runways, accelerometers could be extremely useful.

High speed photography was used to observe tire compression. Considerable tire compression occurs and as discussed earlier, the tire must be considered a significant part of the aircraft suspension. Tires are difficult to model with the required accuracy and present a real challenge to simulate.

About 75 percent of the testing was done using constant speed taxi runs. Stopping from repeated runs heats up the brakes and long taxi distances heat up the tires. To insure safety for people working around the aircraft, an optical pyrometer was used to measure temperatures from a safe distance. This technique proved to be very accurate, within 2^{o}-3^{o}F. Also a hand held thermocouple was used to track temperatures for data purposes and to help to decide when testing could be resumed. To increase the amount of testing that could be done without using up the aircraft brake energy capability, barrier engagements were frequently used to stop the airplane.

Some tests were conducted using takeoffs over mats installed on the main runway at Edwards. With takeoffs being made at well over maximum landing weight, it was necessary to reduce gross weight for landing. To speed up this process and save precious JP-4, external tanks were modified to carry water and to maintain the same weight, center of gravity and moment of inertia with water in the tanks. The tanks were fitted to dump the water overboard after takeoff. Of course, increased safety results from sitting over tanks of water rather than fuel.

Next summer, as real proof of the pudding, plans are to operate over actual runway repairs on an auxiliary field in South Carolina. The craters will be made using planted explosives and repairs will be installed by an operational Rapid Runway Repair team. The repair will be surveyed, simulations will be run of the response to the repair and then the F-4 will be operated over the repaired runway.

VI GROUND LOADS AIRCRAFT TEST FACILITY

An additional approach to flight testing and mathematical model verification is with the use of large computer-controlled hydraulic shakers (see Figure 13). A shaker capable of large forces and amplitudes placed under each landing gear of an aircraft could be used to simulate any rough surface. Although not yet developed or validated, laboratory testing of this type appears to have great potential for a better controlled, safer and less expensive method for verifying mathematical models. Of prime importance, it allows for the testing of severe aircraft loading conditions that could not be tested in a piloted aircraft.

A facility of this type would have been very useful in the F-4 HAVE BOUNCE effort. Accurate wing and pylon modal information could have been generated to get a true gear-down description of the wing/pylon interface problem. The response from spalls and assymetrical loading could also have been more easily determined.

At the present time, the construction of such a facility is in the study and conceptual stages.

VII SURFACE ROUGHNESS CRITERIA

At the time this report is being written aircraft simulations are inadequate to provide a thorough analytical solution to determining loads resulting from surface roughness. In order to provide interim surface roughness guidance, simulations and test data have been used to establish boundaries of safe operation. It is anticipated that further study will increase the known area of safe operation. Establishment of these boundaries has shown that (for an F-4) the most critical part of the Minimum Operation Strip (MOS) is the first part of the MOS, from start of ground roll to rotation. The F-4 is most sensitive to surface roughness in this first portion of the MOS.

The objective of this interim surface roughness criteria is to minimize the time required to repair a MOS and maximize flexibility in selection of the MOS. The price that must be paid for these benefits is increased complexity of the crater repair. This report has defined five levels of repair <u>quality</u>, that together with a repair <u>spacing</u> criteria is used to select and repair the MOS. This complexity of five levels of repair quality and analysis of repair spacing can be reduced, but only by elimination of the option of using the lower quality repairs. This will result in longer repair times since the lower quality repairs can be made more rapidly than the higher quality repairs.

Assumptions: In the process of preparing this interim guidance it was necessary to limit the scope and complexity of analysis by making several assumptions. These assumptions are

(a) Emergency Use Only. This criteria will only be used under conditions of war.

(b) F-4E Aircraft. Simulations and analysis are primarily based upon structural, performance and test data for the F-4E aircraft. A limited amount of F-4K data is also discussed. The result is that this criteria must be revised for application to F-4C and F-4D aircraft.

(c) TAKE OFF Gross Weight. A take off gross weight of 57,000 pounds has been utilized for preparation of surface roughness criteria. Use of this criteria for lower lower gross weight will yield conservative results.

(d) Landing Gross Weight. The criteria assumes that the landing aircraft is approximately 38,000 pounds, which permits a small fuel reserve. Landing the aircraft at gross weights several thousand pounds higher on a runway that meets the minimum roughness criteria may result in exceeding design limit loads.

(e) Critical Component. Development of this criteria is based upon a limit established by a static main gear tire bottoming load. Limited laboratory testing has indicated that under some conditions a new tire will not experience catastrophic failure for loads in excess of twice this limit.

(f) Aborts. Since this criteria is intended for use under conditions of war no provision has been made in this criteria for TAKE OFF aborts. A TAKE OFF abort over a runway repaired to the minimum requirements of this criteria <u>WILL</u> result in exceeding design limit loads. Repairs in excess of the minimum standards are necessary to protect an aborting aircraft from damage. No standards for aborting aircraft have been developed at this time.

(g) Repairs. This criteria assumes that all repairs are made with AM-2 mat. Further discussion of this assumption is included under the section that discusses in detail the repair categories.

(h) TAKE OFF Power. This criteria uses nominal aircraft performance data and assumes max power for TAKE OFF.

(i) Safety Factors. The criteria in this report has been developed for "nominal" F-4E aircraft performance. The user can incorporate safety factors to compensate for performance by incorporating the desired safety factor into his selection of atmosphere density ratio. At a density ratio of 1.0 a 10 percent change in density ratio is approximately equal to a 10 percent change in F-4E aircraft thrust to weigh ratio.

Mat Spacing Criteria: Since testing is not yet completed and mathematical models have not yet been validated exact analytical solutions to predict the effect of mat spacing are not available. Therefore analysis and test data have been used to bound areas outside which mat spacing is not critical. Four boundaries have been established. Damping effects have been used to insure that impact with each mat is essentially a separate encounter, reinforcement effects have been used to bound hazardous speeds for multiple mat encounters, cancellation effects have been used to establish a cancellation corridor where loads are decreased by cancellation, and aerodynamic effects have been used to bound the region where aerodynamic lift reduces loads. Only general trends are presented in this report.

(a) Effect of Damping. When the F-4E aircraft encounters a mat, the aircraft primarily bounces in the "heave mode," (rather than pitch mode). The oscillation or bouncing causes main gear loads on the aircraft to increase or decrease. The increase or decrease depends on whether the A/C is bouncing up or down at that instant and on external forces from the runway surface. A forced upward motion of the A/C causes an increase in acceleration and therefore an increase in loads on the MLG. The bouncing oscillation, after the mat encounter has a small amount of a damping each cycle until after a length of time it is below background levels. An example showing typical damping is shown in Figure 10.

A dangerous situation develops when a second mat is encountered before the effects of the first mat are damped out. This situation can cause a reinforcing interaction, where the effect of two bounces are added together. A reinforcing reaction greatly increases the loads on the A/C, and also could cause the loads after the second mat to be significant for a longer time.

In an effort to avoid the possibility of a reinforcing reaction between bouncing caused by two successive mat encounters, guidelines have been developed to insure that the effect of a first mat is damped out before a second mat is encountered. Then the second repair can be encountered and analyzed as if it were a single mat, and each repair can have "worst case" specifications.

Studies of data from tests already completed indicate the number of cycles that the F-4E requires before the bouncing effect becomes equal to background dynamic load levels. A curve of distance from start of ground roll versus distance that will be traveled before the load damps out has been prepared. This curve can be used to determine how far apart (from trailing edge of the first mat to leading edge of the second mat) two repairs must be to insure that each mat appears to be a separate encounter, (Figure 14). This curve therefore is one bound on mat spacing. It requires that max power be applied and either the actual density ratio must be used or a worst case density ratio (that requires maximum spacing), be used.

(b) Effect of Rotation. At the time the A/C rotates, it begins to significantly reduce MLG loads. As the nose is lifted to 12 degrees, the A/C has generated significant lift and this will decrease the loads on the MLG as the plane approaches lift off. The effect of rotation on the MLG load for a 54,000 F-4E is shown in Figure 15. As a result of the decrease in loads due to rotation, the problems of a second mat encounter are alleviated. At points on the runway past nose wheel lift off distance, the spacing of mats according to the damping time is no longer a consideration due to the large load reduction by aerodynamic lift.

After rotation the mats may be as close together as required and still will not cause a significant problem due to reinforcing reactions.

Figure 16 shows the same curve as Figure 14, with the additional boundary of rotation considered. As discussed earlier, once beyond rotation, mat spacing is not critical, and nose wheel lift off distance or rotation is the controlling factor. Rotation is indicated on the Mat Spacing Chart, Figure 16 by the diagonal line running from equal values on both axis. The curve encountered first is the controlling condition.

(c) Effect of Reinforcement and Cancellation on Trailing Edge of Mat. Reinforcement or cancellation can occur as a result of the dynamic response to the trailing edge of a single mat, and is shown in the test data in Figure 10. This phenomena occurs at certain speeds and therefore can be associated with a certain distance down the runway for a specific aircraft performance. The velocities and the related distances from start of TAKE OFF where reinforcement and cancellation on the mat trailing edge will occur can be used to establish boundaries on estimated loads.

The areas where substantial trailing edge reinforcement occurs are designated as the high load zones, and are defined as any area where the load is greater than 3 times the load incurred at the leading edge of the mat. Assuming small aircraft damping, these high load zones occur in the time zone bounded by 60^{o} either side of 180^{o} (the negative load peak).

Figure 17 shows in a simplified graphical example where high load zones occur. If an aircraft covers the 77 foot length of a mat in between 1/3 and 2/3 the period of the oscillation, loads will be reinforced by the effect of leaving the mat surface. This phenomena also occurs in the other shaded areas. As shown in the figure, a simplified undamped model is used to estimate these areas of high load and 1/2 cycle is assumed from the leading edge of the mat to the first negative peak. This assumption is substantiated in Reference 4.

It should be apparent that multiple mat encounters could be more severe if the second mat is in a high load zone and very high loads can occur if reinforcement occurs on the second mat as well as the trailing edge of the first. Figure 18 shows the approximate mat spacing at which maximum reinforcement would occur on a second mat when reinforcement has occurred on the trailing edge of the first mat. Only the reinforcement for the first three modes have been shown since aircraft parameter differences will increase the variations of location of each mode as the number of cycles increase.

Since half cycle, (first mode), reinforcement occurs on the trailing edge of all 77 foot mats at higher velocities it would be desirable to insure that half cycle, (first mode), reinforcement does not also occur on the second mat. This limit can be achieved by permitting only mat spacing greater than approximately 100 feet. and will permit the small amount of damping to reduce loads by about 15-20 percent. This 100 foot criteria throughout the MOS will prevent most of the reinforcement modes shown in Figure 19, including the potentially very high load (1.1) mode.

Cancellation also can occur as a result of the dynamic response to the trailing edge of a single mat. Cancellation occurs and partially or totally can reduce the bouncing effect after a mat encounter. At certain velocities another mat could be encountered immediately, without any requirement for spacing. This is possible because the effect of encountering the first mat is negated by the effect of leaving the trailing edge of the same mat. The area where this occurs is called a low, load zone, which is defined as an area where the peak loads after leaving the mat are equal to or lower than those occurring due to the leading edge. Again the conservative no damping example is used to estimate where low loads occur. An example of test data showing this cancellation effect is in Figure 10 at 70 knots.

The single mat cancellation effect occurs 60^{o} either side of each full period. These areas where single mat cancellations occur are shown in Figure 19 and the section of the runway which is within this cancellation area for each specific density ratio can be calculated for each cycle of cancellation. In a fairly wide section of the MOS, a corridor exists where the loads induced by going onto a mat tend to be cancelled out by the load leaving the mat. This cancellation corridor is combined with the previous curves as shown in Figure 20, to complete the mat spacing curve. Areas outside the shaded zone represent safe mat spacings.

Repair Tolerances: Examination of Figure 18 shows that if a sag occurred within the first 60^{o} of the first half cycle, cancellation would occur. This conclusion can be extended to conclude that short section of upheaval (fill) followed by short section of sag will tend to cancel each other and will not reinforce if the upheaval and sag are small, randomly spaced, and have a short wave length relative to the aircraft heave frequency. Consequently, it is anticipated that random excursions of the repair profile are acceptable if:

(a) They are no more than $\pm$ 1/2 inch from the specified maximum upheaval or sag

(b) They have an approximate average equal to the specified nominal value

(c) A single excursion length is greater than five feet.

Taxiway Repairs: The damping effect can also be used to determine criteria for taxiway repairs and speeds. By calculating the speed at which the leading edge effcts are damped before the trailing edge we can prevent reinforcement, not only over multiple mats but also between going on and off a single standard mat. This speed prevents reinforcement on the leading and trailing edge and thus it is safe to permit taxiways to be repaired with very rough repairs. Since the same criteria can be applied to loads induced leaving the mat a minimum mat spacing of 70 feet between repair mats is also required otherwise both repairs must be covered with a single long mat, or a correspondingly slower taxi speed must be used.

Repair Categories: A summary of repair categories is in Table 1 and a detailed discussion of each category follows.

(a) Category "A" Repairs. A category "A" repair requires essentially no upheaval and no sag, and as discussed earlier should be made to insure that repair tolerances are met. Single "A" repairs result in small loads but loads near the tire static bottoming limit will occur at 60 knots for two mats spaced at 70 feet as shown in Figure 5. Simulations also indicate that these loads will occur at speeds as low as 32 knots. Similar loads will occur at other velocities as the mat spacing is changed. These loads are combinations of reinforcement on the trailing edge on the first mat and reinforcement on the leading edge of the second mat. Increasing the mat spacing will result in increasing the speed at which the peak occurs, but the loads may be lower if reinforcement does not exactly occur for both the trailing edge of the first mat and the leading edge of the second mat. Consequently, it appears that multiple category "A" repairs are acceptable for mat spacings somewhat in excess of 70 feet, and speeds in excess of 60 knots. As discussed earlier, repairs less than 100 feet apart, should be covered with a single long mat. The speed requirement of 60 knots can be met by not having more than one mat encounter before the aircraft reaches 60 knots, or after about 400 feet from start of take off roll.

(b) Category "B" Repairs. "B" repairs permit up to 1½ inches of upheaval under the repair mat, but prohibit sag. Although test data is not yet available simulations predict that limit loads will not be exceeded by traffic over a single "B" repair at any speed. Engineering estimates predict that design limit loads would be exceeded by "B" repairs at many different mat spacings. A "B" repair represents the "worst case" single mat repair and "B" repairs must meet the mat spacing criteria in order to insure that design limit loads are not exceeded. Two "B" repairs less than 100 feet apart must be repaired with a single mat.

(c) Category "C" Repairs. These repairs specify a maximum of 1½ inches of upheaval and also 1½ inches of sag. Simulations predict extreme loads at lower speeds over "C" repairs. These loads are due to reinforcement as the aircraft is forced up by the upheaval, and then falls down into the sag where it again is thrown up by the upheaval on the far side of the crater. At higher speeds the loads decrease since the aircraft tends to be thrown over the sag by the AM-2 mat ramp and upheaval and since the sag following the upheaval can have a tendency to cancel the load oscillation caused by the upheaval, thus aiding in preventing reinforcement at the trailing edge of the mat. From performance calculations the start point for "C" repairs can be determined such that the aircraft will "bounce" over the sag. It is essential that AM-2 standard 77 foot mat (or shorter) be used for these repairs since the AM-2 ramp helps bounce the aircraft over the crater, and the crater must be less than or equal to 70 feet. If necessary similar calculations can be performed to permit category "C" repairs closer to the start of take off roll using shorter mats for shorter craters or with the leading edge of the crater at the front of the mat. Repairs closer than 100 feet cannot be "C" category but must be "B" category covered with a single mat.

(d) Category "D" Repairs. After rotation, category "D" repairs can be used. These repairs have the same upheaval and sag specifications as category "C", but no controls over mat length or spacing except that repairs less than 100 feet apart should be repaired with a single long mat. The relaxation of the repair spacing criteria is based upon the fact that simulations and test data show load reduction starting to occur (on the order of a factor of two) as the aerodynamic lift becomes effective. The operational commander can reduce the repair time by reducing the rotation distance as discussed earlier.

(e) Category "E" Repairs. These repairs allow three inches of upheaval and three inches of sag with no controls over mat spacing except that repairs less than 100 feet apart must be covered with a single long mat. Simulations (confirmed by test data) predict that at a 12^{o} angle of attack (full rotation), aerodynamic lift is the dominant effect on a rotated aircraft and that gear loads will not exceed limits over category "E" repairs. Since an estimated 500 feet (approximately 2.5 sec) is required to complete rotation, category "E" repairs should not be encountered for at least 500 feet after the nominal rotation distance is reached. Design limits may be exceeded for some repair spacings during the landing roll of the light weight aircraft, therefore a barrier landing must be performed that will prevent the landing aircraft from rolling out over the "E" repair. "E" repairs may be used for access and taxiways for both the light weight and heavy aircraft at speeds less than 10 knots.

General Criteria: Figure 21 shows the general criteria for repair of an MOS. The first section must be repaired with a "B" repair or better. If an "A" repair is used mat spacing is not critical, but use of the "B" repair, which is rougher, requires that repairs meet the mat spacing criteria. If the spacing criteria cannot be met then category "A" repairs are required. The second zone can be repaired with a "C" repair which is even rougher; however, again the spacing criteria must be met or an "A" repair is required. After rotation for 500 feet only a "D" repair is required which is the same upheaval and sag as a "C" repair but does not have any spacing criteria. The last part of the MOS can be repaired with a category "E" repair which allows three inches of upheaval and three inches of sag, and does not have any spacing criteria. If an "E" repair is used, landing aircraft must engage a barrier to prevent them from rolling out over the "E" repair.

Since the section of runway from start of ground roll to rotation is the most critical the operational commander has some control over the critical MOS length and consequently repair time. In Figure 22 a plot of F-4E nose gear lift off distance (rotation) is shown. It can be seen that an aft C.G. can significantly reduce the nose gear lift off distance. Examination of various weapon loads indicate that maintaining a TAKE OFF C.G. location of 33 percent is practical, and test configurations used in this report have this C.G. location.

MOS Selection: Using the surface roughness criteria discussed above, a procedure can now be outlined for selection of the MOS.

(a) The first requirement is to determine the take off direction. The surface roughness criteria are direction sensitive and a MOS repaired to the minimum surface roughness criteria will not be satisfactory for use in the direction opposite to the design direction. TAKE OFF by an F-4E in the opposite direction that results in operation of the F-4E over category "E" and "D" repairs before rotation could result in exceeding design limit loads.

(b) Next the maximum rotation distance should be determined from Reference 1. Rotation distance can be the current estimate for the particular day or it can be a preplanned worst case rotation distance. As discussed earlier the aircraft fuel and weapons loading should be adjusted to provide the maximum AFT C.G.

(c) Select the segment of the MOS from TAKE OFF start point to rotation based upon one of the following:

(1) Select a segment with one or less repairs ("B" or "C") between the start point and rotation. Note that for a single "B" repair one long mat could be used to cover two or more craters.

(2) If a segment with only one repair cannot be located select a segment such that multiple repairs ("B", "C") between the start point and rotation meet the mat spacing criteria.

(3) If spacing criteria cannot reasonably be met, minimize the number of repairs between the start point and rotation. All of these repairs must be category "A".

(d) Evaluate the number of category "D" and "E" repairs required after rotation and on access routes and taxiway. If the number is unacceptable, search for a different MOS. Taxiway repairs must be at least 70 feet apart at taxi speeds of 10 knots. Closer spacing requires slower taxi speeds; i.e. 35 feet spacings require 5 knots taxi speeds.

VIII CONCLUSIONS

The curves and techniques in this report show how surface roughness criteria can be developed using computer simulations validated by aircraft tests. It is anticipated that as improvements are made on these simulations the criteria will be improved. Ultimately this surface roughness criteria must become an integral part of the Post Attack Airfield Damage Recovery Plan.

REFERENCES

1. Gerardi, A. G., Digital Simulation of Flexible Aircraft Response to Symmetrical and Asymetrical Runway Roughness, AFFDL-TR-77-37, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio 45433, August 1977.

2. AFR 93-2, Disaster Preparedness and Base Recovery Planning, Department of the Air Force, Washington, D. C., July 1974.

3. T. O. 1F-4E-1, February 1979.

4. Caldwell, Borowski, McCracken, and Reichers, F-4K HAVE BOUNCE Tests, March-April 79, ESL-TR-79-13. (Confidential).

5. Redd, T and Borowski, R., HAVE BOUNCE Phase I Test Results, AFFTC-TR-79-1, April 1979. (Confidential).

6. Gerardi, Anthony, An Evaluation of the F-4E (LES) Aircraft Traversing AM-2 Bomb Damage Repair Mats, AFFDL-TM-79-54-FDE, dated May 1979.

TABLE 1

Repair Categories

	A	B	C	D	E
MAXIMUM UPHEAVAL	0	1 1/2"	1 1/2"	1 1/2"	3"
MAXIMUM SAG	0	0	1 1/2"	1 1/2"	3"
MAXIMUM LENGTH OF CRATER	ANY	ANY	70 FT	ANY	ANY
MAXIMUM LENGTH OF MAT	>77	>77	77 FT	ANY	ANY
MAXIMUM CHANGE IN SLOPE	0	3%	3%	3%	3%
REPAIR TOLERANCES - SEE TEXT					
SPECIAL REQUIREMENTS	1,3,5	1,2,4,5	2,6	1,3	1,3

SPECIAL REQUIREMENTS

1. IF SPACING BETWEEN MATS IS 100 FT. OR LESS, MAKE ONE LONG REPAIR.
2. MUST MEET SPACING CRITERIA.
3. ANY SPACING.
4. B MATS MUST BE STANDARD 77 FT. MATS IN CLEAR. CORRIDOR SHOWN ON SPACING CHART.
5. ONLY ONE REPAIR IS PERMITTED IN FIRST 400 FT
6. C REPAIRS MUST BE AT LEAST 100 FEET APART. MAXIMUM "C" REPAIR IS 77 FEET.

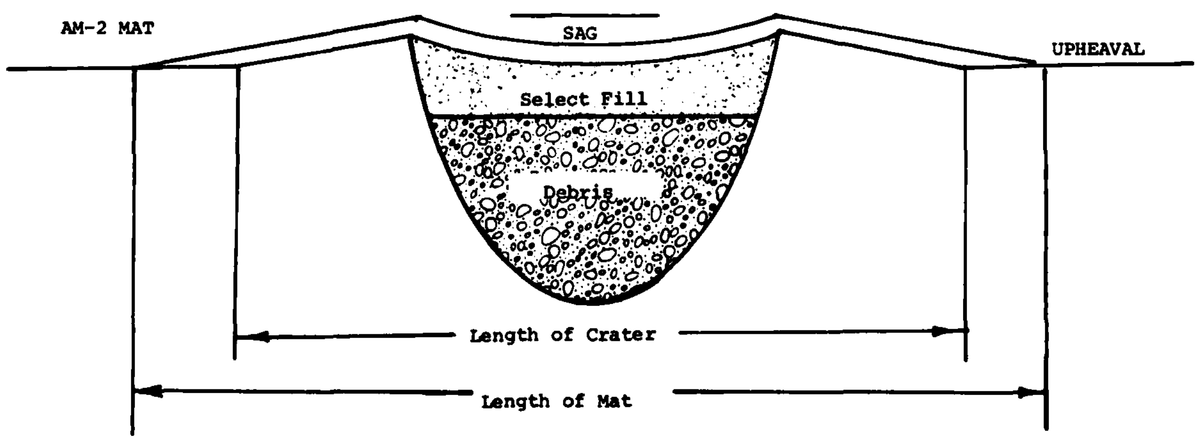

Fig.1 Typical repair

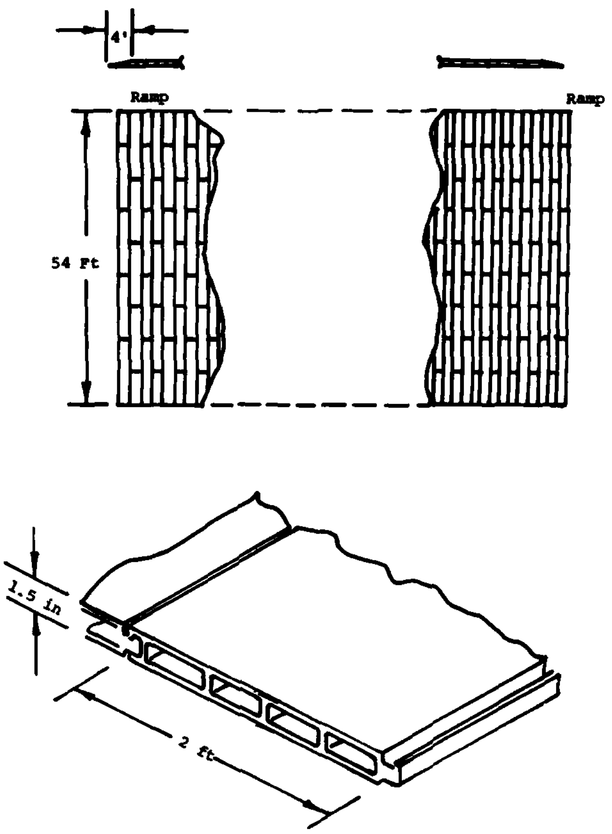

Fig.2 AM-2 mat

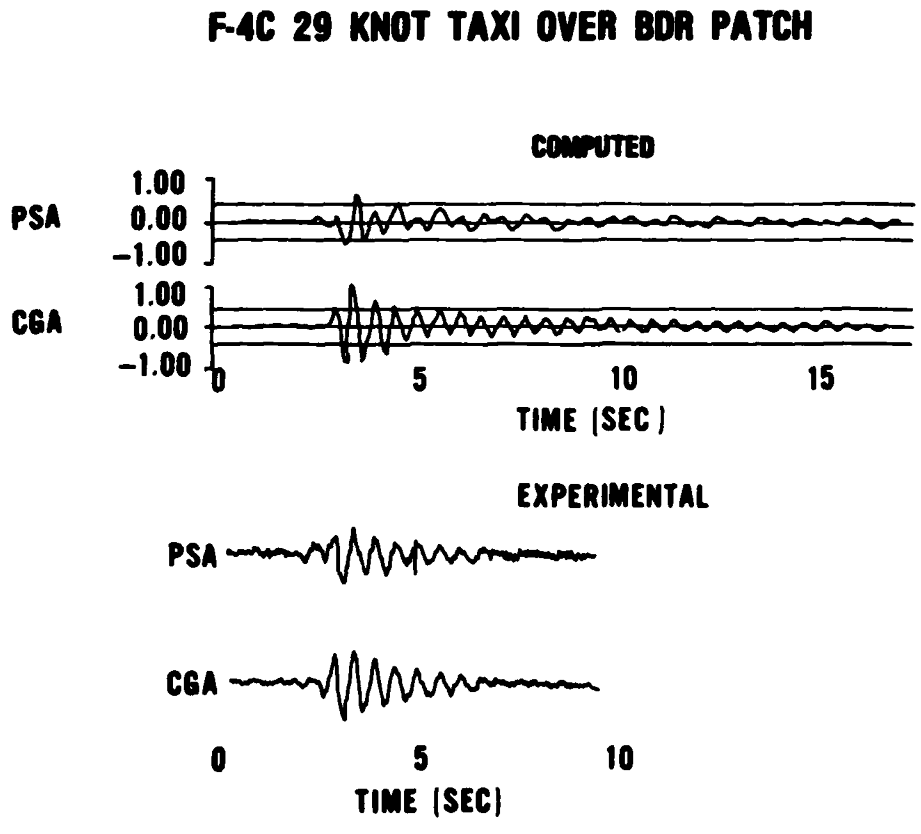

Fig.3 Plotted time history vertical accelerations

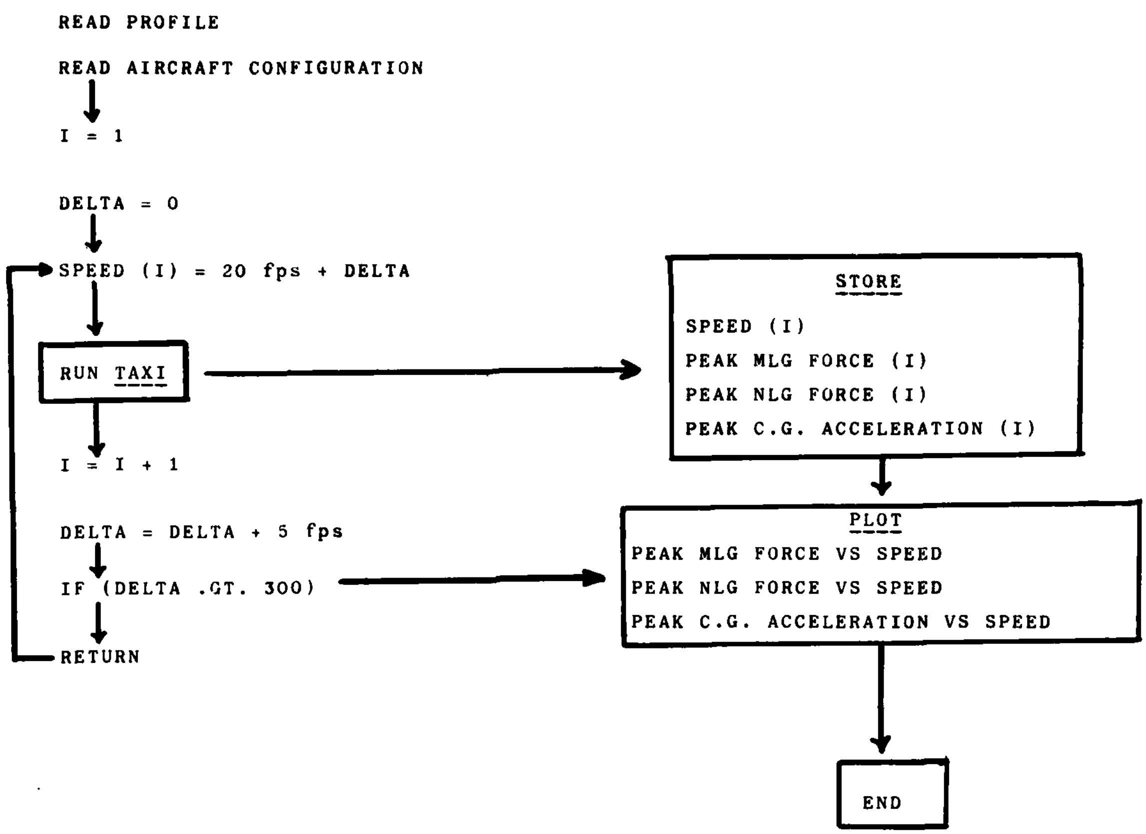

Fig.4 F-4/Profile evaluation flow chart

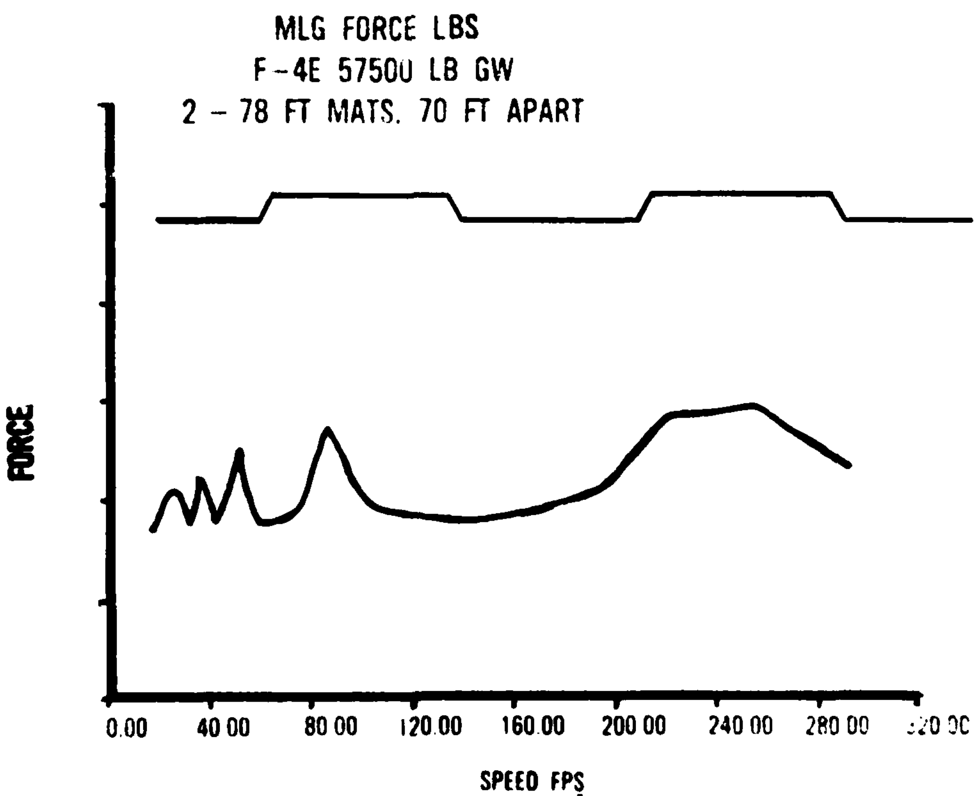

Fig.5 Peak MLG force versus velocity for the heavyweight aircraft for runway configuration two

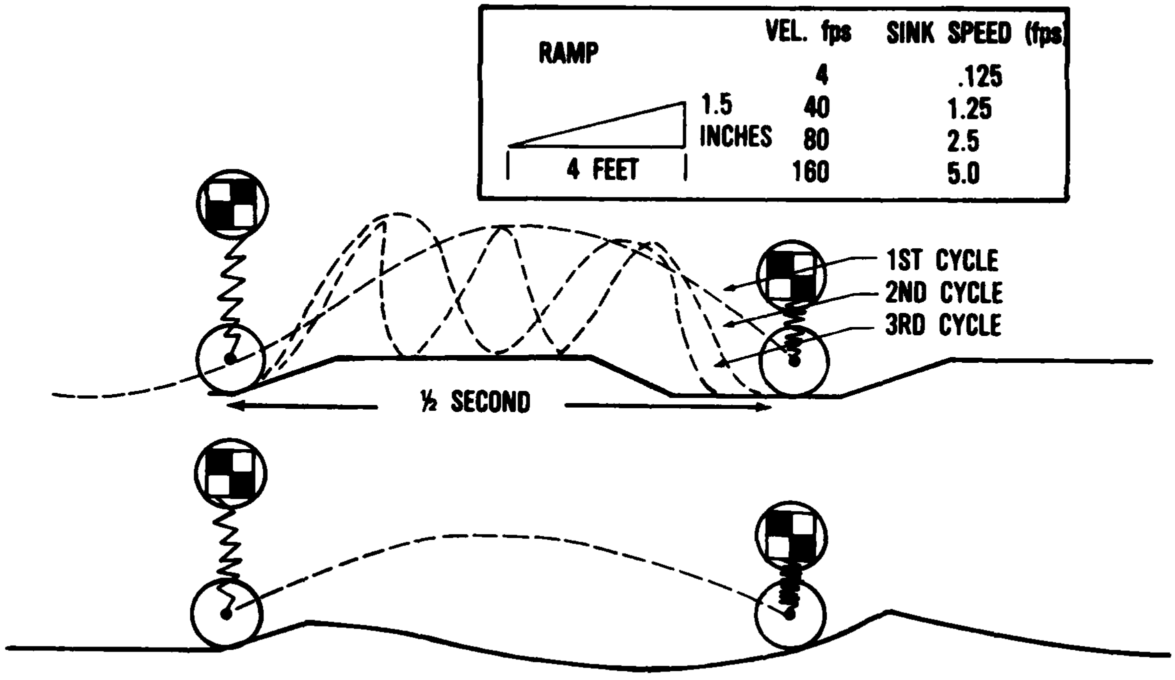

Fig.6 Effect of tuning multiple encounters

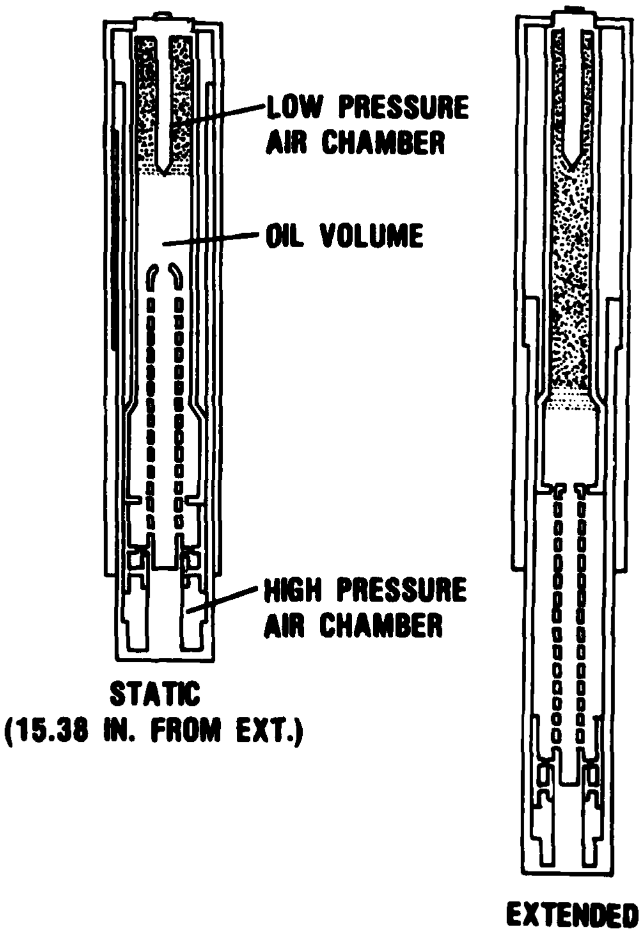

Fig.7 F-4 main landing gear strut internal configuration

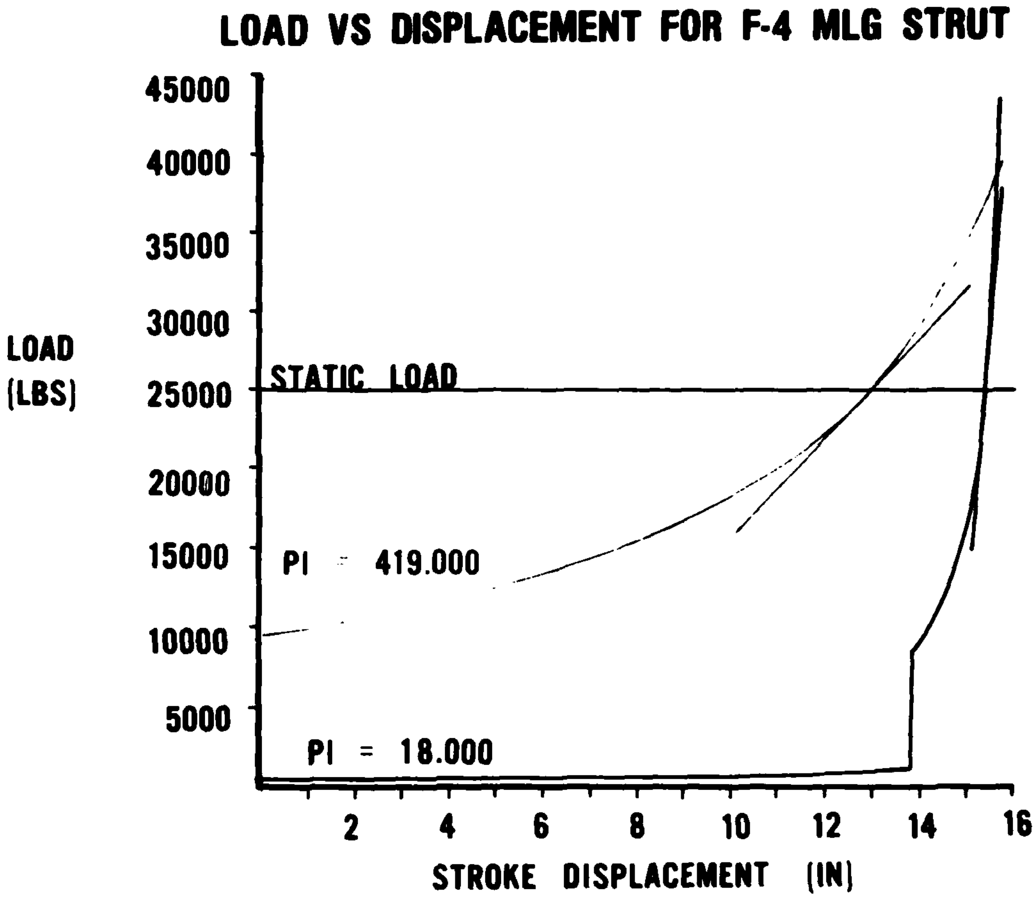

Fig.8 F-4 main landing gear load stroke curve

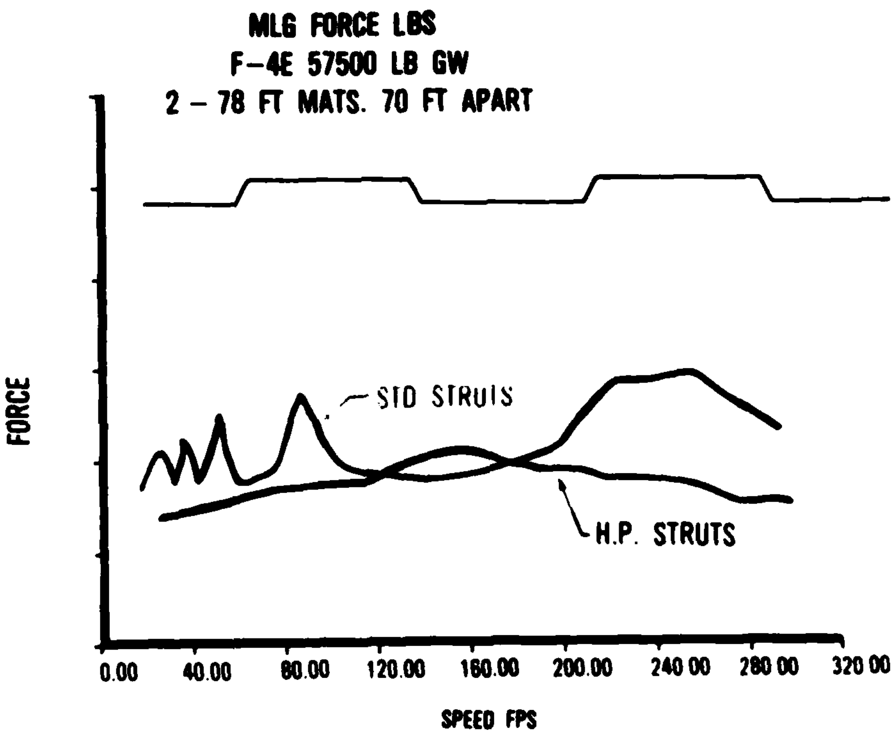

Fig.9 Peak MLG force versus velocity for the heavyweight aircraft with standard and high pressure MLG struts

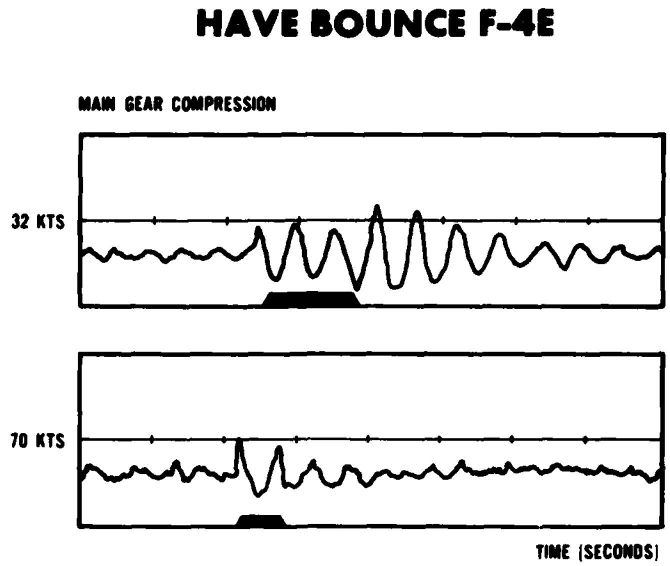

Fig.10 Main gear loads

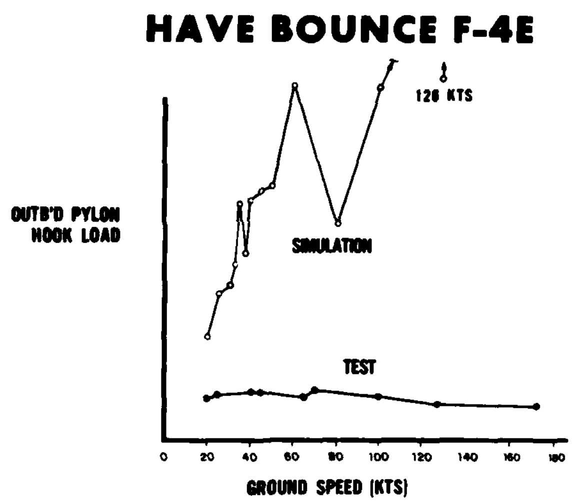

Fig.11 Pylon loads

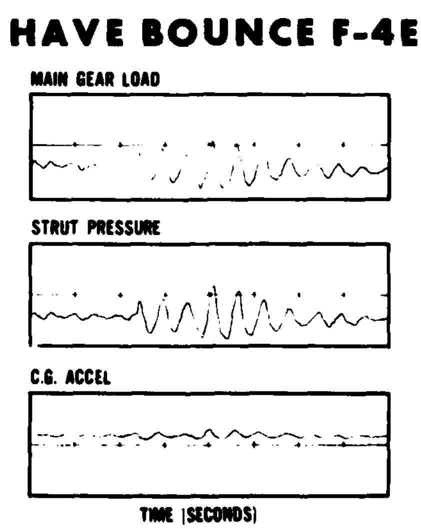

Fig.12 Comparison of instrumentation

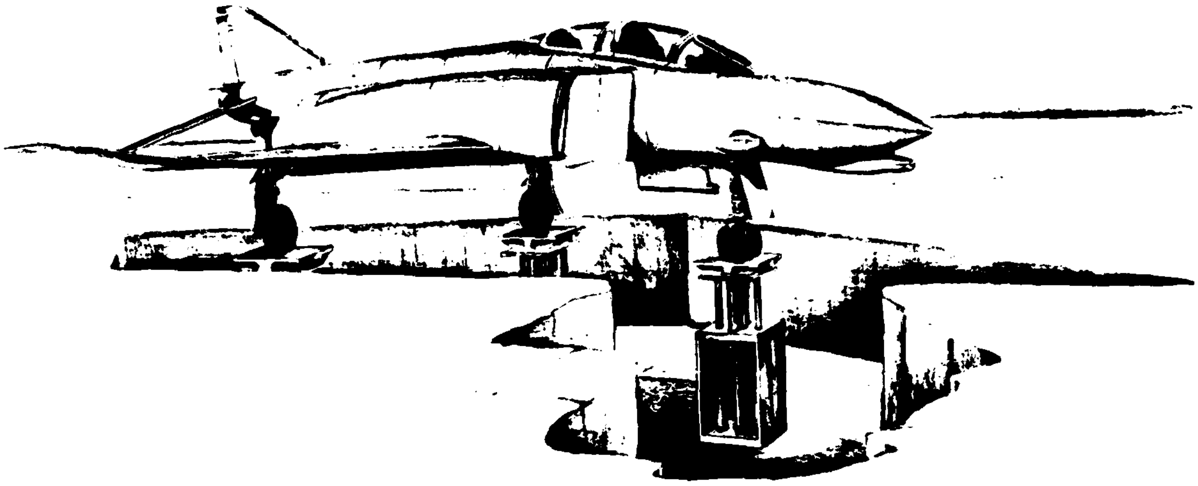

Fig.13 Computered controlled hydraulic shaker facility

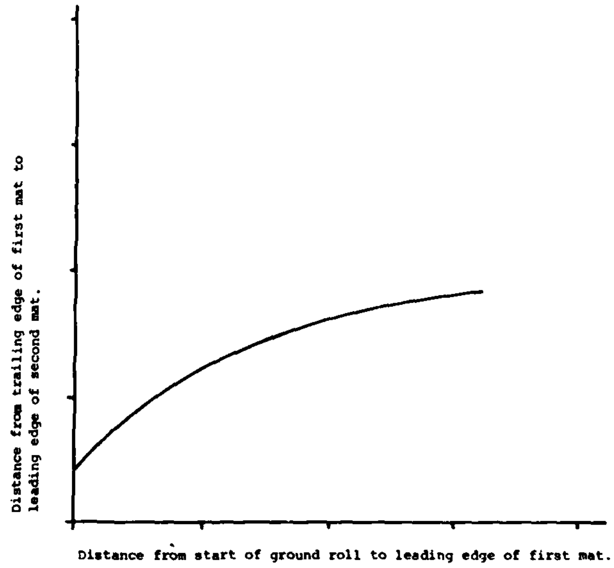

Fig.14 Time required for damping

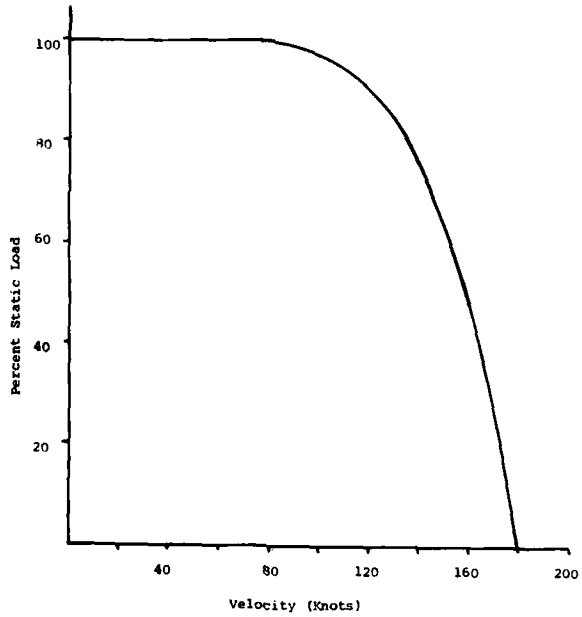

Fig.15 MLG loads versus velocity

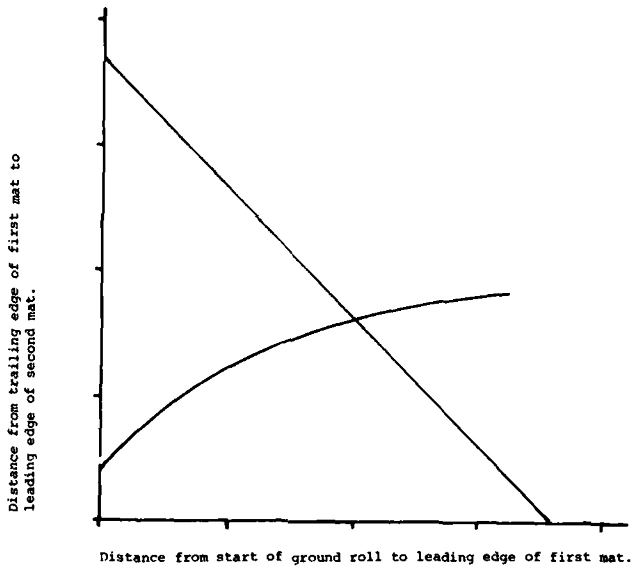

Fig.16 Spacing curve including rotation effects

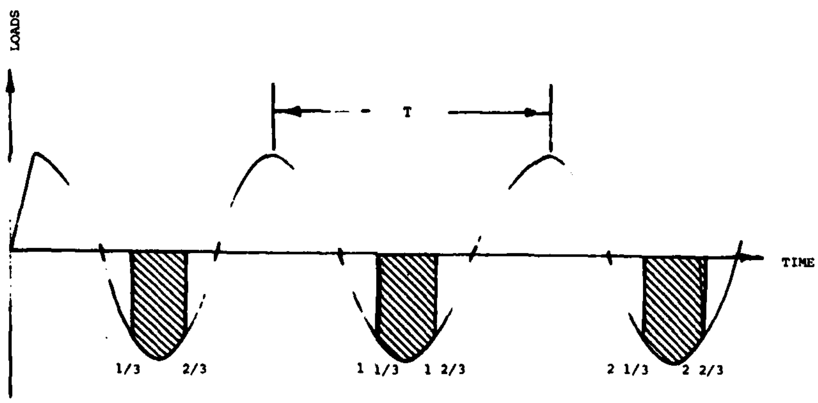

Fig.17 High load zones due to mat trailing edge

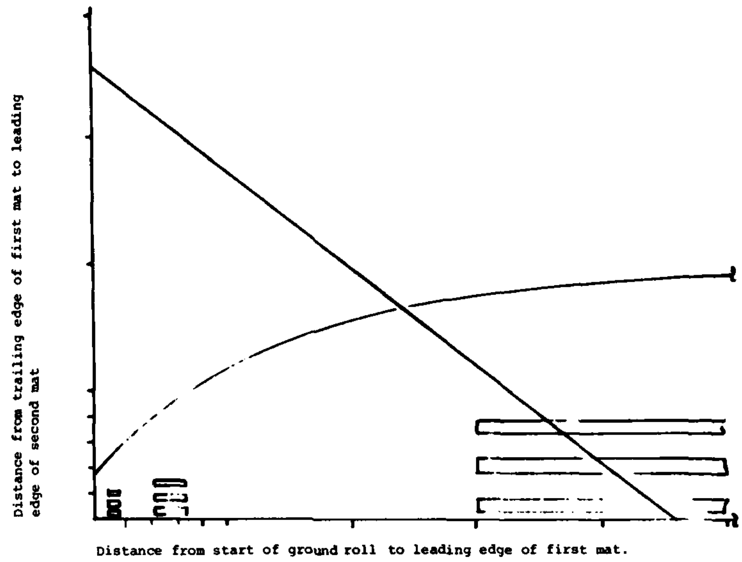

Fig.18 Worst case mat spacing

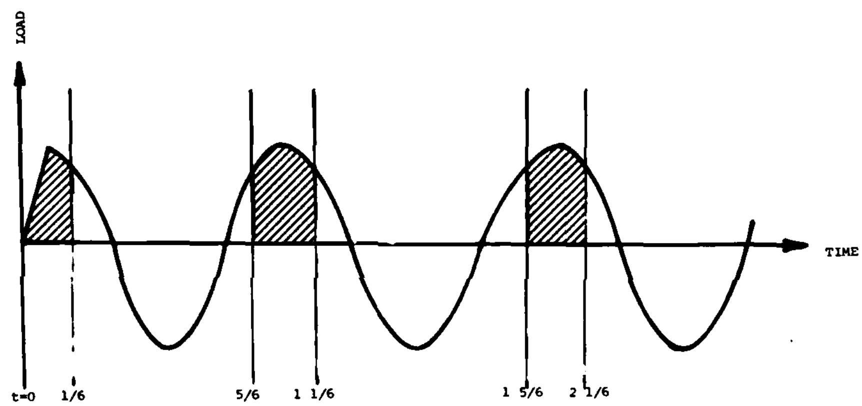

Fig.19 Low load zones due to mat trailing edge

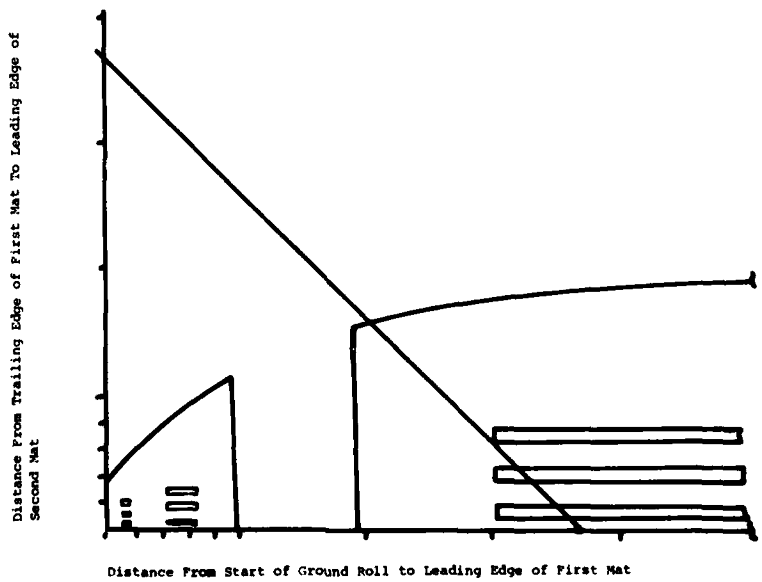

Fig.20 Spacing curve including reinforcement and cancellation effects

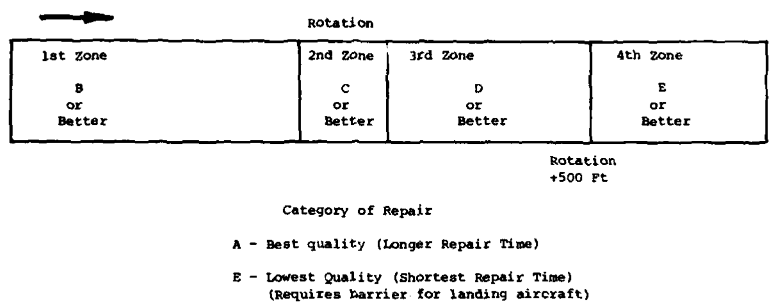

Fig.21 General MOS repair (50 x 5000 ft) (single direction take off)

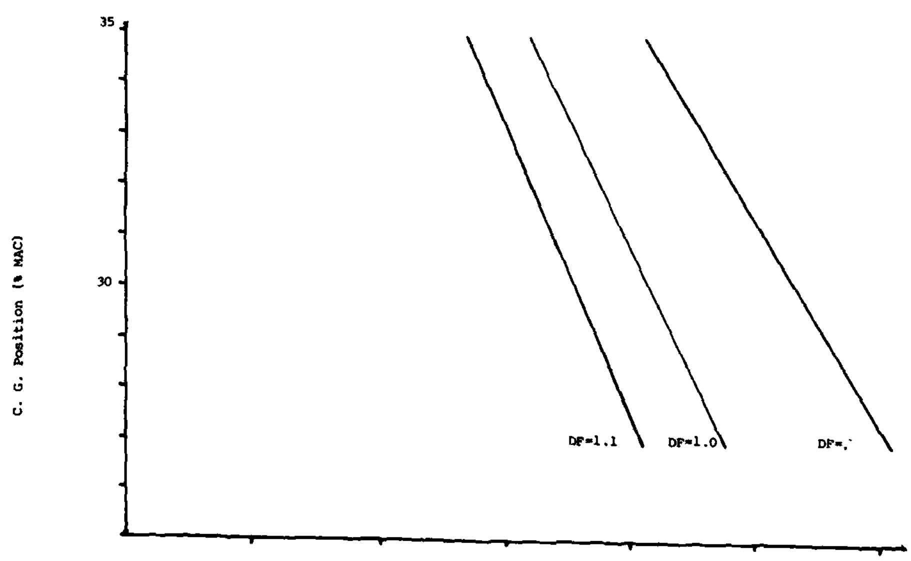

Fig.22 Effect of C.G. on rotation

U.K. APPROACH TO AIRCRAFT DYNAMIC RESPONSE ON DAMAGED AND REPAIRED RUNWAYS

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SUMMARY

For some years now the U.K. has recognised the need for, and been working on, the operation of military aircraft from damaged and repaired runways.

The prediction and trials on a number of aircraft are discussed, including the development of mathematical models of the structure and landing gears, model validation, and predictions and trial results for the operation in this environment, leading to operational recommendations.

Development of an approach suitable for all aircraft is discussed, and areas highlighted where further development work is required.

1.0 INTRODUCTION

For some years now the U.K. has recognised the need for, and has been working on, the operation of military aircraft from damaged and repaired runways.

In negotiating runway damaged or repaired areas the landing gears encounter a disturbed runway surface profile which produces fluctuating forces in them. These forces are vitally dependent on aircraft ground speed which essentially converts the distance dependent input into a time dependent one with a varying time lag between nose and main gear inputs. This time lag corresponds, of course, to a fixed distance lag equal to the wheelbase. The aircraft responds in its rigid body freedoms, notably pitch and heave and the flexible modes of the structure are excited to some lesser or greater degree. Excessive gear forces and structural stresses can result, but so also can excessive aircraft motion or accelerations. A complicating factor is the response to the general runway undulations and landing and braking, which is superimposed on the response induced by the runway damage or repair.

The work on this topic is aimed at defining the capabilities of particular aircraft and at indicating how it should influence future designs.

2.0 OBJECTIVES

The purpose of this paper is to indicate the approach which is being used in the U.K. to tackle the problem of aircraft dynamic response when operating from damaged and repaired runways, and some of the problems encountered, results obtained and future developments.

3.0 FUNDAMENTAL APPROACH

The fundamental approach to this problem is to depend on mathematical modelling of the relevant aspects of the environment, landing gears and structure for extrapolation to limit conditions (or beyond) from those conditions which can sensibly be covered in aircraft trials, and also for covering those variations which would be too numerous and expensive to test. The mathematical model is used with deterministic techniques to establish the aircraft's capabilities. For this model to achieve its full potential it must be validated against component tests and aircraft trials. In general these should have as wide a scope as possible.

The aircraft trials have an additional important purpose in exposing any general operational or engineering problems, which the mathematical model could not be expected to cover, such as handling or manoeuvrability limitations on the aircraft capability, or repair durability.

The steps involved in the general approach are:-

- Define the aircraft configurations to be investigated.
- Assess the probable critical areas of the aircraft.
- Set up mathematical model/s.
- Establish data for the model/s, some of which will come from component tests, some from whole aircraft tests and some from the normal design process.

3.0 FUNDAMENTAL APPROACH (cont.)

- Use the model to predict results of validation trials.
- Conduct validation aircraft trials.
- Adjust data and/or model to match the trials results if necessary.
- Conduct engineering aircraft trials. These may either combine with or extend the validation trials.
- Use the model to predict limit conditions and operational data.
- Use the model to define possible modifications to improve the aircraft's capability.

In practice these steps have been telescoped or overlapped.

4.0 JAGUAR TRIALS AND PREDICTIONS

4.1 On the rough field test programme for this aircraft, aimed at establishing clearance criteria for its operation from repaired, semi-repaired and grass runways, a co-ordinated series of aircraft trials and computer predictions has been performed in which the steps mentioned earlier have been interwoven.

4.2 Mathematical Model - The main bulk of the mathematical modelling and of the computer predictions have been carried out by the Dynamics Department of the Weybridge-Bristol Division of British Aerospace contracted to the Warton Division. Mathematical models have been developed for the response of this aircraft and landing gear to symmetric inputs, and these include the following features and freedoms:-

- Aircraft pitch, vertical and horizontal translation freedoms.
- Aircraft flexible normal modes.
- Nose and main gear lever rotations.
- Several tyre models.
- Brake torque time-history.
- Elevator or Tailplane angle time-history.
- Parachute deployment.

These allow the simulation of taxy, take-off and landing.

4.3 Validation and Engineering Trials - Initial trials were conducted at an airfield with the aircraft running over a range of planks attached to the runway. These trials helped with assessment of critical areas and with general engineering aspects but response measurement for model validation was the primary purpose.

4.4 Model Matching with Trials Results (Validation) - The principal quantities compared between trials and model were landing gear lever normal and compression forces and oleo travels. Before it was finally considered that adequate matching had been obtained, several models were employed and various values for nose and main oleo parameters were tried. For large amplitude rigid body aircraft motion the oleo overall compression curve was of dominant influence.

An example of the level of agreement achieved between model prediction and trials measurement is shown in Fig.1. Cockpit, wing and tailplane tip vertical oscillations were not well predicted but since these were not a critical feature no attempt was made to use more appropriate aircraft elastic modal data to improve the match.

4.5 Further Validation and Engineering Trials - The models were further used to predict the response of the aircraft to a repair mat on a runway (together with braking) and to a grass strip containing three 50 ft. (nominal) wavelength bumps. The ensuing trials were primarily engineering trials but were used also to confirm the model. The repair mat was less high than the validation planks but much longer. Although the response data which was obtained only covered a few interesting quantities some comparisons with predictions were possible, in particular on nose gear lever bending forces.

Predictions with the mat on a flat runway gave good agreement with the trials after allowing for the forces just prior to the mat arising from the general runway undulations. The forces were well below the limit values. Taxi runs on grass bumps of nominally sinusoidal form with 50 ft. wavelength and 4" depth were carried out. The predictions showed that main gear forces were non-critical, but nose gear forces were expected to approach the limit value.

The evolution of the successive load peaks with speed and the actual peak values were shown to be well predicted.

5.0 JAGUAR REPAIRED RUNWAY CLEARANCE

5.1 General - In most military aircraft designs there are three major potentially critical areas where response to rough ground may be significant:-

(a) Undercarriage loads
(b) Pilot environment
(c) Heavy store attachment loads

For Jaguar the wide range of calculations and trials has established that the most critical parameter is nose undercarriage vertical load.

5.0 JAGUAR REPAIRED RUNWAY CLEARANCE (cont.)

In employing a deterministic technique it appears at first sight that we are left with tedious and time consuming time history analyses covering a wide range of ground profiles and aircraft configurations. However, close inspection of the responses that cause the peak loads can help to simplify this procedure.

For Jaguar the peak undercarriage loads arise from response in the rigid aircraft pitch mode. Furthermore, although the aircraft can carry a wide range of external stores and has a large internal fuel capacity the non-linear nature of the oleo and tyre stiffnesses are such that this pitch mode frequency is broadly independent of aircraft configuration.

The dependence of critical load on response in a nominally single degree of freedom has allowed us to follow a much simplified technique for the two clearance programs we have attempted to date.

5.2 Repaired Runway Clearance - The problems of damaged runways fall into two groups:-

(a) Small craters (arising from cannon shells etc.). These have effectively short wavelengths and can give peak responses in both rigid and flexible aircraft modes, and in the unsprung (wheel) mass vertical mode. There is also the problem of high impact drag loads as the wheel hits the far side of the crater.

(b) Large Repaired Craters. Crater length and spacing,repair characteristics, and aircraft wheelbase are all significant factors in aircraft response. For Jaguar we have assumed that craters have been repaired by compacted fill suitably levelled and covered by standard length U.K. repair mats, and that responses to small undulations left on the fill surface are negligible.

Initially responses have been calculated for crossing a single mat for various depths of fill and covering the full operating ground speed range. Rigid aircraft pitch mode dominates the response giving maximum nose gear loads at speeds where the wavelength of the response matches the mat length.

Multiple mat clearance is much more complex. Crater spacing may well be unequal and it is prohibitively expensive and time consuming to check directly all possible mat spacing combinations. Further, operational recommendations must enable a station commander to assess the distribution of craters in such a way that he can decide quickly if operation is possible.

Currently, two slightly different approaches to this problem are being investigated.

(a) Superposition of responses from single mats. Results indicate that this approach gives higher loads than a full calculation.

(b) Calculations on pairs of mats to determine spacings which do not lead to load increase.

Both these approaches indicate positions on the runway and spacings which predictions show are likely to cause exceedance of undercarriage limit loads. However, the techniques are pessimistic and some of the resulting "forbidden" areas could in fact be safe for operation.

5.3 Rough Field Clearance - If runways are damaged beyond repair there remains the possibility of operating from the grass areas alongside. A wide range of trials and calculations have been conducted to assess Jaguar's grass field capability.

Clearance calculations are based on measured centre line profile data which is filtered at various aircraft speeds to produce a profile amplitude variation at the critical rigid aircraft pitch mode frequency. Using aircraft take off and landing performance data it is then possible to select potentially critical areas for more detailed time history analysis.

6.0 PHANTOM, BUCCANEER AND LIGHTNING TRIALS AND PREDICTIONS

6.1 Overall Programme - When it became apparent that the techniques being used for the Jaguar repair mat trials were capable of producing worthwhile results A. & A.E.E. Boscombe Down were tasked with carrying out similar work on the Phantom, Buccaneer and Lightning aircraft. This three-aircraft programme has given a unique opportunity for comparison between the effectiveness of different undercarriage design features for operation from repaired runways and has dispelled the myth that aircraft designed for high rate-of-descent landings are necessarily superior in these circumstances. The conduct of this programme was influenced by the lessons learnt during the Jaguar programme, but there were a number of differences which will be highlighted in the following brief descriptions of the individual steps.

6.2 Mathematical Models - All the simulation work for this programme has been carried out at Boscombe Down. The mathematical models used were based on that developed by A. & A.E.E. during the Jaguar trials. This differs from the B.Ae model in a number of respects, the main points being that it uses ground axes instead of aircraft axes and is basically a rigid airframe representation. Separate models have been used for each aircraft, since it was found that the differences between them precluded the use of a common simulation programme, with separate data files and component sub-routines.

6.3 Aircraft Instrumentation - In order to be able to rapidly instrument aircraft for this type of trial, A. & A.E.E. developed a podded instrumentation system. This is unlike Jaguar where a fully instrumented development aircraft was used. This A. & A.E.E. pod is based on a standard bomb and is self-contained with its own battery power supply, miniature signal conditioning units, digital magnetic tape recorder and split-image 35 mm cine-camera. The latter provides high-speed coverage of all three undercarriages with a display of instrumentation time. The pod also contains high-accuracy six-degree-of-freedom inertial sensors, the outputs of which, suitably filtered and time correlated, provide the principle means of deriving the dynamic loads on the undercarriages. The use of undercarriage strain-gauging was rejected because it was not considered cost-effective in this application. Transducers are also used at other locations on the airframe, together with strain-gauging on other critical parts of the aircraft structure, and the outputs from these are also recorded in the pod.

6.4 Trials - No separate validation trials were carried out on these aircraft. The trials were planned using a mission-related philosophy, implying the use of accelerating and decelerating runs, rather than more usual constant-speed runs, which have no operational significance above taxy speeds. They covered single and multiple U.K. and U.S. repair mats, of various lengths, using simulated crater fill profiles under the mats. Aircraft crossings were made with one or two wheels off the edges of the mats, in addition to the normal symmetric crossings. Work was also carried out crossing small unfilled scabs or spalls.

6.5 Validation of Models - Similar validation processes were used to that employed on the Jaguar, except that in these cases different components were dominant. One example of a comparison between test and simulation results is shown in Fig.2. During this validation process it became apparent that the undercarriage characteristics were subject to considerable variability. In one trial two different aircraft of the same type were tested and the responses were different, although they should have been similar. This significant variability of characteristics has also been confirmed from a number of other tests and so work is in hand in the UK to quantify some of the critical parameter variations, so that ranges of values can be used in future calculations.

7.0 GENERAL RECOMMENDATIONS

There are three areas which should be considered. These are the variability of the environment and of the aircraft, the details associated with the modelling, and the philosophy of operational limitations.

7.1 In the area of variability, consideration needs to be given to:-

- Height and shape of crater fill.
- Range of speeds at which given repairs will be met, which will depend on the positioning of take-off and touch-down points relative to the repairs and variations in aircraft thrust and drag.
- Differences in background aircraft response due to different undamaged runway profiles.
- Range of aircraft mass and C.G.
- Configuration of aircraft and stores.
- Variability in nominally identical landing gears, e.g. inconsistency in oleo charging pressures, oleo heating and cooling, tyre pressures, stiffnesses and sizes.

7.2 In the area of modelling, the following points are important:-

- A good assessment of the likely critical features of the aircraft/landing gear is needed so as to avoid wasteful work.
- An understanding of the tyre behaviour is needed, e.g. forces at "sharp" edges, influence of heating, tyre damping.
- A proper understanding of the internal workings of the oleos is important. Component tests could be necessary in this respect to establish accurate data, e.g. load-deflection tests, drop tests, tests at moderate to low stroke rates, orifice or valve tests.
- If aircraft structural modes are important then reliable data for mass, stiffness and damping and mode shapes are needed, together with information from ground resonance tests for validation purposes.
- Aerodynamic forces (including dampings) are important even at moderate speeds.
- Aircraft trials for model validation should cover as wide a range as feasible.

7.3 For the philosophy of operational limitations the following points merit consideration:-

- The load limits which should be used in relation to normal proof and ultimate definitions and in relation to functional limits of undercarriages.
- What probability of aircraft failure should be accepted and what factors are required to give these safety levels.
- How repaired runway operational recommendations for individual aircraft types can be integrated to give a useable system for the safe inter-operation of NATO aircraft.

8.0 CONCLUDING REMARKS

8.1 Over the past few years the U.K. has investigated the rough ground operational capabilities of several aircraft.

8.2 Mathematical modelling and associated validation trials have been successfully employed to predict the dynamic response of aircraft on damaged and repaired runways and together with engineering support trials allow the operational capability of the aircraft to be defined, provided proper consideration can be given to the variability of the environment and the aircraft.

8.3 Clearance problems arise from two major sources:-

- Rigid aircraft response in pitch and heave or roll giving rise to high undercarriage loads and/or unacceptable handling problems for the pilot.
- Flexible structural response leading to high aircraft structure loads, especially for heavy external stores.

8.4 Considerable simplification has been achieved on these aircraft because the critical features come essentially from single degree of freedom response.

8.5 It is expected that future military aircraft will have, as an early and continuing part of the design process, an assessment of the response on repaired runways so as to highlight features which could influence its overall as well as its detailed configuration.

8.6 A number of general recommendations have been given. The U.K. is giving careful consideration to these, and is making use of them in current aircraft clearance programmes.

AIRCRAFT DYNAMIC RESPONSE TO REPAIRED RUNWAYS

Validation of Model

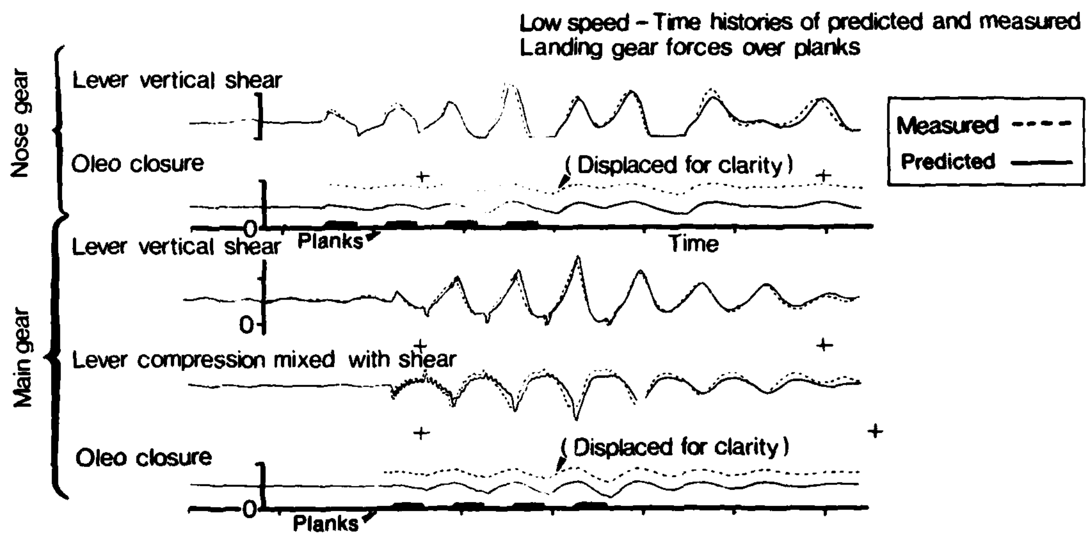

Fig. 1 Jaguar over test bumps

AIRCRAFT DYNAMIC RESPONSE TO REPAIRED RUNWAYS

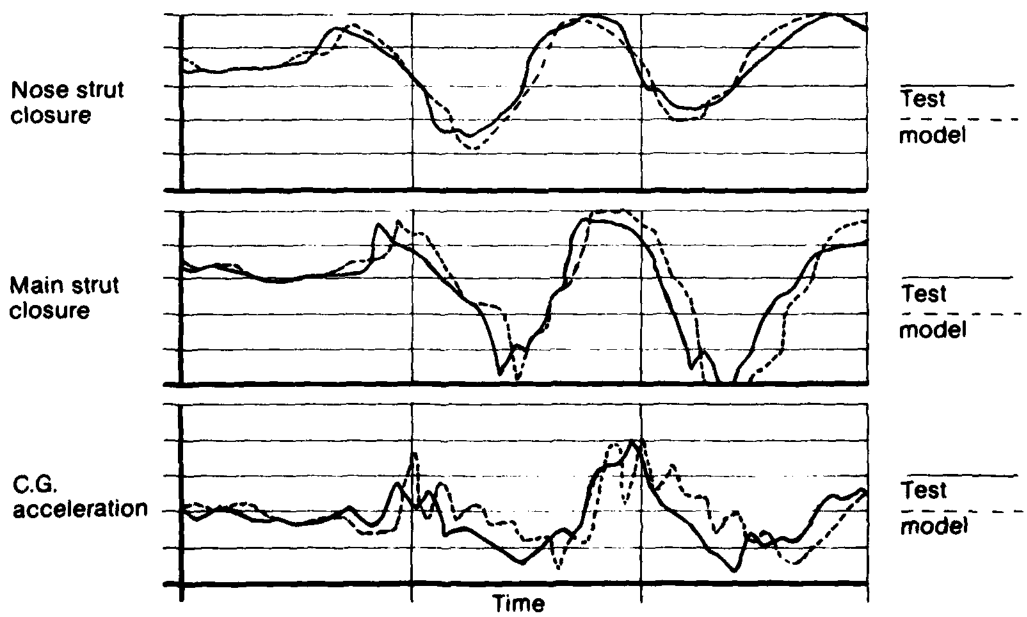

Fig. 2 A comparison between model and test results for a high speed 2 mat crossing

PARAMETERS AFFECTING AIRCRAFT PERFORMANCE ON RUNWAYS IN BAD CONDITION

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SUMMARY

Based on a review of properties of aircraft undercarriages it is postulated that calculations of dynamic response to damaged runways must account for the nonlinearities of the undercarriage. Examples taken from simulations of the F-104G running across AM2 runway repair mats serve to identify the influence of some of these nonlinearities and to discuss possibilities to improve undercarriage performance. The subsequent considerations on structural response of the airframe deal with the validity of models and with cost effective ways of determining aircraft performance on runways in bad condition.

1. INTRODUCTION

"Runways in bad condition" is a relative term, e.g. a runway which is extremely comfortable for an agricultural aircraft may be completely unacceptable for a fighter aircraft. In the context of this short paper " bad condition" means that the properties of the runway jeopardize the structural integrity of the aircraft and/or its payload when operating on this runway. A damaged and hastily repaired runway generally may be considered to be in bad condition with respect to aircraft normally operating from this base in an undamaged condition.

One of the most important factors affecting A/C performance on runways in bad condition is the undercarriage, not only because it supports the A/C and excites rigid body and elastic degrees of freedom of the A/C but also because some properties of an undercarriage can be modified rather easily as compared with for instance shifting a structural eigenfrequency of the A/C.

This paper deals mainly with parameters related to the undercarriage.

2. NONLINEARITIES

It is hard to find any linearity in undercarriage of modern fighters and transport aircraft. Taking the most widely used type of undercarriage - an oleo pneumatic strut equipped with one wheel (Fig. 1) - it consists of a nonlinear spring commonly called the tyre and a semi-cantilever beam of variable length commonly called oleo strut, with the so-called "unsprung mass" of wheel and brake (and lower part of the oleo strut) between the tyre and the oleo strut.

The oleo strut in its most simple form (Fig. 2) consists of a piston rod (which in A/C application normally forms the lower end of the strut) moving within a cylinder. The space within the cylinder is filled by hydraulic fluid and gas (mostly nitrogen) at higher than atmospheric pressure.

A compression force (F_C) applied to the strut does not result in a relative displacement of piston and cylinder as long as $F_C < F_{C_O}$ = (gas initial pressure times effective area of piston) + (friction forces at upper and lower bearing) - (atmospheric pressure times effective area of piston) . If $F_C > F_{C_O}$ the piston begins to move into the cylinder this movement being opposed by (neglecting inertial forces)

- o Gas spring force F_S
- o Hydraulic damping force F_D
- o Bearing friction force F_F .

The gas spring force relates to the displacement of the piston (stroke s) by the well known expression for polytropic compression of gases

$$F_S = F_{S_O} \left[s_{end}/(s_{end} - s)\right]^n$$

where s_{end} is the stroke at which the trapped gas volume theoretically is compressed to zero. Following normal undercarriage design practice the stiffness of such a gas spring in the oleo strut fully compressed position can be up to 250 times the stiffness in the fully extended position (compression ratio 10:1; n = 1,4).

The hydraulic damping force results from the differential pressure across the damping diaphragm. This differential pressure is deduced from the physics of efflux out of a pressurized vessel and is proportional to the square of the stroke velocity:

$$F_D = C_D \cdot \dot{s} \cdot |\dot{s}|$$

Adapting undercarriages to such widely different tasks as landing and taxying has led to a vast variety of designs for hydraulic damping, e.g. floating ring to increase return stroke C_D over the compression stroke C_D, metering pin to make C_D a function of s, limiting valves for the differential pressure across the damping diaphragm. Thus the damping force coefficient in itself is far off from being a constant.

Friction produced by sealings contributes to the bearing friction force. However, the major portion of F_F results from the shear forces on lower and upper bearing. These shear forces are a function of forces and moments acting at the wheel, and of the distance between the bearings. That portion of the bearing friction force which is due to vertical force acting excentrically to the strut axis (e.g. by lateral offset of a single wheel) is of self-augmenting nature. Bearing friction force may well reach up to 10 % of the maximum total compression force of the strut during the landing impact.

There are quite a few nonlinearities more in the undercarriage than those which were sketched in this very coarse outline. However, this sketch should be sufficient to prove one very essential point:

> If dynamic response to damaged runways is investigated, accounting for the non-linear properties of the undercarriage is indispensable.

3. U/C RESPONSE ON AM 2 REPAIR MATS

In order to give a better idea of the influence of these nonlinearities some results are presented and discussed of a theoretical study performed by MBB [1, 2]. Subsequent tests [3] showed good agreement with the theoretical predictions. The subject of the study and of the tests was to determine the U/C loads of the F-104G when rolling across AM 2 repair mats. Though the study is almost ten years old it is a good source of some instructive examples.

3.1 Basic Situation

In order to identify primary influences we took a very straight forward approach in the beginning (see Fig. 3).

We simulated the A/C rolling on perfectly even ground at constant speed and let the A/C cross a perfectly even AM 2 mat.

3.2 Tyre Loads

Fig. 4 shows ground reaction at the nose tyre versus horizontal distance. Point 1 marks the beginning of the ascending ramp. Tyre force reaches its maximum after approximately two thirds of the ramp, when the upwards velocity of the wheel becomes greater than the apparent upwards velocity of the ramp surface (this latter velocity being 1.7 m/s at 50 m/s forward speed). At point 2 the nose tyre has crossed the crest of the ramp and rolls on the even surface of the AM 2 mat, until the crest of the descending ramp is met (point 3). A rapid drop of tyre force occurs on the descending ramp and eventually the tyre loses ground contact at point 4. After leaving the mat, a downwards motion of the centre of gravity of the A/C combines with a pitchdown motion to produce maximum loading on the nose tyre at point 5 .

3.3 Assessment of Tyre

The most critical point for the nose tyre appears to be point 5 . If there were the beginning of another AM 2 mat at this point, tyre bottoming (also one of the nonlinear features of the problem) would occur and produce U/C load far beyond ultimate design load. Computer simulation showed that the load produced by that case was twice the limit load of the nose U/C. Most probably at this point a solid up-step of say half the height of an AM 2 mat would destroy the tyre. However, this was not calculated because very little information if any is available on the capabilities of tyres to cross obstacles of different shapes at varying angles. This lack of information is probably due to the fact that tests of this kind would be extremely expensive.

With respect to tyre bottoming there are several possibilities to improve the situation:

a) With the original tyre, increase inflation pressure to gain reserve deflection at the original bottoming load level (see Fig. 5).

   However, this is only feasible if neither inflation pressure is already at its maximum in the original state of the tyre nor tyre footprint pressure is limited by the quality of the ground.

b) Redesign the U/C (and the A/C) for a bigger tyre with more overall deflection (dash-dotted line in Fig. 5) such that additional deflection is provided. (This is very expensive).

c) Arrange length and distance of AM 2 mats such that no ascending ramp is met at high basic load of the tyre (this is rather hypothetical, because damaged and repaired runways will not present a well defined environment).

d) Change characteristics of the U/C such that load amplitudes resulting from low frequency A/C rigid body modes (heave and pitch for the nose U/C, heave and roll for the main U/C) are reduced.

e) Change characteristics of the oleo strut such that a greater proportion of the height of an obstacle is converted into compression stroke.

Point d) and e) will be considered in context of the oleo strut (para 3.4 and 3.5).

A remark is due concerning points 3 and 4 of Fig. 4. Whatever method of runway repair is applied, special attention must be paid to the avoidance of water puddles under wet conditions. Aquaplaning and loss of directional control are enhanced by the fact that generally load on the tyre is reduced on the descending slope which leads into a puddle. However, the quality of the runway is only one side of the medal. The design of the U/C and especially of the oleo strut contributes considerably to the ground contact of the tyre, as is shown in Fig. 6 . This figure shows load envelopes of a single main U/C leg rolling along a wavy runway, starting with long wavelength/high amplitude and continuously proceeding to short wavelength/low amplitude. The solid line pertains to a single stage airspring design, while the dashed line pertains to a two stage airspring design.

The two stage design shows favourable properties, because

- ground contact is improved around 1 Hz and 7 Hz (lower leg of the envelope)
- peak load at 1 Hz is drastically reduced
- the load amplitude is lower throughout the frequency range, thus yielding less excitation for structural modes of the airframe.

3.4 Oleo Strut Loads

Returning to the F-104G study and coordinating the tyre load time history of Fig. 4 with the load along the oleo strut will provide some insight into the problem of adapting a (nose) U/C to the demands of a repaired runway.

Fig. 7 shows a plot of oleo compression load versus stroke. At point 1 the tyre force on the ascending ramp produces a compression of the oleo strut. That proportion of the load which is above the dotted line of the airspring force results from hydraulic damping (recall the apparent upward velocity of the ramp of 1,7 m/s). Due to very strong recoil damping a sharp drop of the load occurs, when the crest of the ramp is passed and the oleo strut enters the return stroke (point 2). The strut has just begun a new compression stroke when at point 3 the end of the mat is encountered. Again the load falls off very rapidly due to the strong recoil damping. The oleo strut has extended only two or three millimeters when the tyre loses ground contact at point 4 . After having regained ground contact the extending stroke is continued until the load on the tyre exceeds the airspring force at the most left point of the load/stroke curve. Since the subsequent compression stroke results from a rigid body motion of the A/C it is slow as compared with the compression stroke on the ramp. Thus the hydraulic damping force is almost negligible and the compression occurs along the airspring curve until maximum compression load and stroke are simultaneously obtained at point 5 .

3.5 Assessment of Oleo Strut

It is apparent that the load peak at point 5 would not be so high if hydraulic damping at low compression stroking velocity were higher. However, a marked increase of the compression damping coefficient would have a quite detrimental effect on the capability of the U/C to cross the AM 2 ramp, because damping-induced resistance of the oleo strut progressively increases with forward speed of the A/C. If for instance the forward speed of the aircraft is twice that of our example (100 m/s instead of 50 m/s) the peak value of the load increase in the oleo is caused by hydraulic damping and is roughly three times the load increase produced by the airspring.

A look to Fig. 7 shows that at 50 m/s the peak load increase is only marginally higher than the load increase of the airspring.

Thus a straightforward increase of hydraulic damping is not a suitable means to curb low frequency load fluctuations of the U/C, it has to be accompanied by some load-limiting device.

Passive hydraulic devices such as relief valves operated by the differential pressure across the damping diaphragm only partially serve this purpose, because they limit only the load increment and do not account for the basic load level.

Much more effective with respect to limiting absolute load level is a two-stage airspring with a highly preloaded but only weakly damped second stage. The load/stroke characteristic of such an airspring is sketched in Fig. 8 together with a schematic model. As one may easily realise from the model the second stage starts to yield when the sum of airspring plus damping force of the first stage exceeds the preload of the second stage. Thus absolute peak load is limited if not too much stroke is required by the height of the obstacle. If the design of the second stage is such that it does not respond to normal landings on even ground, much less demand is put on the evenness of the touchdown section of the runway. This is due to the fact that for instance landing into the ascending ramp of an AM 2 mat produces a stroke velocity which may well be twice the design sinkrate of the U/C, while the limited height of the obstacle requires only ten or fifteen percent of the total available stroke. A properly designed second stage cuts excessive damping load while providing the additional stroke required by the obstacle.

It is too early to assess the impact of so-called "active" U/C's on A/C operations on damaged and repaired runways, because published studies [e.g. Ref. 4] reveal a vast variety of technological and control law problems.

Returning to "passive" U/C's there is another characteristic of an oleo strut which has a very strong influence on A/C performance on runways in bad condition. This important parameter is the recoil damping coefficient of the oleo strut. If there is no special requirement with respect to runway unevenness the recoil damping generally is chosen to yield optimal ground contact (least "bouncing") during the landing impact. However, if such an U/C is simulated running across a randomly uneven runway (which simulation we performed, too) it may exhibit "climbing", which means that the oleo strut has not yet recovered stroke after the first bump, when it is again compressed by the next bump. Although at constant rolling speed the mean static load on the leg remains the same, the oleo shortens with increasing roll distance until it eventually reaches "equilibrium" of increased airspring stiffness, recoil damping force, and runway unevenness.

The rather dramatic effect of recoil damping on peak loads on tyre and U/C attachment (nose U/C) is demonstrated in Fig. 9. By reducing the recoil damping force coefficient to one half of its original value, peak load on the tyre could be reduced to 57 % of its original value while peak load transferred to the U/C attachment was lowered by 20 %. This result was achieved without undue compromise in landing behaviour of the A/C.

4. STRUCTURAL RESPONSE OF AIRFRAME

Provided the U/C were capable to operate on a runway in bad condition it is still questionable if the structural flexibility of the airframe and the strength limits of the airframe or other components (e.g. external stores) will not cut back this capability to a lower level.

Since the bulk of literature on structural response deals with inflight problems and comparatively little is published on structural response to undercarriage forces, [e.g. Ref. 5] some special aspects of the problem are addressed in the following.

4.1 Retroaction from Airframe Flexibility to U/C

The capability of the tyre to roll on a runway in bad condition is rather unsensitive to structural vibrations of the airframe. Depending on the general arrangement of the U/C, in most cases accounting for rigid body heave and pitch and for the lowest structural mode exhibiting primarily vertical bending is sufficient for the nose U/C; for fuselage-mounted main U/C even rigid body heave alone may be sufficient.

If U/C "climbing" could become important, higher frequency bending modes must be looked at. This can be done in a first step by calculating responses for single structural modes by means of simple and easy-to-run models like the one shown in Fig. 10.

When judging the influence of different structural modes one must keep in mind that the validity of the tyre/oleo strut/onepoint U/C leg attachment model reduces with increasing frequency. This is due to several reasons, as for instance:

- o Tyre models mostly do not contain damping.
- o Structural flexibility distributed over the length of the U/C produces up to 10 % of the total static vertical displacement of the wheel hub relative to the attachment.
- o The equation for the hydraulic damping force does neither account for instationary high acceleration/small displacement processes nor for backlash in switching from compression to recoil damping.
- o U/C's mostly are attached at three points distributed over a considerable area (what is the real displacement of the structural mode with respect to the U/C leg?)
- o Local flexibilities of the U/C attachments are not accounted for.

Although it is possible to eliminate some of these deficiencies of the U/C model, this investment does not appear worthwhile if only U/C loads are to be considered.

4.2 Airframe Structural Loads

Aircraft with wing-mounted main U/C's gain some reduction in peak vertical U/C load during landings due to impact energy being stored in the elastic structure of the wing.

However, this advantage is turned into a disadvantage when heavy stores are carried under wing: In landing all three load components at the wheel, namely vertical, fore and aft, and lateral gain considerable magnitude and excite vertical bending and torsional oscillations of the wing, which may produce beyond-design conditions at the external stores.

Modern computers are big enough to cope with a model containing six nonlinearized rigid body degrees of freedom, fully nonlinear U/C legs with three dimensional attachment flexibilities, and say 10, 20, or 30 structural modes of the airframe. Although it may be alright to use such a huge model for determining rational design loads (but watch the validity of the model!), we feel that assessing structural limitations of an aircraft with respect to rolling on damaged runways must be done with less expenditure.

This probably can be achieved by running simplified models similar to that shown in Fig. 10 on "representative" damaged runway profiles and by filtering out those structural modes which really pertain to the problem.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on simulations of the F-104G it was demonstrated that on the U/C side a considerable potential might exist to improve A/C performance on runways in bad condition.

However, this is only a partial answer to one facet of the question, how fast and in which number our aircraft can be airborne after an enemy attack on the runway.

We at MBB feel that this question represents a classical model of an interdisciplinary optimization task. In our opinion this truly complex task should be tackled in the following way:

- Let experts in runway construction and experts in runway destruction set up a damage classification scheme, which can be easily applied on site.
- Let experts in rapid runway repair determine to what extent runways pertaining to a certain damage class can be repaired after half an hour, one hour, four hours .....
- Perform destructive tyre tests in order to gain data on failure probability on damaged runways.
- Let experts in U/C and structural load dynamics compare the capabilities of the aircraft with the runway standards.
- Perform strategical/tactical/financial trade studies of runway repair quality requirements versus aircraft improvement.
- Devise a means (perhaps tables or charts; Fig. 11) which correlates aircraft capabilities to runway initial damage class and repair standard, in order to support command decisions.
- Introduce runway damage into the design criteria for new aircraft.

This enumeration of tasks is far from being complete. However, the problem has been recognized and first steps to its solution have been undertaken.

REFERENCES

1 A. Krauss, G. Kempf: Theoretische Untersuchung der Fahrwerksbeanspruchung F-104G beim Überrollen von AM 2 Matten, Teil 1; Dezember 1979, MBB-Bericht Nr. 452-69

2 A. Krauss, G. Kempf: Theoretische Untersuchung der Fahrwerksbeanspruchung F-104G beim Überrollen von AM 2 Matten, Teil 2; Mai 1970, MBB-Bericht Nr. UFE 689-70

3 Bundesamt für Wehrtechnik und Beschaffung (BWB AFB-LG III): Ermittlung der Fahrwerksbelastungen beim Überrollen von unebenen Start- und Landebahnen (AM 2 Bodenbelag-Matten); 1979.

4 John R. McGehee and Huey D. Carden: A Mathematical Model of an Active Control Landing Gear for Load Control during Impact and Roll-out; February 1976, NASA TN D-8080.

5 J. Ijff: Analysis of dynamic aircraft landing loads, and a proposal for rational design landing load requirements; 1972, Technische Hogeschool te Delft (Netherlands).

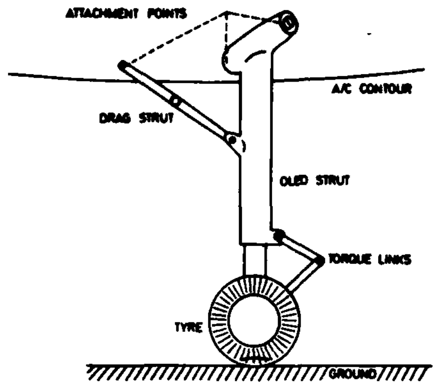

FIG. 1 OLEO-PNEUMATIC U/C LEG

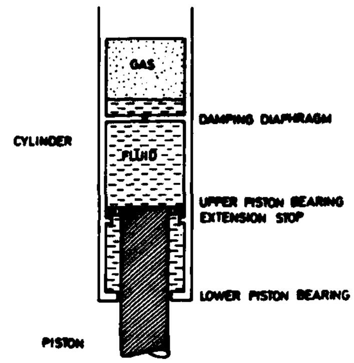

FIG. 2 OLEO STRUT (SCHEMATIC)

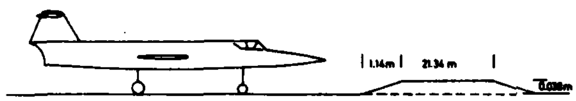

FIG. 3 BASIC SITUATION (AM 2 MAT)

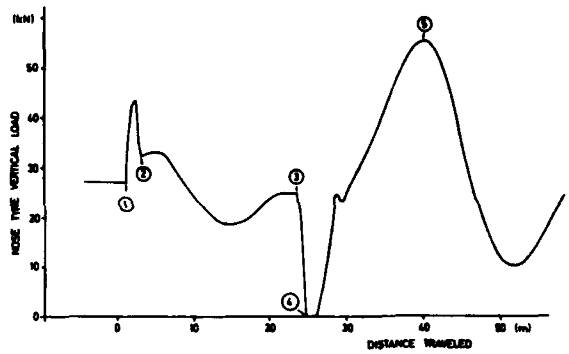

FIG. 4 GROUND REACTION AT NOSE TYRE

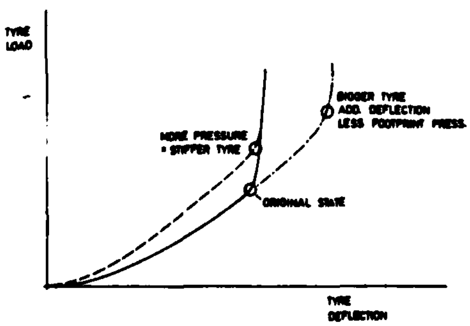

FIG. 5 SHIFT OF TYRE BOTTOMING POINT

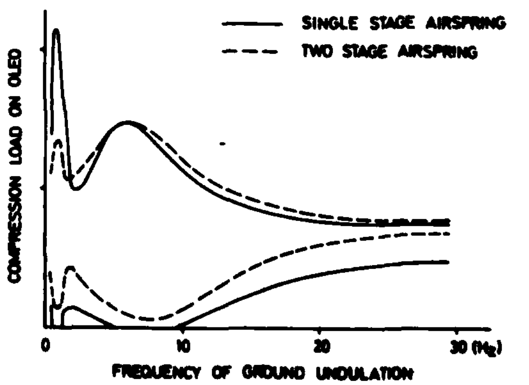

FIG. 6 SINGLE STAGE VS. TWO STAGE AIRSPRING

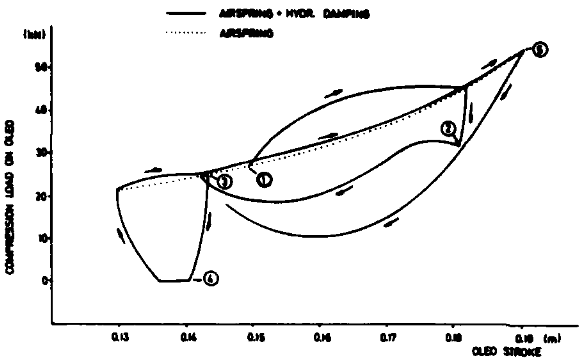

FIG. 7 OLEO LOAD PERTAINING TO GROUND REACTION OF FIG. 4

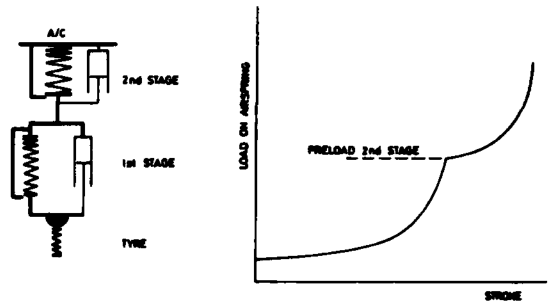

FIG. 8 TWO STAGE AIRSPRING

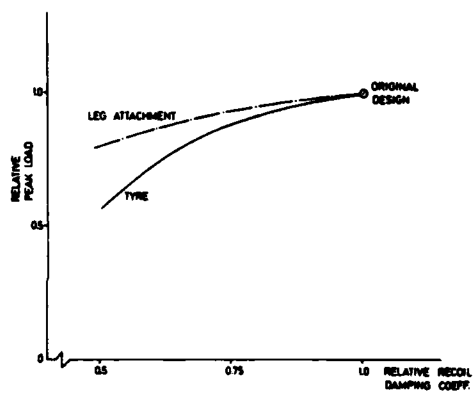

FIG. 9 INFLUENCE OF RECOIL DAMPING

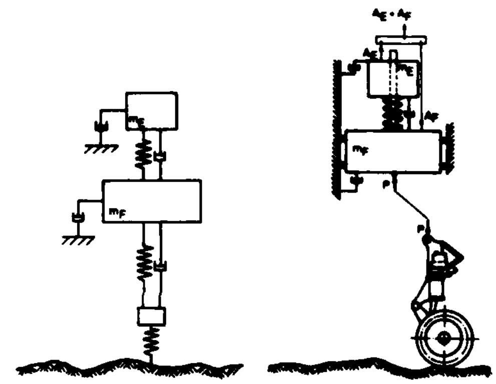

FIG. 10 SINGLE ELASTIC MODE MODEL

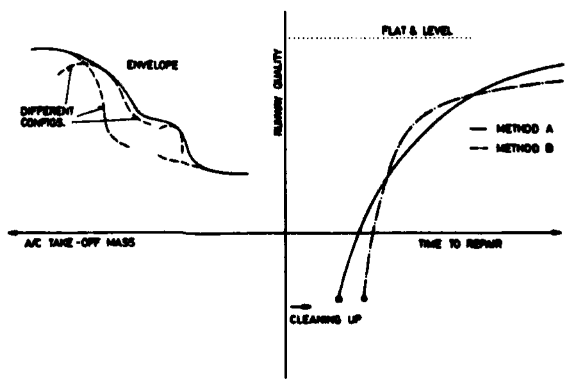

FIG. 11 OPERATION FEASIBILITY CHART (OFC)

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14. Abstract

The three papers included in this Report were presented as the first stage of a study of the potential problems of aircraft dynamic response to damaged and repaired runways, and arrived at the following general conclusions. For small aircraft with relatively simple landing gear, the operation over nominal repairs was dominated by rigid body motions of the aircraft. The prediction of those motions was possible and compared reasonably well with experimental data. For larger aircraft or aircraft with large external stores, the prediction of detailed loads in critical areas has met with limited success so far. Since landing gear equations are highly nonlinear, the prediction of aircraft dynamic response has required time-consuming numerical integrations. Also, the behaviour of large external stores can be affected by nonlinear effects (such as rigging loads), and both landing gear and external stores nonlinearities are affected by aircraft servicing procedures and by the ambient environment.

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