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SHOCK AND VIBRATION BULLETIN

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FOREWORD

These Symposia were organized just a year ago on 7 January 1947. At that time a need existed for the interchange of technical information among naval activities working in the field of shock and vibration. The Naval Research Laboratory was designated as the centralizing agency, with the specific assignment to collect, correlate and disseminate all the scientific information in this field.

During the first year, interest and participation in the work of the Centralizing Unit have expanded beyond original expectations. Every phase of this program has been wholeheartedly supported by all branches of the Armed Forces. In addition, the British have contributed to the meetings and discussions, for the benefit of all concerned. Measured in size, the attendance at the meetings has increased, the diversity of the subject material has expanded and the Bulletin has grown.

Certain achievements have been attained and further worthwhile results are expected in the future. Personnel from many of the participating organizations have expressed themselves on this subject. They have affirmed that their technical work and their workers have benefitted from the meetings, from the discussions and from the Bulletin. Seven technical Symposia were held in the Washington area during 1947. Those in attendance inspected and observed the facilities and instrumentations used at the different local laboratories for studying shock and vibration. Lists of the uncommon equipments available at various activities were published in the Bulletin. The technical subjects of the meetings included a brief survey of the tests and experiments on surface ships and submarines when subjected to shock and vibration. The way in which shock affects the various phases of ordnance developments was outlined. The problems of operating military land vehicles, with their equipments and instrumentations, were examined. This bird's-eye view of past achievements in the field of shock and vibration brought into focus many unsolved problems. All of the material which was presented at the meetings, together with the discussions which followed each paper, was published in six separate Bulletins and distributed to all participating activities.

A start has been made toward the goal of correlating research information in this broad subject, by means of these Symposia and technical discussions. In the light of accumulated knowledge and experience in shock and vibration, the participating activities may now proceed more directly with the job of interchanging and disseminating the research information, so urgently needed by all workers in this field. The designer and builder must be provided with useable, systematic knowledge instead of rule-of-thumb procedures. Scientific progress and steps in the accomplishment of the mission will then be made.

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THE EIGHTH SYMPOSIUM
Naval Research Laboratory
7 January 1948

EFFECT OF SHOCK AND VIBRATIONS ON STRUCTURES

By

Henri Marcus, BuY&D

Impact and vibration problems affecting Bureau of Yards and Docks design of structures are enumerated briefly. The factors which determine the dynamic resistance of structures subjected to explosive forces are discussed. Mention is made of the research work now in progress and of the methods to determine the most favorable conditions for location of bombproof tunnels.

INTRODUCTION

The analysis of the effect of shock and vibrations on structures involves quite a number of problems on which much work has been done by the Design Division of the Bureau of Yards and Docks and yet much work remains to be done.

One of our problems is the resistance of structures to such very short-timed forces as, for instance, earthquake forces, the blast caused by an explosion, or the impact of a ship striking against a dolphin or pier while approaching a mooring berth.

We have to deal also with forces pulsating more or less regularly during a longer time as, for instance, the pressure produced by a wind gust or the impact caused by an imperfectly balanced locomotive on a bridge. Still other forces are those due to irregularities in the track and flat spots on the wheels, or the successive blows of a hammer driving a pile.

Another set of problems is, for instance, the analysis of the vibrational characteristics of a concrete framework supporting an engine rotating at high speed, or the analysis of the dynamic stability of suspension bridges.

I shall give you a brief outline of our studies on the one problem which to us is the most important and the most difficult: the problem of the resistance of structures to explosive forces.

EFFECT OF THE BLAST ON SURFACE STRUCTURES

Let us consider first the effect of the blast produced by atomic or high-explosive bombs on surface structures.

Here we face two difficulties. The first is to obtain a reliable picture of the magnitude, distribution, and duration of the forces acting on the structure. The second is to analyze the response of the single members of the structure as well as the motion of the whole structure and the soil reactions.

Distribution and Duration of the Explosive Forces.

Although we do possess charts which indicate the peak pressure exerted by bombs of different types and weights exploding at various altitudes on targets

located at varying distances, we do not know to what extent the effective duration of the pressure is dependent on the size and shape of the target. Many observations indicate that a structure which is relatively low but very long will develop a resistance to the flow of the blast different from one which is very high but narrow. Cylindrical and dome-shaped structures also show resistances different from prismatic structures.

Moreover, isolated structures of a certain type do not seem to react the same as structures of the same type grouped closely together.

A wide research program is needed for a correct and complete evaluation of the various factors affecting the distribution of the blast in time and space.

If the duration of the impulse is considerably greater than the time required for the travel of a pressure wave from the front to the back face of a structure, we may assume as a first approximation that both faces are subjected simultaneously to triangular impulses of different magnitudes.

Vibrational Characteristics

Since the response of a structure is dependent on the simultaneous action of all its elements, our problem is to determine the vibrational characteristics of the whole structure. We must take into account all members, like beams and frames or partition walls, connecting the front with the back face and, last but not least, the interference of the soil deformations. In this investigation we have to study various types of structures, such as trusses, frames, arches, and cylindrical and spherical shells.

The knowledge of the period of the vibrations is necessary because it is the ratio of this period to the duration of the impulse and the shape of the impulse diagram which govern the magnitude of the dynamic stress and strain.

Dynamic Stiffness. - One of the factors affecting the period is the stiffness EI, E being the modulus of elasticity of the material, I, the moment of inertia of the sections. We may assume that for each member of the structure, the product EI has a constant value, but we must bear in mind that this dynamic stiffness factor is not necessarily identical with the value of EI derived from static tests. This distinction is especially necessary for structures in reinforced concrete. In fact, an analysis of the results of impact tests performed on reinforced concrete beams at the University of Illinois during the war indicates that the formation of cracks in the concrete and a subsequent yielding of the reinforcing steel reduces considerably the stiffness of the beams. The analysis further indicates that the development of plastic strains does absorb a greater amount of strain energy.

Kinetic Energy and Energy of Deformation. - It is on account of this increased flexibility that the impact test specimens were able to withstand a kinetic energy many times greater than the energy of deformation required to produce a rupture in static tests, without suffering damage which would reduce appreciably their static strength.

Various hypotheses were advanced to explain this considerable difference between dynamic and static strength and various conclusions were drawn from these tests results. The most significant for our design purposes is the contention that a reinforced concrete structure is able to withstand an extremely short-timed dynamic stress ten times as great as the ultimate static stress.

The validity of this assumption seems more or less questionable, and for this reason an experimental investigation of the dynamic resistance of structures was

initiated recently by both the Army and the Navy. The National Bureau of Standards and M.I.T. are working on various aspects of this subject. This new research requires the development of instruments and methods for measuring the magnitude and duration of the impulsive loads acting on the specimens of the deflections and strains of these specimens and, last but not least, of the motions of the supports. This is by no means a simple problem.

A correct interpretation of the test results will also lead to a further development of the mathematical analysis of the dynamic response of systems with nonlinear characteristics.

Such a broad research program is indispensable for a sound and a rational design of structures which must withstand such terrific forces as those produced by high-explosive or atomic bombs.

EFFECT OF THE BLAST ON UNDERGROUND STRUCTURES

The necessity of providing a protection against these forces leads to the problem of the resistance of underground structures to subsurface explosions. Here again, the first task is to determine the magnitude and duration of the stresses and strains induced by the explosion in the soil layers surrounding the structure.

Research on the Effects of Underground Explosions. - The results of the important research work made during the war by the Committee on Fortification Design on this subject are condensed in empirical equations which give, for certain types of soft soils, the peak pressure exerted in a radial direction at any distance from the point of explosion, the total value of the positive impulse, the magnitude, velocity and acceleration of the displacements of the soil particles, and the dimensions of the crater produced by the explosion. The main factors in these equations are:

1) the type, weight and buried depth of the charge,

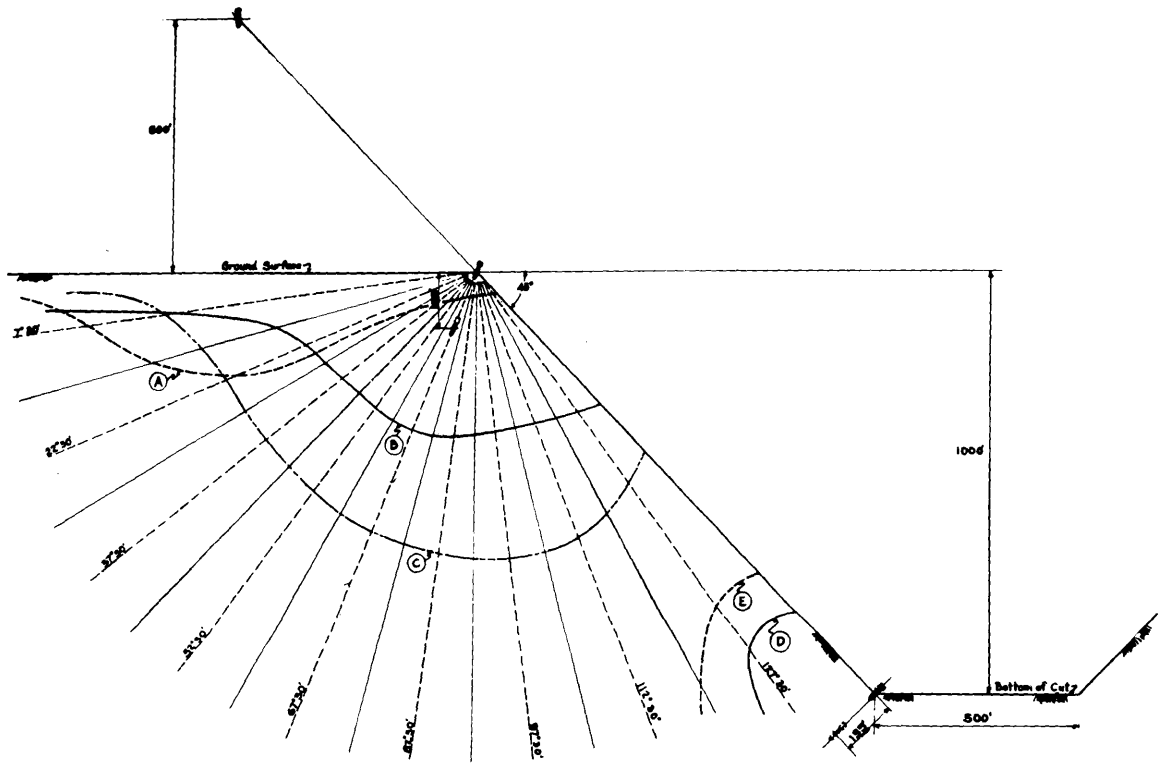
2) the distance from the point of explosion, and

3) a set of soil constants which depend upon the soil density and upon the velocity of propagation of seismic waves through the soil.

The correlations expressed by these empirical equations are a very valuable help in evaluating some effects of underground explosions. However, there is an urgent need for a more complete and more consistent analysis of these effects, especially for such material as rocks, which, as mediums of propagation of shock waves, have not yet been investigated.

A new and very wide research work, recently initiated by the Army, deals with the effect of charges up to 320,000 pounds, exploding at varying depths in various compressible soils and rocks on different types of structures, located at various depths and at various distances from the point of explosion. The results of this research will be used to determine the critical radius of damage for both surface and buried structures and the necessary overburden for deep tunnels. These findings will help us in establishing rational criteria for the design of structures.

A correct evaluation of the data already obtained from the former tests and expected from the new tests requires a further development of a theory embracing the whole mechanism of the explosion. Our actual studies show, for example, that in order to compute the stress and strain produced by the explosion, the size and shape of the crater and the deformation of the soil layers, we have to know not only the conditions determining the propagation of the radial pressure, but also the tensile stresses in surfaces normal to the radial pressure. These stresses, which



ZONES OF RUPTURE FOR VARIOUS EXPLOSION CONDITIONS

(A) Limit of the Z. of R. for a bomb exploding at 600' height

(B) Limit of the Z. of R. for a bomb exploding at the surface.

(C) Limit of the Z. of R. for a bomb exploding 135' below the surface

(D) Limit of the Z. of R. for a bomb exploding at the bottom of the slope

(E) Limit of the Z. of R. for a bomb exploding 135' below the bottom.

Figure 1

tend to split the soil, are particularly important for such soil materials which have but a moderate tensile and shear strength. These stresses govern, for instance, the stability of the slopes of a deep cut, when an explosion above the ground adds a sudden and very heavy overburden. In Figure 1 is shown, for instance, the effect of a bomb on a 1000-foot deep cut. The shape and locations of the zones of rupture are visualized:

1) by the curve A for a bomb exploding 600 feet above the top surface,

2) by the curve B for a bomb exploding at the top surface,

3) by the curve C for a bomb exploding 135 feet below the surface,

4) by the curve D for a bomb exploding at the bottom of the slope,

5) by the curve E for a bomb exploding 135 feet below the bottom.

The evaluation of the critical conditions for a triaxial state of stress and strain is dependent upon a great number of factors affecting the strength of the soil. Unfortunately, we do not have as yet any satisfactory experimental knowledge of the resistance of soil and rock to the great variety of combinations of triaxial principal strains which may produce a failure (not even for static conditions). An urgently needed experimental research program on this subject and on the soil resistance to extremely short-

timed triaxial strains and stresses is contemplated by the Bureau of Yards and Docks.

This short description of the various theoretical and experimental studies connected with the problem of the dynamic resistance of structures to explosive forces shows how much remains to be done before a comprehensive and satisfactory design method can be established. These new investigations will require considerable time. Meanwhile we are faced with the necessity of providing, temporarily, some practical design rules for bomb-resistant structures which must be built now.

For this purpose we have to make the best use of our judgment in applying the meager data which is available today. A few indications of the considerations which guide us in the adjustment of this data to our design problems may be of interest to you.

Dynamic Resistance of a Box-shaped Structure. - Let us take, as an example, a box-shaped structure used as a model for explosive tests and shown in Figure 2. The sides of the reinforced concrete box have a length and width of 25 feet, a wall thickness of 60 inches on the front, of 40 inches on the rear, and of 25 inches on the side faces.

The pressure produced by a charge of 1000 pounds exploding at 31.5 feet from the front face was measured by gauges placed at various points on the walls. Knowing the peak pressure and the duration of the positive impulse, we may compute the explosive stresses. For this purpose it seems expeditious to assume that the side walls do not move at all. In this case the front wall acts practically as a freely supported beam. Since it is very stiff, the period of the slowest vibrations is extremely short and much smaller than the duration of the positive impulse. The bending stresses produced by the heavy shock are therefore extremely high.

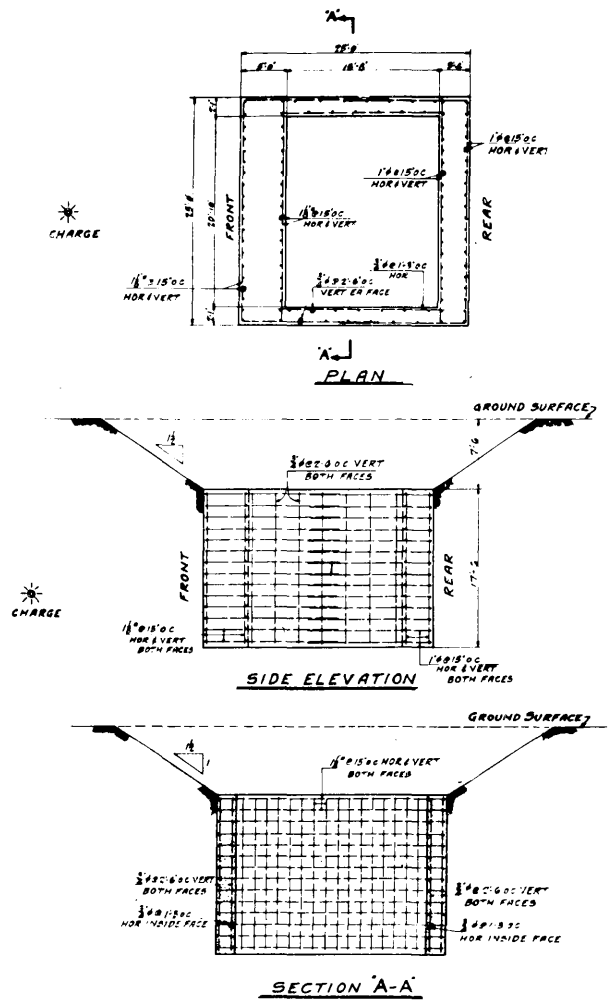
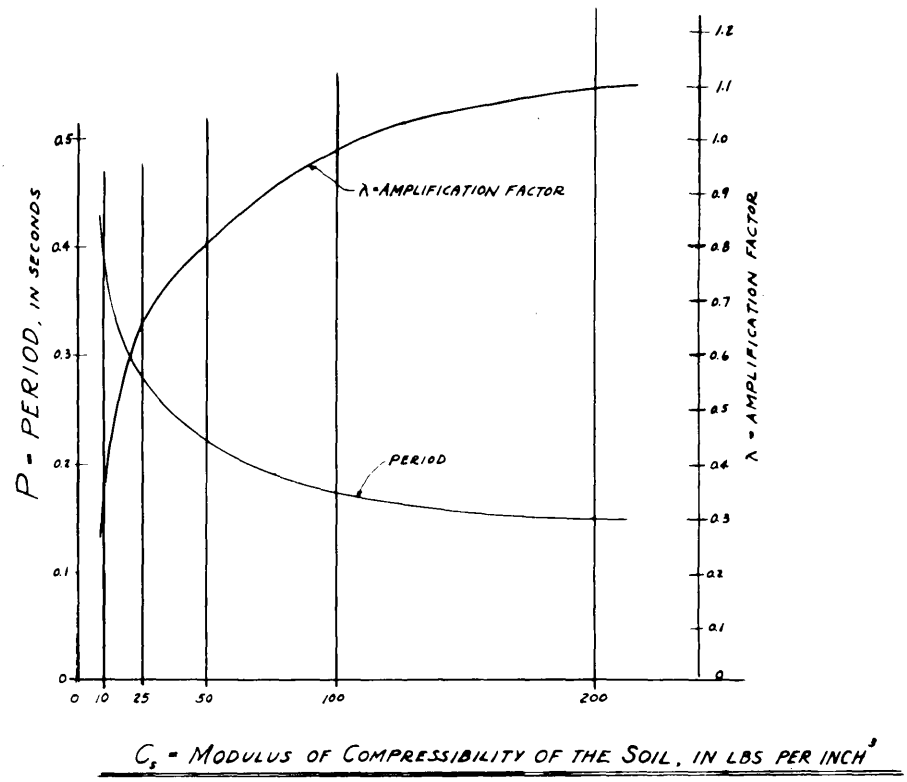


Figure 2. Details of a Typical Target

If the computations based on this conclusion were correct, the front wall should have totally collapsed. In reality, it suffered but a moderate damage. This fact can be explained only if we take into account the horizontal motion of the whole structure. This motion depends upon the compressibility of the fill on the back of the rear wall and upon the horizontal displacement of the whole soil surrounding the box.

The effect of the soil compressibility is visualized by the diagrams in Figure 3 which show that the compressibility of the back-fill is able to slow the vibrations to such an extent that the period



λ = AMPLIFICATION FACTOR CORRESPONDING TO THE DURATION OF THE IMPULSE AND TO THE PERIOD OF VIBRATIONS OF THE STRUCTURE

Figure 3

of the whole box may be twenty times as long as the period of a rigidly supported front wall. Thus, the ratio of the duration of the impulse to the period of the structure is totally changed, and the stresses imposed upon the structures are reduced, consequently, to a fraction of those which would act on a structure resting on rigid supports.

The second factor, the motion of the soil surrounding the box, also has a very significant effect.

Figure 4 shows the pressure exerted on the concrete wall AB and on the adjacent earth walls A-A' and B-B'. The energy absorbed by these earth walls produces a motion of the earth not only along the lines C'-C and D-D', but also behind the rear wall CD. It is as if the fill were pulled away from the rear wall. Thus a motion of the whole box meets much less resistance.

Since a considerable part of the energy imparted to the front wall is diverted into a motion of the whole box, the available energy for the deformation of the structure is much smaller and much less dangerous.

In fact, the test results show that only a fraction of the pressure exerted on the front wall is carried over to the rear wall and that the latter, although it has a smaller thickness and a much lower bending resistance than the front wall,

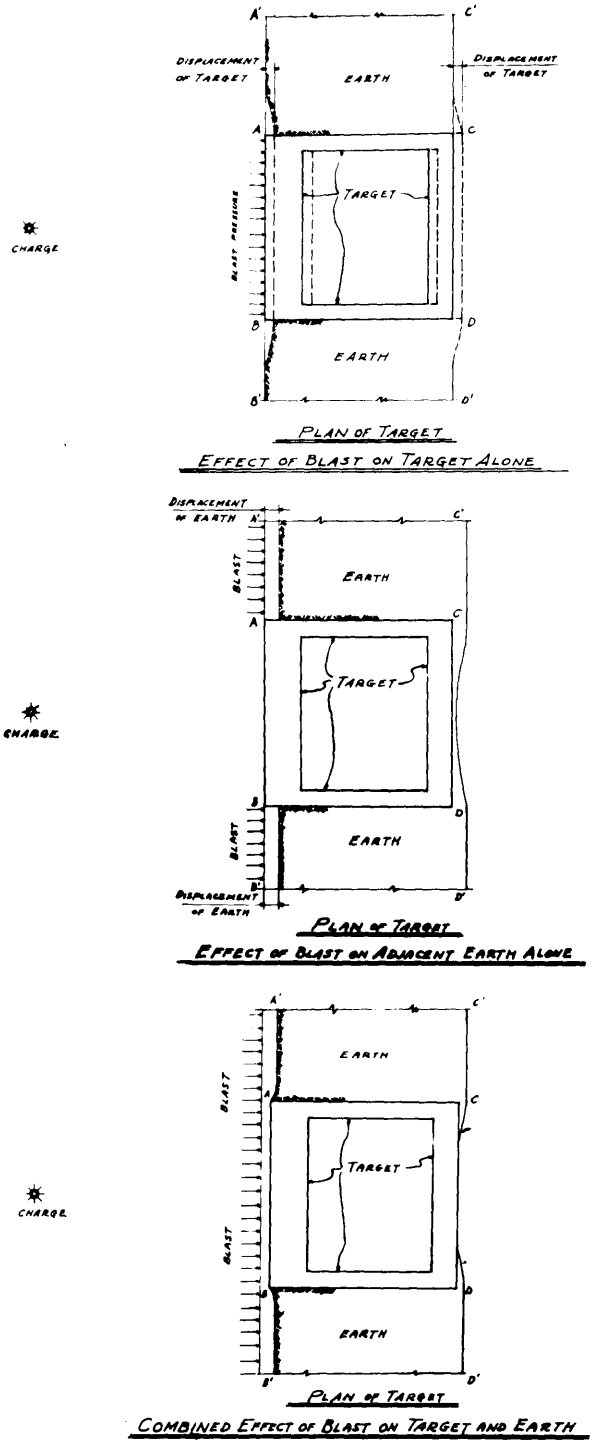


Figure 4. Dynamics of Structures

remained almost intact. The motion of the whole box is confirmed by the permanent displacement after the explosion.

These test results, which corroborate our experiences with the impact absorbed by fender piles and piers, indicate that a restraint of the motions of a structure subjected to dynamic forces is not always desirable. A structure has a much greater chance to survive the impact if its supports are able to yield and to absorb a considerable amount of kinetic energy.

Dynamic Resistance of Tunnels. - Considering from this point of view the conditions which must govern the design of underground structures, we come to the conclusion that an ideal solution is to build tunnels in such a rock material and at such depths that the rock would be able by itself, without any lining, to resist the shock.

In order to determine the bearing capacity of the rock, we have to determine (1) the permanent stress and strain produced by the tunnel opening in the layers surrounding this opening, and (2) the transient stress and strain caused by the explosive force.

Evidently, a reasonable solution of these problems is to be expected only if these layers are not composed of a weathered material, are not deformed by faults and folds and are not overstrained locally to such an extent that a further strain may produce a disintegration or a plastic flow.

Our actual theoretical studies, based on a sound homogeneous material, able to absorb a considerable strain energy, deal with tunnels of circular and elliptical shape, of various dimensions, and located at various depths.

Figure 5 shows a circular opening of 30-foot diameter located in a weak limestone at a depth of 200 feet. The state of stress in the soil above the tunnel, before the explosion, is characterized by the permanent radial stress S_r and by the

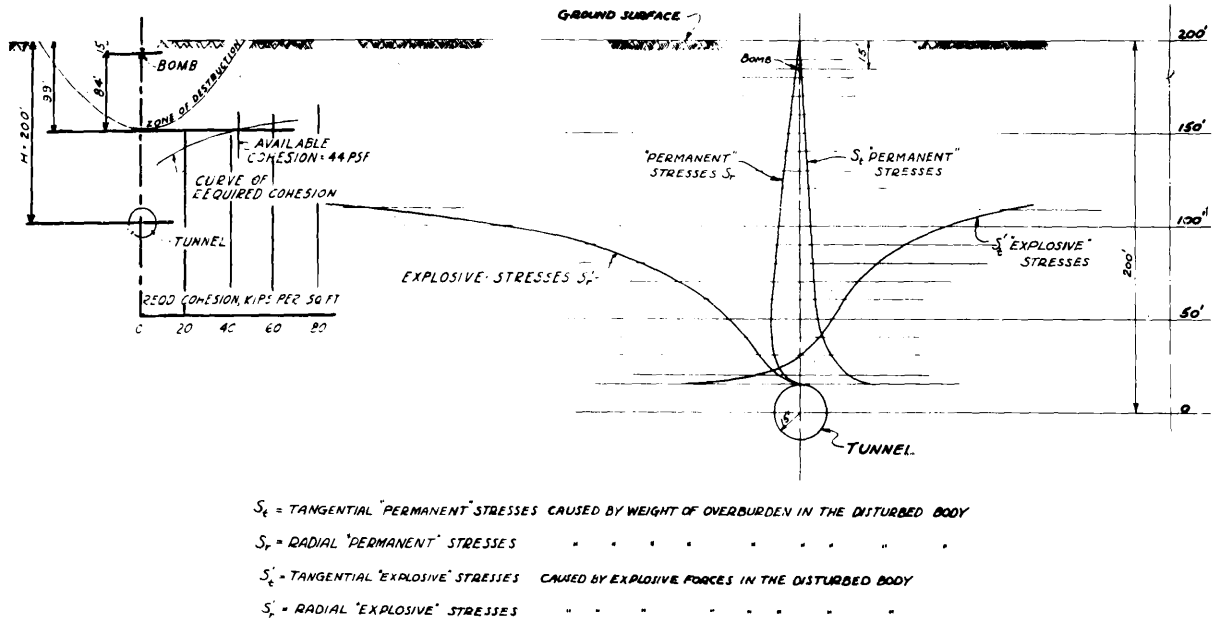


Figure 5. Stresses Along the Vertical Center Line Above the Tunnel Due to the Explosion of a Bomb at -15 Feet

permanent circular stress S_t. The additional transient stresses produced by a bomb exploding 15 feet below the ground surface are indicated by the curves S'_r and S'_t.

Combining the two sets of stresses, we determine the amount of cohesion required to withstand the resulting principal stresses and thus locate the points at which the required cohesion is equal to or greater than the available cohesion of the rock. The curve connecting these points indicates the limits of the zone in which the explosion may produce a sudden disintegration of the rock. Below this zone the cohesion of the soil is not destroyed, and if the remaining cover above the crown of the tunnel still has a considerable depth, it may be able to withstand even a second hit.

If the soil at the considered site and depth has but a moderate bearing capacity, then the tunnel opening must be strengthened by a lining.

In this case an adjustment of the lining to the deformation of the surrounding rock is possible without excessive strain only if the lining is flexible enough and if the shock is cushioned by a compressible fill inserted between the lining and the rock.

The determination of the soil reactions opposing the displacement and the deformation of the lining is based on the conditions that the energy spent in this deformation is a minimum and equal to the difference between the kinetic energy flowing through the rock at the top of the opening and the energy transmitted to the rock at the bottom of the opening. Applying these conditions, for instance, to a tunnel 30 feet in diameter, located at a depth of 150 feet and subjected to a charge exploding 15 feet below the ground (Figure 6) we see how the impact transmitted to the upper part of the tunnel is balanced by radial and tangential forces acting on the sides and bottom of the tunnel. We further see how the disturbance

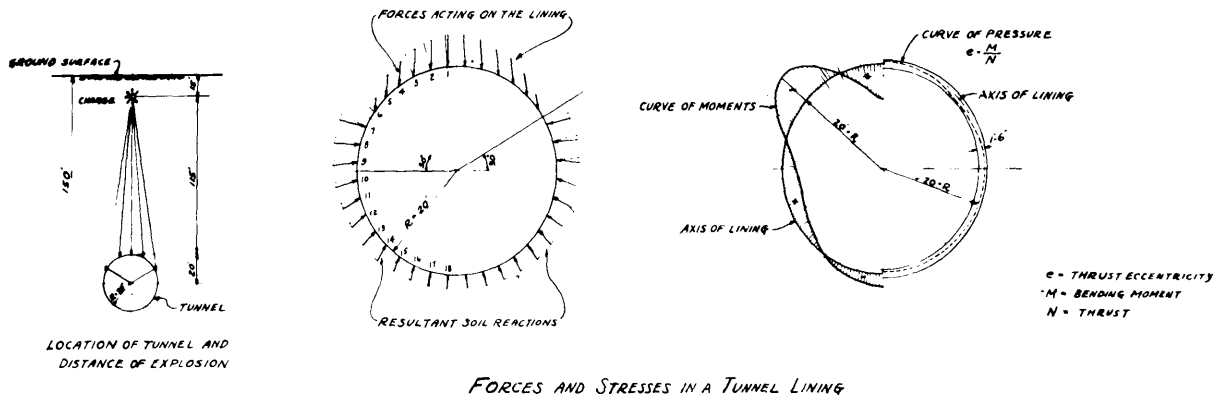


Figure 6. Design of a Tunnel Lining

of the initial equilibrium is reflected in the deviation of the curve of pressure within the lining and in the bending moments.

Note that a comparison of the explosive stresses acting on tunnel linings having a similar shape and the same thickness, but different diameters, indicates that an increase of the span does not necessarily imply an increase of the dynamic stresses. This is true since the ability for absorbing energy is relatively much greater for the lining which has the greater span and flexibility than for the short lining which is relatively very stiff.

CONCLUSION

I have attempted to give a picture of the nature and scope of the problems involved in the design of structures which must withstand the terrific strain caused by an explosive force. It is understood that our actual methods of coping with such problems are still quite rudimentary. Under such conditions, one might suppose that we have only to reduce the allowable stresses and to increase the so-called "factor of ignorance" in determining the factor of safety. Such a method would lead to structures which would be too heavy and too rigid for dynamic strains and, thus, inadequate both with respect to the safety and to the costs of the structures.

A rational design will be possible when the results of the new research work on the dynamic resistance of soils, materials, and structures will have cleared the way to a satisfactory solution of our difficult impact problems.

DISCUSSION

J. T. MULLER, BELL TELEPHONE LABORATORIES: Would it be possible for Dr. Marcus to explain Figure 5 once more?

HENRI MARCUS, BUDOCKS: Figure 5 shows the magnitude and distribution of the principal stresses along the vertical center line above the tunnel; S_r is the vertical, S_t the horizontal pressure. We have to consider two sets of stresses: the permanent stresses acting on the soil before the explosion, and the additional transient stresses produced by the explosion. Our problem is to determine the amount of strain energy corresponding to the combined effect of the two sets of stresses and to check whether and where this total energy exceeds the critical strain energy of the soil.

In this analysis we have to take into account that the modulus of elasticity of the extremely short-timed explosion strains is not identical with the conventional modulus of static strains.

H. M. TRENT, NRL: What is the ratio of the duration of impulse to the period of the structure? Do you find it necessary to consider some of the higher modes and, also, what is the frequency distribution of those?

HENRI MARCUS: As shown in Figure 3, the period of the slowest vibrations varies, according to the compressibility of the soil, between .02 second for an extremely stiff soil and .4 second for a very soft soil. The duration of the positive impulse being .03 second, the ratio of the duration of the impulse to the period of the structure varies between 1.5 and .075.

The effect of the higher modes of vibration was not taken into account, because the response of the structure is largely dependent upon the motion of the whole structure and of the surrounding soil, and much less on the higher modes of vibration.

L. M. BALL, NOL: In several of the figures, you show underground explosions and speak of 15 feet underground. What are the conditions of bomb explosions underground; for example, the delay element in one creating a cavity and then exploding later.

HENRI MARCUS: The effect of underground explosions is dependent upon many factors, such as shape, weight, burial depth of the charge, nature of the soil, etc. In order to determine the strain imposed upon the soil surrounding the tunnel opening, we must know the amount of explosive energy induced into the soil. This energy follows the path of least resistance and will be absorbed to a much larger extent by a soft, compressible soil than by a stiff rock.

IRWIN VIGNESS, NRL: You mention that you measured pressure on top of a concrete, structure. I wonder what the pressure wave looked like.

HENRI MARCUS: The box-shaped structures, used for the model tests, were composed of four walls, without any top or bottom slab. The blast pressure was measured on the front and on the rear walls. The tests indicated that the peak pressure on the rear was but a small fraction of the front pressure, although the time required for the travel of the pressure wave from the front to the rear is very small.

Information on the shape of the pressure wave is given in the report on the tests; a systematic evaluation of this information has not as yet been performed by our group.

R. L. BISPLINGHOFF, MIT: I would like to make an addition to Dr. Marcus' comment relative to the importance of ratio of applied period to natural periods of structure. He mentions that it is one of the most important factors in transient problems. This is true. However, an almost equally important factor is the mode shape. The ratio of periods gives an indication of how much each of the various modes are excited. However, in actually computing the stress distribution in the various modes, the most important factor is the mode shape. This situation makes the transient problem unique as compared to other dynamic problems involving resonance and stability in which an accurate knowledge of the mode shape is not nearly so important. Therefore, in design work involving transient stresses, it is desirable to define the mode shapes as accurately as possible.

HENRI MARCUS: The statement of Prof. Bisplinghoff is correct. In our study of the effects of shock on structures, various shapes of impulses--such as rectangular, triangular, parabolic, and hyperbolic--were investigated. An exact computation of the dynamic stress is, in many cases, extremely difficult because the

shape of the impulse imparted to the front wall is not necessarily similar to the impulse received by the rear wall.

C. J. BASTIEN, NRL: Regarding the travel of explosives, we had a problem in the Army of placing a charge and getting away from it. If you put anything on the charge, a great deal more damage is done. If you take off your hat and lay it on the charge, more of a crater is formed than if you just put an ordinary charge on the ground.

H. M. FORKOIS, NRL: Do you have any information regarding vibration isolation and the nature of the soil surrounding the building? Would you select one type of vibration isolation for rocky and another type for muddy soil?

HENRI MARCUS: Much attention is given by our design section to the problem of finding an adequate method for preventing the transmission of vibrations or reducing the impact. The selection of the insulating material is dependent upon many factors: nature of the medium through which the shock is propagated; size and shape of the structure; local conditions, such as the compressibility, moisture content of the surrounding soil, changes in the elastic properties of the insulating material; etc.

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VIBRATION PROBLEMS IN AIRCRAFT

By

James E. Walsh

Bureau of Aeronautics

The method of vibration isolation of reciprocating engine-propeller combination is described. Present specifications for allowable cockpit vibrations are discussed critically. Finally, a brief comment on the problems of turbo-jet and prop-jet engine vibration isolation is presented.

The purpose of this paper is to give a brief survey of the vibration problems encountered in naval aircraft and to describe the ways in which these difficulties have been overcome. My discussion will be confined largely to those vibrations induced in the fuselage by the engines and the propellers. Aerodynamically excited vibrations of the wings, tails, and control surfaces are covered in the other papers.

The principal sources of vibration in an aircraft fuselage are the various unbalances in the propellers and in the engine. In a radial type reciprocating engine, unbalances of the rotating and reciprocating parts cause first and higher order vibrations of the engine in pitch, yaw, lateral translation, and vertical translation. One-half, first, and higher order vibrations of the engine in roll are excited by fluctuations in the torque reaction in the cylinders. Vibrations in yaw, pitch, lateral translation, and vertical translation at first order propeller frequencies result from static unbalance of the propeller, misalignment of the blades, failure of the blades to track properly, and unequal aerodynamic loads on the separate propeller blades. In addition, a rather complicated array of higher order propeller vibrations are present.

Theoretically, most of these sources of vibrations are not inherent unbalances and so could be eliminated by accurate machining and proper maintenance of the engine and the propellers. However, while an attempt is made to keep these unbalanced forces at a minimum, it has been found impossible under practical operating conditions to reduce the engine and propeller excited vibrations to a point where, with a rigidly mounted engine, the resulting fuselage vibrations are at a satisfactory level. Because of this, the reciprocating engines and propellers on all naval aircraft are flexibly mounted.

The flexible mounting system used is called "Dynamic Suspension." This system utilizes a ring of directional spring attachments located at the rear of the engine, which are designed to give true center of gravity support to the engine-propeller combination, thus decoupling the modes of vibration of the system. The development of "Dynamic Suspension" was required because of the necessity of locat-

ing the engine mount attachment points well to the rear of the center of gravity of the engine-propeller mass. This method of mounting has been described in several papers, such as the article by Mr. Browne, of the Wright Aeronautical Corporation, in the SAE Journal of May, 1939. The mounting systems are designed so as to be stiff longitudinally, since there are usually no important longitudinal vibrations excited, and soft enough in the other five degrees of freedom so that first and higher order vibrations of the engine and the propeller are effectively isolated.

While the engine and propeller unbalances have, in the past, proven to be the major source of fuselage vibration, some vibration difficulties have also been experienced whenever the tips of the propellers were allowed to pass too close to the fuselage. The fuselage wall at or near the plane of the propeller disk would, under those conditions, vibrate at the propeller passage rate, because of the pressure fluctuation which the propeller blades induced on the side of the fuselage.

With the development of large, high powered aircraft with large diameter propellers, this problem has become a major one. For example, one naval aircraft, a large flying boat, has four 3000 h.p. engines with large four-bladed propellers, the tips of which pass 27 inches from the hull of the aircraft. At full power, the fuselage wall at or near the plane of the propeller disk vibrates at a frequency corresponding to the propeller passage rate, with amplitudes of as large as .06 inch double amplitude. Equipment, such as the navigation table, vibrates at such an amplitude as to make work impossible, and the sound level in the cabin is as high as 127 decibels.

Analysis of the different airplanes in which this problem has appeared indicates that the vibrations are not resonant vibrations. The solution, therefore, appears to require (1) reduction of the forces themselves by such means as the use of smaller propellers and (2) stiffening of the fuselage wall. A program has been instituted to determine the magnitude of the forces involved and to compute the effect of varying tip speed, tip clearance, etc. When this has been completed, a more rational approach to the problem will be possible.

The vibration problems in aircraft powered by turbo-jet engines can be summed up quite briefly with the statement that the experience of the Navy indicates that low-amplitude, high-frequency vibration associated with turbo-jet engines can be screened out adequately with simple, resilient pads incorporated in the engine mounts.

There are three different effects of vibration which are of concern in aircraft: (1) the effect on the structure, (2) the effect on the instruments and other equipment, and (3) the effect on the personnel.

In regard to the structure, the engine isolators generally are adequate to prevent any resonances which might cause structural failures due to engine or propeller vibrations. The vibrations set up by the propeller tip passage have been large enough to cause local breaks in the fuselage skin, but, in general, it appears that vibration failures of the primary structure from that source is not a major problem.

The problem of the vibrations of the instruments, radio equipment, etc. has also been adequately handled by using rubber mounts on the instrument panel and on the other equipment sufficiently delicate to require shock mounting.

The third problem, the effect of vibration on the flight personnel, is the most difficult to handle. The various sources of vibration on an airplane set up vibrations at frequencies ranging from 15

to 75 cps at amplitudes which, while not great enough to cause structural failures, are sufficient to cause considerable fatigue and discomfort among the personnel, with a resultant impairment of their efficiency.

Before a specification can be devised giving the allowable vibrations on an airplane, an attempt must be made, of course, to determine the magnitude of the vibration which will result in discomfort to a human being. In 1932, Mr. H. Constant, of the Royal Aircraft Establishment, made an attempt to determine these thresholds of comfort. He seated his assistants on the end of a beam, which he could vibrate at various amplitudes and frequencies, and requested them to define the limit of unpleasant vibration. The limits at which he arrived were .009 inch amplitude at 750 cpm, .004 inch at 2000 cpm, and .003 inch at 5000 cpm (which was the upper limit of the frequencies). Unfortunately, however, there is some uncertainty as to whether by "amplitude" he meant single amplitude or double amplitude, whether the subject was seated on a parachute pack or on the hard board, and, in addition, whether the limits included observations made with the subject standing.

Other studies, such as those by Reiher and Meister, indicate that the threshold of comfort for frequencies of about 5000 cpm is around .0003 inch amplitude, which is considerably smaller than the thresholds according to Constant.

On the basis of these and other reports, the Bureau of Aeronautics now specifies that cockpit vibrations in naval aircraft must not exceed .004 inch double amplitude. This requirement was intended for reciprocating engine aircraft, but it is also being applied to jet aircraft until measurements at the higher frequencies are available, because it is thought that it is, if anything, on the conservative side. The Naval Medical Research Institute is engaged in a program to investigate this problem in a systematic manner, and it is hoped that a much more rational specification can be written after the results of that program are available.

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THEORETICAL AND EXPERIMENTAL RESEARCH ON FLUTTER IN AIRCRAFT

By

L. P. Clark,

NAES, NAMC, Philadelphia, Pa

Deals with the conventional theoretical approach to flutter calculations, flutter model testing, and flutter flight test techniques. Emphasis is placed on flight flutter studies as conducted in Europe and this country.

INTRODUCTION

Due to their destructive natures, flutter and other forms of aero-elastic instability are among the most important problems in any phase of engineering. Accordingly, aircraft contractors and procuring agencies have been inclined to give serious consideration to these problems during the past few years, especially since the size and speed of aircraft have increased so rapidly.

Historically, the work of Theodorsen in this country, Birnbaum, Kussner, and Ellenberger in Germany, and Duncan and Frazer in England comprised the most important early investigations of the problem. Theodorsen's researches yielded a reasonably complete theory of the two dimensional airfoil as well as a detailed computation scheme for the determination of the critical flutter speeds for binary and ternary modes. In the early days of the airplane, flutter was considered to be a purely mechanical phenomenon; but more recently it has been treated as an aerodynamical problem, and many investigators have concerned themselves with studying the nature of the air forces, non-stationary potential flow, the unsteady lift of the oscillating airfoil, and related topics.

Flutter is defined as "an oscillation of definite period but unstable character set up in a part of an aircraft by a momentary disturbance and maintained by a combination of aerodynamic, inertial, and elastic characteristics of the member itself." This means that flutter is an example of dynamic instability of an aircraft structural component for which requisite energy is furnished by the aerodynamic forces and moments. The inertial and natural frequency characteristics of the structure combine with the airstream velocity in a manner such that energy is absorbed from the airstream and is used to continually increase the amplitudes of the oscillations until the structure is permanently deformed, or until failure occurs.

The most general requirement for the existence of flutter in any given system is that two or more types of motion of the

components of the system be capable of existing simultaneously. Further, these motions involved must be coupled so that a force producing motion in any one of the degrees of freedom will also cause forces and resulting motions in the other degree, or degrees, of freedom. There are many examples of such couplings existing in aircraft structures, and it is practically impossible to isolate the motion of any structural component of an aircraft so as to preclude the possibility of motion of some other component. In an airplane wing, mass unbalance of the aileron acts to produce such coupling between the motion of the wing and the motion of the aileron.

MATHEMATICAL APPROACH TO THE FLUTTER PROBLEM

Derivation of Equations

In this discussion we shall restrict ourselves to consideration of a wing-aileron system with three degrees of freedom: the bending and torsional deflections of the wing, and the rotation of the aileron about its hinge line. The theory of small oscillations is applied to this system which is non-conservative, since it absorbs energy from, or loses energy to, the surrounding air. However, the overall system, including the air, wing, and aileron, may be treated as a conservative system, providing the viscosity (friction) of the air is neglected.

The general procedure is to obtain the equations of motion for a system such as that described above. This can be done by obtaining the total forces and moments acting and setting up the equilibrium conditions. The aerodynamic forces and moments on an oscillating wing-aileron combination with three independent degrees of freedom have been determined independently by Theodorsen, Kussner, and others, and are in exact agreement. The differential equations of motion have been obtained by Theodorsen by expressing the equilibrium conditions of the moments of the entire wing about its axis of rotation, of the moments of the aileron about its hinge line, and of the vertical forces on the wing at the mid-chord point. Another method of obtaining the equations is to determine expressions for the kinetic and potential energies for each degree of freedom and to derive the Lag range equations therefrom.

Solution of Equations

The solutions of the equations of motion are obtained by making substitutions of the form

$$q_j = Q_j e^{i(\omega t + \epsilon_j)}$$

where ω = flutter frequency, q_j = coordinate of the jth degree of freedom, Q_j = the maximum deflection, and ϵ_j is the phase angle with respect to a given reference line. The determinant of the coefficients of the q_j's (upon being set equal to zero) establishes the criteria for stability.

The expansion of the flutter stability determinant for the system under consideration gives an expression of the form

$$C_3X^3 + C_2X^2 + C_1X + C_0 + i\ (D_3X^3 + D_2X^2 + D_1X + D_0) = 0$$

where X is a function of the flutter frequency (ω) and the C and D coefficients are functions of the "reduced frequency" ($K = \frac{b\omega}{v}$, or 2π times the number of waves in the wake in a distance equal to the wing semi-chord) and other parameters of the airplane.

Theodorsen solved for the critical flutter speed by evaluating the C and D coefficients in the above equations for several values of K and equating the real and imaginary cubics to zero separately. The roots of these cubics (values of X)

were then obtained and plotted against K. Each intersection of the X_R versus K and X_I versus K curves would correspond to a critical flutter speed which could be obtained from the relationship

$$V_F = \frac{A}{K\sqrt{X}}\,\omega_\alpha$$

where A is a constant which can be evaluated from measurable airplane parameters, and ω_α is the torsional frequency of the wing.

This method of obtaining the critical flutter speed is straightforward and reasonably simple, but its chief disadvantages are that it requires a prohibitive amount of time, and for a shift of the natural frequency in any degree of freedom (or a change in any parameter of the airplane) a new calculation must be made.

Other methods of solving the stability determinant, and obtaining the critical flutter speed, include the following: (1) vector and graphical methods, (2) analytical methods in which the flutter speed is obtained as a function of some important airplane parameter, (3) matrix methods, and (4) various electrical or mechanical methods.

LIMITATIONS OF FLUTTER THEORY

Three-Dimensional Considerations

Early flutter analyses were based on two-dimensional methods with all of the flutter parameters being taken at a certain "reference" station whose characteristics were supposed to be representative of the member being investigated. More recently, two-dimensional methods have been used only for airplanes having limited speeds below 300 mph, and even then the effects of partial span control surfaces and aerodynamic balance have been included in an effort to improve the accuracy of the calculations.

Two-dimensional theory implies that:

a). All spanwise elements of the oscillating airfoil are identical with respect to the flutter parameters, such as weight, chord, center of gravity, etc.

b). Amplitudes of vibration in the various modes do not differ from those of the spanwise location of the element under consideration.

c). The aspect ratio is large.

d). Aerodynamic flow over the oscillating airfoil is not disturbed by interference.

None of these implications are valid, and they serve to indicate the limitations of the two-dimensional theory. Three-dimensional equations (which closely resemble the two-dimensional equations) can be obtained if it is assumed that the corrections due to deviations from two-dimensional flow are negligible and that the true deflection curves at the critical flutter speed may be approximated as the vector sum of a series of normal uncoupled modes of vibration at zero airspeed. Three-dimensional considerations automatically include inertia and aerodynamic spanwise effects and obviate the necessity of correcting for partial span control surfaces and the like.

Compressibility Correction

The expressions for the aerodynamic forces and moments acting upon an oscillating airfoil are generally based on the assumption that air is an incompressible fluid. It is well known that at high speeds the pressure distributions are changed severely, due to compressibility effects. It has been shown that the slopes of the lift and moment coefficient curves at speeds below the critical Mach number can be expressed approximately by the following relation:

$$\frac{\left(\frac{dC_L}{d\alpha}\right)_{com}}{\left(\frac{dC_L}{d\alpha}\right)_{inc}} = \frac{\left(\frac{dC_M}{d\alpha}\right)_{com}}{\left(\frac{dC_M}{d\alpha}\right)_{inc}} = \left(1 - M^2{}_{com}\right)^{-\frac{1}{2}}$$

Another expression which is generally used to correct for the effects of compressibility in flutter analyses is based on the assumption that the lift force during an oscillation of given amplitude and frequency is proportional to the product of the square of the airspeed and the slope of the lift coefficient curve, so that:

$$L = C_1\left(V_i\right)^2\left(\frac{dC_L}{d\alpha}\right)_{inc} = C_1\left(V_C\right)^2\left(\frac{dC_L}{d\alpha}\right)_{com}$$

From these two expressions it can be shown that:

$$V_C = \left[V_i\ 1 - M_C{}^2\right]^{\frac{1}{4}} = V_i\left[1 - \left(\frac{V_i}{C}\right)^2\left(1 - \frac{V_i{}^2}{2C^2} + \frac{V_i{}^4}{8C^4} + \right)\right]^{\frac{1}{4}}$$

is the desired expression for the compressible airspeed in terms of the incompressible airspeed at a certain altitude and the velocity of sound at that altitude.

EXPERIMENTAL FLUTTER AND VIBRATION INVESTIGATIONS

When a new airplane is being designed, it is desirable to know in the very early stages of development whether it will be safe from flutter at all speeds below its design maximum speed. Accordingly, preliminary flutter analyses which are based on theoretical frequencies and elastic characteristics are conducted in order to obtain some indication as to whether flutter difficulties may be anticipated. These preliminary analyses are generally followed by wind tunnel tests on small models of the airplane and ground vibration and flutter flight tests on the full scale airplane.

Wind Tunnel Tests

The results on flutter model tests in wind tunnels have been in reasonably good agreement with theory. When discrepancies have arisen, it has been found that the calculated critical flutter speeds have been conservative, even though the model tests usually indicate a wider range of unstable speeds.

One of the basic disadvantages encountered in the solution of flutter problems by model tests is the inherent difficulty of attempting to construct a dynamically similar model of a full scale airplane in a reasonable length of time and at a cost which is not prohibitive. In addition, Reynold's number and compressibility effects cannot be taken into account in wind tunnel tests.

Ground Vibration Tests

The importance of ground vibration tests of an aircraft lies in the fact that they afford a means of determining, in a preliminary fashion, how susceptible the aircraft might be to flutter and other forms of aero-elastic instability. They provide a means of determining the natural frequencies, mode shapes, and damping coefficients, as well as a criteria for determining which modes are likely to be coupled.

If the experimentally determined natural frequencies and modes of vibration are in good agreement with the theoretical values used in the preliminary flutter analyses (or are conservative with respect to the theoretical values), additional flutter calculation may not be required, since the preliminary calculations will be

assumed to be reasonably accurate.

Flutter Flight Tests

The best method for determining at what speeds flutter will occur is to conduct flight tests of the full scale airplane. The fundamental principle upon which a flutter flight test investigation is based is that the response amplitude of an aircraft component to a forced oscillation varies inversely with the damping coefficient, and that for a given forced oscillation the damping will decrease with airspeed and will approach zero as the airspeed approaches the flutter speed, while the response amplitude will increase with airspeed and become infinite at the flutter speed.

The technique usually employed in tests of this type consists of:

a). Incremental (step by step) increases in flight speed.

b). Varying the frequency of vibration (during each flight) through frequency ranges which are considered to be critical.

c). Measurement of peak response amplitudes at several points on the structure at each flight speed.

The agreement between flutter calculations and flight flutter tests has not been especially good, but the theoretical values always appear to be conservative by an unknown margin. It is believed that considerable improvement could be obtained, if finite aspect ratio effects were included and if a sufficient number of degrees of freedom could be employed to describe the motion of the airplane more accurately.

The greatest disadvantage of the flight flutter tests is that they are of a hazardous nature, particularly in the proximity of the critical flutter speed. Although the initial tests conducted by von Schlippe in Germany (1936) resulted in the loss of an airplane, several successful flight tests of this type have been conducted in this country and in Germany in recent years. It is now believed that the element of danger can be minimized in these tests if they are conducted along the following lines:

a). Considerable care be exercised in the preparation and planning of the detailed flight test program.

b). Adequate safety precautions be observed.

c). The airplane, including the vibration exciting and measuring equipment, be operated by automatic (remote) control.

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PHOTOVISCOUS FLOW CHANNEL

To illustrate the vibration of turbine blades, a colored movie film was shown. This film was made at the NACA Flight Propulsion Research Laboratory, in Cleveland, in connection with the study of vibration of turbine blades and further study of the effect of wake on turbine blades. It illustrates the Bentonite Photoviscous Flow Channel in which polarized light passed normal to the flow shows shear planes and, thus, velocity gradients within the liquid by means of fringe patterns similar to those produced by plastic models in photoelastic investigations. This film shows two turbine blades, with a third in their wake and demonstrates the effect, very clearly, of vortices shed on the third blade. The third blade is freely pivoted, so the motions will not be indicative of actual vibrations in the engine. It should also be pointed out that in the final motions of the pivoted blade, it does not revolve completely, although it appears to.

DISCUSSION ON THE TWO PRECEDING PAPERS

R. T. McGOLDRICK, DTMB: I should like to ask whether the electrical flutter predictor is an analogy or electronic computing device.

L. P. CLARK, NAMC: I believe it is an analogy device. This electrical flutter predictor is rather large and contains many resistors, capacitors, and electrical networks. What they really do is to evaluate the parameters of the airplane and convert them to their electrical analogies. When these electrical constants are inserted in the machine, it is possible to determine the flutter characteristics of the airplane in a reasonably short period of time.

J. P. WALSH, NRL: In computing the frequency and mode shapes of a wing, I assume you use the lumping process.

L. P. CLARK: Yes, that is generally the case. We use matrix methods and are able to obtain very good agreement between calculated values and experimental ground vibration test values.

J. P. WALSH: In this work, how many stations do you use for span of wing?

L. P. CLARK: Four or five stations can be used for most cases, and no more accuracy is obtained with eight or ten. We use, more or less, the same number of stations as are used when measuring the vibration characteristics in the laboratory. For an airplane wing, we consider four or five stations on the leading and trailing edges of each side of the fuselage and excite the wing in the various resonant modes of vibration.

J. P. WALSH: At any one station you lump half the mass on each side of the station?

L. P. CLARK: Yes.

G. M. SCHROEDTER, NOTS: To what Mach number do you consider your compressibility corrections valid?

L. P. CLARK: Up to about .7. Above values of about .7 or .75, we think it is almost pointless to try to make any correction at all for compressibility.

G. M. SCHROEDTER: Has Dr. Bleakney, of the West Coast, recently had the benefit of experience with propeller excited fuselage vibrations? Also, I wonder whether his problem has contributed anything to your recent experience.

J. E. WALSH, BU AER: I am not sure of the answers to your questions. In connection with this problem, the most recent experience we have had is on the XP4M-1. Professor Den Hartog was called from MIT to look over the situation. His tentative conclusion was that it was a resonance problem. It seemed to be a problem of a tremendous amount of energy being fed into the system.

C. B. LYMAN, BU AER: There was a Lockheed airplane that contributed to the experience, so that Dr. Bleakney has been involved in the trouble and, thus, is aware of the experience of BuAer.

L. B. TUCKERMAN, NATIONAL BUREAU OF STANDARDS: It should be mentioned that the resonance problem has something to do with the propeller tip problem. I remember that the propeller tips on a Loening amphibian passed within three inches of the top of the pontoon and induced something like one-inch double amplitude vibrations of the pontoon skin at resonant frequency. In propeller tip induced vibrations and in others, subharmonic resonance has to be considered, as well as regular resonance.

There was a Navy plane, Type BF2C1, with a two-blade propeller. At about 1600 RPM strong resonant vibrations were excited in the wings and from time to time the tail showed large vibrations. It was at first thought to be due to major engine and propeller imbalance, but inserting various vibration dampers in the engine mount and even adding weights to one blade of the propeller, to produce as large imbalance as was practical, did not appreciably change the wing vibrations. It was finally traced to subharmonic resonance. At 1600 RPM the propeller tips exerted aerodynamic forces 3200 times per minute on the wings, producing vibrations with a frequency of 1600 per minute which, in turn, produced vibrations in the tail with a frequency of 800 per minute. This was checked by blowing on the wings by a separately mounted engine with a two-blade propeller. It produced the same vibrations as were produced by the plane's own engine and propeller. When a three-blade propeller was substituted for the two-blade propeller, the vibrations were not excited.

J. E. WALSH: There is no question that resonance will make the condition far worse. Up until recently, with the engine powers involved, the propeller induced vibration problem was not so great. Now, with 3000 h.p. engines with 19-foot diameter of propellers, the effect of power is getting tremendous with non-resonant vibrations in the fuselage walls. The only way of cutting down the vibration appears to be to stiffen up the sides.

N. H. JASPER, DTMB: Would this vibration due to propeller blades persist over a range of propeller RPM's? Isn't it mainly noise that causes the trouble? Have you tried coating the walls of storage space with noise-absorbing cork or some such material?

J. E. WALSH: In answer to the first part of your question, the only plane on which accurate measurements have been made is the XP4M-1. This airplane was flown at 2700 RPM at 350 mph at various powers ranging from full to very low power. It was found that vibrations in the fuselage did not vary at all, indicating that the tip speed of the propellers was the important parameter. When the RPM was cut to 2400 or lower, the vibration amplitudes dropped.

In answer to the second part of your question, it is not mainly noise that causes difficulty. In the case of the XP4M-1, Martin engineers expressed confidence that they would be successful in cutting down on noise, since the main amount of power was in the high frequency above the usual frequency in which the human voice operates. Vibrations themselves are a big problem; they make the cabin and cockpit areas untenable in the airplane.

C. B. CUNNINGHAM, NRL: Measurements of the frequency and amplitudes of vibration in a Type HRP-1 helicopter were recently made. A frequency of 36 cycles per second, with quite small amplitudes, was due to the engine vibration. The vibration at 12 cycles per second, caused by propeller passage, was quite large (approximately 40 mils double amplitude). At 4 cycles per second, which was the rotor shaft speed, the amplitude was also quite large. The natural frequency of most of the shock-mounted equipment on the craft was in the vicinity of 12 cycles per second, so that extreme vibration of this type of equipment was general throughout the ship. One instrument panel was unusable at flight speeds. It is thought that careful consideration should be given to vibration mount design before mounts are applied to equipment.

L. B. TUCKERMAN: I have not been able recently to follow the developments of flutter theory, but you did not mention the question of lowering of flutter speed when triggering action is present. I am thinking particularly of an investigation of a Beechcraft. Many had been flown without any trouble, until three serious accidents occurred in which the wings tore off in the air, scattering their fragments over long distances and killing the pilots. We had no explanation of these accidents until a fourth plane of the same type struck a bump in the air which produced a violent symmetrical flutter of the wings and broke the wing spars. In spite of that, the pilot managed to land the plane safely. We were able to determine that the plane was flying at normal cruising speed (180 mph), at which the wings of these planes had never before been known to flutter.

The other remarkable case of triggering off action that I remember was the Tacoma Narrows bridge. It had been subjected to much higher winds before its final collapse but had shown only vertical vibrations. Under a wind considerably lower, one of the suspension wire clamps slipped on the main cable. That triggered off the torsional flutter which destroyed the bridge.

At these lower speeds it takes some triggering action of suitable amplitude and suitable phase to start flutter. In using mechanical oscillators in an attempt to study flutter, the particular combination of amplitude and phase necessary to set it off may not always be produced. You all know about that German plane which was being studied by means of mechanical vibrations. The Germans were making this part of their study of an airplane before they would accept it for final production. A number of tests had been made with no indication of destructive flutter taking place, but one time the right combination evidently was found. Destructive flutter occurred, the wings tore off, and the occupants of the plane were killed. I made up a model, in which I had nonlinear coupling between a mass vibrating at two cy-

cles per second and one at one cycle per second, and excited it with nonharmonic vibrations of varying frequencies. Exciting it four times per second with the other masses at rest, nothing would happen, but by proper jiggling of the mass, which vibrated at two cycles per second, large vibrations would be set up - both at two cycles per second and at one cycle per second. I had to stop the excitation to prevent destruction of my model. I have seen no theoretical presentation which takes account of this triggering action.

H. C. B. THOMAS, BRITISH SUPPLY OFFICE: Is any work being done on correlation between vibration and the life of the structure?

L. P. CLARK: Yes, a good bit of work has been done along that line. When we were having trouble with certain planes, we attempted to test these airplanes in the laboratory by imposing forced oscillations for certain periods of time. If we found no failures, we would increase the amplitude of forced oscillations and try again. Tail failures were experienced in the F6F, and it was felt that a combination of normal air loads and buffeting might have been inducing these failures; so we measured loads on the tail surface of the plane in flight and attempted to duplicate these loads on an airplane in the laboratory under carefully controlled conditions. We were able to get results that led to increased strength of the tail surface.

L. B. TUCKERMAN: In these tail failures, where did you locate the start of the failures? I have examined the fatigue failures in airplanes and every one could be traced to a local concentration of stress. In our investigations, I have never seen a failure from vibration (other than flutter) due to a major structural element, that did not involve localized concentration of stress.

L. P. CLARK: I believe there were local concentrations in the F6F but am not too certain, however. The main problem was to duplicate in the laboratory the types of failures encountered in flight. These tests took place four years ago. Cracks were obtained at the leading edge of the stabilizer, and in each case it was the same type of failure. What we did was to stiffen the leading edge and try to retard the failure, and then see if we could fail it again. The time required to produce failure was considerably increased, but when the surface failed, it would always occur at the same spanwise location at a point aft of the stiffened leading edge.

L. M. BALL, NOL: The fatigue failures of propeller hubs do not always occur at a discontinuity.

J. T. MULLER, BELL TELEPHONE LABORATORIES: Is there any inherent high resistance to flutter failure in magnesium? Would a magnesium fuselage have higher or lower inherent susceptibility to flutter than an aluminum fuselage, because of the higher damping of magnesium?

L. P. CLARK: I can't answer the former with assurance and don't know which of the latter would be true. I don't know of magnesium having been used in an airplane fuselage. I know of aluminum wings, but I don't think any special tests, other than regular static tests, were conducted on these wings. I never knew of any actual flutter calculations indicating whether there would be a greater or lesser tendency to flutter. It would be more a comparison of natural frequencies, densities, damping coefficients, or other structural parameters of the two materials. I don't know how you would determine the answer in an exact scientific manner because of the inherent complexity of aircraft structures.

E. KLEIN, NRL: To restate this question another way, is incipient flutter a factor of the "Q" of the material?

L. B. TUCKERMAN: Magnesium tuning forks will stay in vibration longer than aluminum.

C. B. LYMAN, BU AER: I think it is safe to say, in answer to the general question, that, all other things being equal, the wing with higher damping will have higher flutter speed.

J. T. MULLER: A report has been made by Purdue University on the effect of vibrations on human beings. The results are available at BTL. It has been found that the effect of vibration on humans is directly proportional to acceleration. Every human being has a critical value beyond which he begins to feel the effects.

J. E. WALSH: The effect of vibration on human beings depends mainly on acceleration - not amplitude. You can stand large amplitude at low frequency and low amplitude at high frequency - the effect will be the same.

D. E. GOLDMAN, NMRI: One can stand greater amplitude at low frequency than at high frequency. The problem has been attacked by several investigators by exposing people to various amplitudes and frequencies and asking them how they felt about it. Subjective criteria of this kind are very difficult to apply. In general, three criteria have been used: first, is the vibration perceptible; second, is it unpleasant or uncomfortable; third, is it so unpleasant or uncomfortable that the subject is unwilling, for any of several reasons, to tolerate it further? In addition, complications arise from different interpretations of these criteria and different experimental conditions. However, it is possible to combine results which have been obtained by various observers, provided it is clearly understood that spread is large and that anything attempted in this way is necessarily preliminary. The result is shown in Figure 1. The range of the data in amplitude is so wide that some other method of plotting is usually more convenient. This is the basis for using acceleration as a parameter. It turns out that the range is greatly reduced, as shown in Figure 2. However, it does not follow that the criteria are those of constant acceleration. In fact, one is mildly tempted to consider the curves as parts of resonance curves having peaks between 5 and 10 cycles per second.

Finally, it should be added that while the curves have considerable uncertainty (about one-half log unit), a few experiments carried out at accelerations up to 5 or 10 g (below 100 cycles) and at about 50 g (up to 300 cycles) resulted in marked fatigue, headache, and discomfort. Also, chronic exposure of the hands to 13 g at 200 cycles results in chronic injury to the hands. This indicates that there is something more than guesswork as a basis for placing upper limits. However, it is obvious that much more work will have to be done and that, even then, there will be the problem of compromises with engineering limitations.

B. J. W. GRIER, DTMB: What difference have you found in threshold in regard to direction of vibration? The work at Purdue showed 20 or 30 percent difference in threshold with respect to vertical, longitudinal, or lateral vibration.

D. E. GOLDMAN: There is a difference. I did not want to go into the matter in such detail. The differences are smaller than the overall variations, so that while direction is important, we have no means as yet of deciding how much. It is just a matter of getting enough data under controlled conditions to be able to decide whether the differences are significant or not.

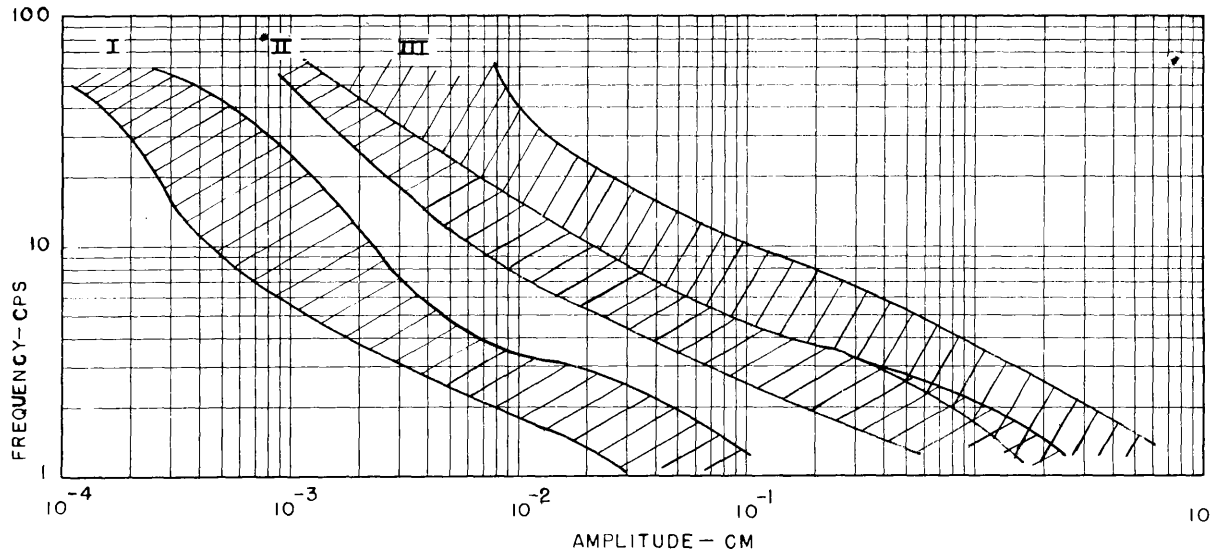


Figure 1

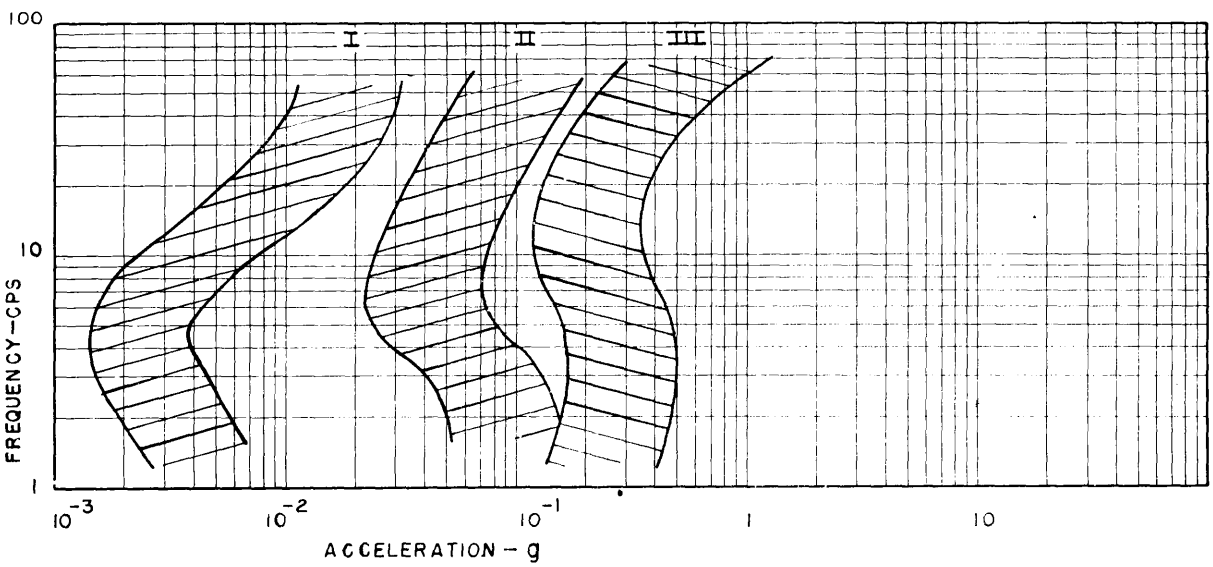


Figure 2

B. J. W. GRIER: Are you referring to the entire body?

D. E. GOLDMAN: Yes. All data used here refer to exposure of a large area of the body. Some data have been taken on point exposure; however, in determining vibration thresholds in engineering problems which turn up, people are usually interested in large-area exposures.

L. B. TUCKERMAN: Are you familiar with the analgous problem of the permanent effects in using pneumatic hammers and pneumatic drills? They are very definite, evidenced by permanent paralysis of the wrists.

D. E. GOLDMAN: There is no doubt as to the importance of such phenomena. However, while the literature is full of clinical studies, there is no information as to the frequencies and amplitudes encountered.

DYNAMIC STRESSES IN AIRCRAFT STRUCTURES

by

R. L. Bisplinghoff, G. Isakson and T. H. Pian

Massachusetts Institute of Technology

An outline of the problems associated with transient stresses in military airplane structures. Discussion of the present status of methods for predicting these stresses while the airplane is in the design stage.

INTRODUCTION

The recent war hastened the development of larger and faster military aircraft which introduced new structural design problems.

Loads computed on the assumption of a rigid airplane often proved inaccurate, and numerous service failures occurred as a result of dynamic stresses which had been ignored by the designer.

Dynamic stresses are associated with structural design problems in which inertia forces are applied to the structure in addition to external loads such as air or ground loads. These inertia forces, in general, do not arise merely as a result of rigid body rotational and translational accelerations of the airplane, but in addition, are a consequence of accelerations due to small deformations of the structure. Airplane stress analysis usually proceeds on the assumption that all loads applied to the structure are static loads. The structure deflects statically to its maximum deformation and remains stationary until the loads are relaxed. However, many loads are applied rapidly. Such loads cannot be considered as static loads since their effect is to cause the structure to oscillate. During oscillation, because of inertia forces, the stresses produced are often more severe than would be the case if the loads were applied statically.

In those cases in which the structure is stable under its system of forces (wing flutter is an example of instability) the time history of deformations and stresses in the structure must be examined in studying a dynamic stress problem. Figure 1 illustrates a comparison between the computed stress at a particular point in the wing of a 23,000 pound seaplane during

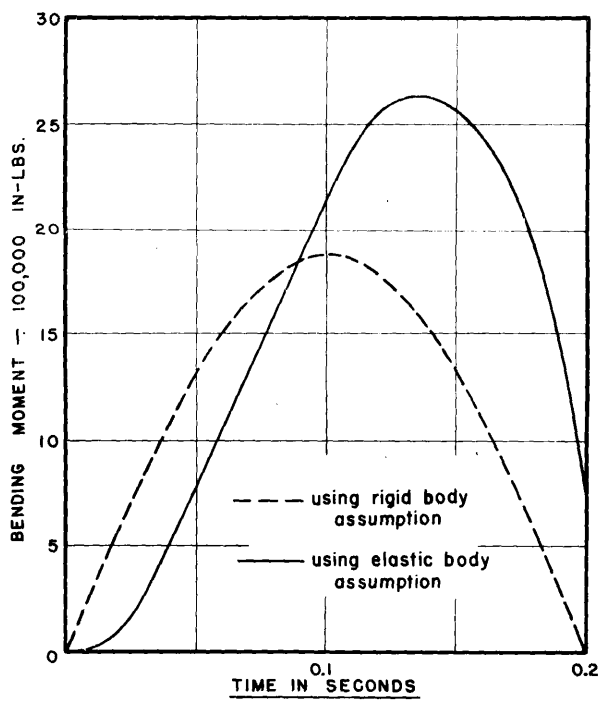


Figure 1. Computed Stress in Wing of a 23,000 Pound Seaplane During Landing Using Rigid Body and Elastic Body Assumptions

landing, using the usual rigid body assumption and then taking elasticity into account.

Dynamic stress failures are usually characterized by buckling or sometimes complete rupture of structural components in the vicinity of large mass items.

Rapidly applied forces may arise in a variety of ways in military airplanes. Sharp impact forces during landing of landplanes and seaplanes have constituted one of the most serious causes of failures. In general, because of the severity of rough water operation and the circumstance that the impact force is generally applied in the plane of symmetry, the seaplane is subjected to more severe dynamic stressing during landing than the landplane. Sharp-edged gusts are potentially dangerous as a cause of dynamic stress failures. Measurements on present-day aircraft which have experienced severe gust conditions have indicated that the existing gust criteria, based upon rigid body considerations, are adequate. However, present indications are that such design criteria may be inadequate for the larger high speed aircraft now being contemplated. Gun blast, rocket blast and gun recoil often produced structural failures of serious nature during wartime. The rapidly moving pressure wave from gun muzzles and rocket igniter charges excites the higher vibration modes in the airplane structure. In particular, high frequency vibrations of control surfaces and of flimsy wing trailing edge structures accounted for a significant number of failures.

Rapidly applied forces may also be experienced by aircraft structures during catapulting, sudden dropping of bombs, transient aerodynamic disturbances such as buffeting, and rapid maneuvering due to quick deflections of control surfaces. Structural design problems involving dynamic stresses have arisen to some extent in each of the last mentioned items.

Two important factors make dynamic stress considerations more important in present-day military aircraft. These are, first, lower natural frequencies of the airplane structure and, second, more rapid application of design loads. The first factor is a consequence of increased size, increased flexibility, and the increasing tendency to place large mass items remote from the center of gravity. The second factor results from higher performance which may, in general, mean higher sinking speeds during landing, more rapid penetration of gusts, and more rapid control surface movements.

BASIC MATHEMATICAL APPROACH

We come now to a consideration of the basic mathematical problem, which is found to be common to all of the special problems mentioned earlier. It consists in finding a suitable form for the equations of motion of the elastic system representing the airplane. These equations should be such that they can be solved conveniently, and the solution should be in a form which can be easily related to stress in the airplane structure.

The general form known as Lagrange's Equation is found to be particularly useful here. It depends, in turn, upon the concept of generalized coordinates. These coordinates are defined as being any set of independent coordinates which will completely describe the configuration of the mechanical system. Lagrange's Equation has the following form,

$$\frac{d}{dt}\left(\frac{\delta T}{\delta q_i}\right) - \frac{\delta T}{\delta q_i} + \frac{\delta V}{\delta q_i} = Q_i \qquad (1)$$

in which q_i represents the displacement of the system in the ith generalized coordinate, q_i represents the first derivative with respect to time of this displacement, T represents the total kinetic energy of the system at any instant and in the general case is a function of displacements

and velocities, V represents the total potential energy of the system and depends upon those forces which are related to a potential, such as elastic forces and gravity forces, and, finally, Q_i is a quantity known as the generalized force corresponding to the ith generalized coordinate and is defined as follows,

$$Q_i = \frac{\delta W_i}{\delta q_i} \tag{2}$$

where δW_i is the work done by all external forces which cannot be derived from a potential, in a virtual displacement δq_i. There will be as many equations as there are generalized coordinates. If the generalized coordinates are chosen at random, the functions representing the kinetic and potential energy will contain terms consisting of products of the displacements and of the velocities, and consequently each of the equations of motion may contain several of the coordinates. It is possible, however, to choose a set of generalized coordinates such that the terms in Lagrange's Equation derived from the kinetic and potential energy depend only upon the generalized coordinate corresponding to that equation. Such coordinates are known as normal coordinates, and in the case of an elastic body the normal coordinates describing the deformation of the body will be the displacements of the natural modes of vibration of the body. Using these coordinates it is found that the equation of motion can be put in the form

$$M_i \ddot{q}_i + M_i \omega_i^2 q_i = Q_i \tag{3}$$

in which $\ddot{q}_i$ is the second derivative with respect to time of the displacement of the ith normal mode, ω_i is the circular frequency of the ith principal oscillation, and M_i is a quantity known as the generalized mass, defined as follows,

$$M_i = \int_M \phi_i^2 \, dm \tag{4}$$

where ϕ_i is the linear displacement of an element of mass corresponding to a unit displacement of the ith normal mode, and the integration is carried out over the whole mass of the system. If the generalized force derives only from arbitrary external forces and is independent of the motion of the system, the equations of motion are independent and each reduces to that of a simple harmonic oscillator. If, on the other hand, the generalized force depends upon the motion of the system, for example if it includes the effect of damping forces, it may contain terms coupling the modes and the equations of motion must then be solved simultaneously if an exact solution is desired. In this case, however, the coupling is due only to forces other than the inertia and elastic forces, and it can be considered to have been reduced to a minimum.

The main purpose of using normal coordinates, therefore, lies in the fact that coupling effects can be eliminated or reduced to a minimum, depending upon the nature of the generalized force. While there is still, theoretically, an infinite number of degrees of freedom in the case of an elastic body, in most practical problems some of the normal modes are excited to a much greater extent than the others. The system can be considered to have a relatively few degrees of freedom, only the significant modes being taken into account. In the case of an elastic body moving freely in space, there are normal coordinates representing the rigid body displacement in addition to those describing the elastic deformation. The rigid body modes involve displacement of the principal inertia axes, while the vibration modes involve only deformations with respect to these axes.

We will now proceed to show how this general procedure can be applied to specific dynamic load problems in the case of the airplane. This is a problem of an elastic body moving freely in space or subjected to certain constraints and initial conditions. Only the generalized force expression will depend upon the particular problem considered, since the remaining terms in the equations of motion depend only upon the elastic and inertia properties of the airplane and are independent of the external forces applied to it.

THE LANDING PROBLEM

This problem may be approached in two different ways. For the landplane we may consider the structure and the landing gear as a single system, and for the seaplane the structure and the surrounding water may be considered as a single system. In this method of approach the nonlinear force-displacement characteristics of the landing gear and the variable-mass effects of the water render the equations of motion nonlinear; hence the solution becomes laborious.

In the second approach we may consider the airplane structure to be subjected to landing impact forces, which are assumed to be independent of the response of the structure. This assumption is justified in the case of the landplane landing problem. Drop tests of dynamic models have been conducted at the National Bureau of Standards to determine the force developed in the shock strut as a function of the flexibility of the attached structure. (National Bureau of Standards. Report, "Influence of Wing Flexibility on Force-time Relation in Shock Strut Following Vertical Landing Impact," Report to Bureau of Aeronautics, Navy Department, August 1947. NBS Lab. 65181, PR. 2 BuAer TED NBS2410.) It was found that the peak force showed a reduction of not greater than 10 per cent due to wing flexibility.

Considerable insight into this problem of coupling between structure and landing gear may also be obtained from a simple analytical study by considering the landing gear as a single spring. Figure 2 shows the variation of the ratio of impact force for a flexible airplane to that for a rigid airplane for different ratios of

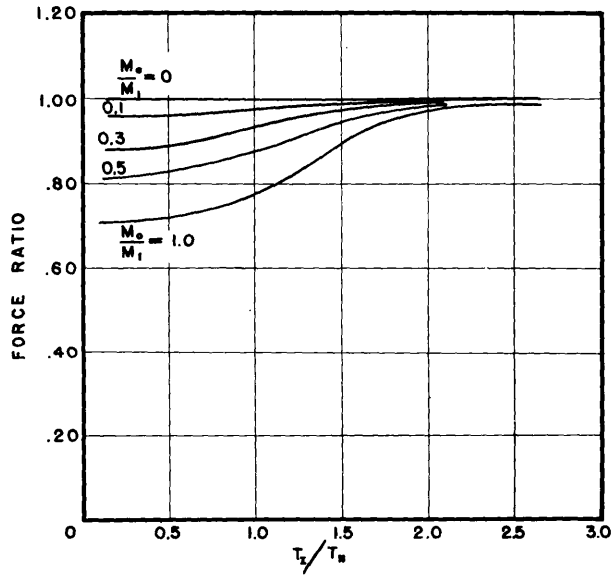


Figure 2. Ratio of Impact Force for a Flexible Airplane to that for a Rigid Airplane

$\frac{T_I}{T_N}$ and $\frac{M_o}{M_I}$, where T_I is the duration of impact, T_N is the natural period of the wing, M_o is the actual mass, and M_I is the generalized mass of the wing in its fundamental mode, which is so normalized that the displacement of the point of impact is taken as unity.

This shows that for $0.25 < \frac{T_I}{T_N} < 2.5$ and $0 < \frac{M_o}{M_I} < 1$ - the impact force for the flexible structure is 0.71 to 1 times that for the rigid structure. For current design of large airplanes with $\frac{T_I}{T_N} \approx 1$ and

$0.06 < \frac{M_o}{M_1} < 0.2$, the impact force for the flexible structure would show a reduction of less than 10 per cent as compared with that for the rigid structure.

For seaplanes, the effect of the flexibility of the airplane structure on the hydrodynamic impact force has been investigated by Mayo (Mayo, W. L.: "Solutions for Hydrodynamic Impact Force and Response of a Two-mass System with an Application to an Elastic Airframe," N. A. C. A. Technical Note No. 1398, Aug. 1938). Theoretical results indicate that the shape of the force-time curve might be considerably changed, and the maximum hydrodynamic force might be either reduced or increased. Therefore, the second method of approach may lead to larger errors in the case of the seaplane than in that of the landplane. In general, the convenience of the second method far outweighs its inaccuracies and is therefore preferred from the designer's point of view.

The landing problem may be further simplified by neglecting the effect of structural and aerodynamic damping forces. This is a conservative assumption. The structural damping of the airplane is, in general, small. The aerodynamic damping is proportional to the airplane speed, hence it is a minimum at the landing speed.

With these simplifications, the differential equation which determines the response of each of the natural modes is given by Equation 3. In this case $Q_i(t)$, the generalized force, is proportional to the landing impact force $F(t)$ and depends upon the location of its point of application.

The solution for q_i may be written in the form of Duhamel's integral as follows:

$$q_i = \frac{1}{M_i \omega_i} \int_0^t Q_i(\tau) \sin \omega_i (t - \tau) dt \quad (5)$$

This integral may be evaluated either graphically or analytically. By this means the time history of the displacement of each natural mode may be determined. The time history of the displacement of any point in the structure may be determined by superposing the displacements of the individual modes in the appropriate proportion. A graphical or analytical evaluation is quite lengthy in a practical problem. It has been found more convenient to use a mechanical simulator, consisting of a system of torsion pendulums, each tuned to one of the natural modes of the airplane structure, as shown in Figure 3. This simulator operates on the same

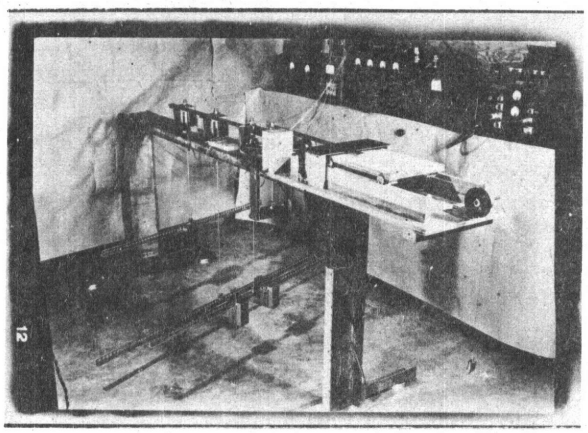


Figure 3. Mechanical Simulator

principle as that used by Biot in studying dynamic stresses in buildings, due to earthquakes. (Biot, M. A.: "Analytical and Experimental Methods in Engineering Seismology." Trans. *Am. Soc. of Civil Eng.*, Vol. 108, 1943, P. 365.) Each pendulum may be easily excited in a manner appropriate to the generalized force corresponding to its mode of motion. The displacements of the pendulums are picked up and superposed by an electronic device to yield the complete time history of the displacement or stress at any particular point of the airplane structure. The present device is limited to cases in which three airplane natural modes predominate.

THE GUST PROBLEM

In the case of the gust problem the aerodynamic forces depend not only upon the distribution of velocity in the gust but also upon the motion of the airplane, and tend to couple the modes.

The use of a linearized aerodynamic theory makes it possible to apply the principle of superposition and simply sum the components of the aerodynamic forces due to separate influences, such as distribution of velocity in the gust, vertical motion of the wing sections, and pitching rotation of the wing sections. Due to the presence of a vortex pattern in the wing wake, the aerodynamic forces on the wing depend not only upon instantaneous values of the displacements and their derivatives, but also upon the previous time history of the motion and the gust pattern traversed, so that it is necessary to use an unsteady flow theory. The aerodynamic forces, due to an arbitrary gust and a resulting motion, may then be expressed conveniently in the form of Duhamel integrals involving certain indicial functions. The displacements and their derivatives remain as unknown functions of time. One of these indicial functions represents the lift on a wing section following passage through a sharp-edged gust, another represents the lift following a sudden change in angle of attack. Expressions for these functions have been derived from thin airfoil theory for unsteady two-dimensional flow of an incompressible, nonviscous fluid. They are due mainly to Wagner (Wagner, H.: "The Production of Dynamic Lift on Wings," *Zeitschrift fur Angewandte Mathematik und Mechanik*, Vol. 5, February 1925) and Küssner (Küssner, H. G.: "Stresses Produced in Airplane Wings by Gusts," N.A.C.A. Technical Memorandum No. 654, 1932) in Germany and von Karman and Sears (v. Karman, Th. and Sears, W. R.: "Airfoil Theory for Non-uniform Motion," *Journal of the Aeronautical Sciences*, Vol. 5, No. 10, August 1938) in the United States. While the exact mathematical expressions for these functions are highly complicated and hardly practical, they can be closely approximated by simple exponential functions (W. R. Sears and B. O. Sparks: "On the Reaction of an Elastic Wing to Vertical Gusts," *Journal of the Aeronautical Sciences*, Vol. 9, No. 2, p. 64, Dec. 1941).

In this way we can set up expressions for the aerodynamic lift and moment on each section of the wing, using as coordinates the vertical displacement and angle of pitch. From these we find an expression for the work done by the external forces in any virtual displacement; then, changing to normal coordinates by appropriate transformations, the work done may be found in a virtual displacement of any one of the normal modes. As mentioned previously, this finally yields an expression for the generalized force which is found to involve all of the normal coordinates, showing that the aerodynamic forces have the effect of coupling the modes.

The solution of the equations of motion may be accomplished in principle by the application of the Laplace Transformation. By applying the transformation to all terms of the equations of motion, we obtain a set of algebraic equations which are linear in the transforms of the generalized displacements, and the coefficients are functions of the Laplacian operation "p". It would thus appear possible, at least in theory, to solve the equations simultaneously for the transform of each of the displacement functions, obtaining functions of p, which can then be inverted. It is, however, in the inverse transformation process that the main difficulty arises. A simultaneous solution of the equations yields functions of p which are far too complicated to permit a practical inversion process. For example, it may be necessary to find the roots of a polynomial whose degree is of the order of forty or fifty, in which there are several pairs of complex roots. This is hardly a practical procedure.

Another method, which has been applied to similar problems in the Instrumentation Laboratory at M. I. T., appears much more promising (v. Karman, Th. and Biot, M. A.: "Mathematical Methods in Engineering." McGraw-Hill Book Co., Chapter X, pp. 388-391). It consists in assuming a sinusoidal forcing function (in the present case a gust with a sinusoidal velocity distribution in the direction of flight) and finding the amplitude and phase of the steady response of each of the modes. This is accomplished by using the complex-variable method of vibration analysis. That is, the forcing function and response functions are assumed to be of the form $Ae^{i\omega t}$ where ω is the circular frequency of oscillation, and the coefficient A is a complex number determining amplitude and phase.

The solution for a particular mode may then be written in the form,

$$q_i\ (t) = H(\omega)\, f(t) \qquad (6)$$

where f(t) is the forcing function and $H(\omega)$ is a complex function of ω which relates the response, in amplitude and phase, to the assumed sinusoidal forcing function.

If we wish now to find the response to some arbitrary forcing function F(t), we apply the Fourier Transformation to this function,

$$h(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} F(t)\, e^{-i\omega t}\, dt \qquad (7)$$

and the solution for the response can be written

$$q_i(t) = \int_{-\infty}^{+\infty} h(\omega)\, H(\omega) e^{i\omega t}\, d\omega \qquad (8)$$

The response to a unit-step function reduces to the form

$$q_i(t) = \frac{1}{2\pi i}\int_{-\infty}^{+\infty} \frac{H(\omega)}{\omega} e^{i\omega t}\, d\omega \qquad (9)$$

The infinite integral is not suitable for practical solution but may be approximated by a trigonometric series, as follows:

$$q_i(t) = \frac{|H|_o}{2} + \frac{2}{\pi}\sum_{n}^{\infty} \frac{|H| \sin(n\omega_o t + \phi)}{n} \qquad (10)$$

$$n = 1,\ 3,\ 5 \ldots\ldots$$

ω_o is a small increment of frequency, and the value of H at $\omega = n\omega_o$ is represented by an amplitude $|H|$ and a phase angle ϕ. $|H|_o$ is the amplitude of H at $\omega = 0$.

This form actually gives the steady response to a square wave of period $2\pi/\omega_o$. It will, however, give a good approximation to the transient response to a step-function over a finite interval if the square wave is long enough and there is sufficient damping to cause the disturbed motion effectively to die out before the end of each wave is reached. The initial value of the displacement and its derivatives must be zero. The amplitude of H generally becomes small as ω becomes large, so that only a finite number of terms is necessary in the series. The convergence is further improved by the presence of "n" in the denominator.

The method is particularly suitable for application to the gust problem. The two-dimensional aerodynamic force expressions for passage through a sinusoidal gust and for a sinusoidal motion are well known, the latter having been developed for flutter analysis purposes. In addition, a method of determining finite span corrections has been developed by Reissner (Reissner, E.: "Effect of Finite Span on the Airload Distributions for Oscillating Wings, I - Aerodynamic Theory of Oscillating Wings of Finite Span, "N. A. C. A., Technical Note No. 1194, March 1947. Reissner, E. and Stevens, J. E.: "Effect of Finite Span on Airload Distributions for Oscillating Wings, II - Methods of Calculation and Examples of Application," N. A. C. A. Technical Note No. 1195, October 1947) and can be applied here.

The solution gives the response to a sharp-edged gust which may have a curved front and variable velocity in the spanwise direction. The response to other gust forms can be obtained by application of the Duhamel integral.

It should be noted that the function $H(\omega)$ need not be determined explicitly but need only be evaluated numerically for particular values of the forcing frequency, and a curve of H vs. ω can then be plotted. In this way all coupling effects can be taken into account without involvement in highly complicated mathematical expressions which cannot be handled practically.

OTHER PROBLEMS

The methods suggested for the landing and gust problems are typical of methods which may be used in the solution of other problems. However, in order to permit the designer to apply such methods, it is necessary that the problem involve structural components in which the pertinent vibratory modes may be readily predicted. The only applications up to the present time which have led to useful quantitative results have involved the first two of three vibration modes of large structural components such as wings or fuselages. Such problems include the landing problem, the gust problem, the problem of dropping heavy objects, and the problems associated with rapid control surface deflections. Gun recoil and blast problems, on the other hand, involve high frequency vibration modes of local sections of the structure. These modes are very difficult to predict, and therefore analytical studies can be expected to give only qualitative results. However, such results may be valuable to the designer. For example, rib failures near the trailing edge of control surfaces often result from blast loads. Control surface ribs are tapered members, and the type of failures experienced may be readily understood when one studies the stress distribution in tapered members and under dynamic loads. One of the most serious problems involving dynamic stresses is that of tail buffeting in modern fighters during flight at high Mach number in the region represented by the upper righthand corner of the V-n diagram. There has been little success in rationalizing this problem, primarily because of lack of knowledge of the wake characteristics behind wings at high angles and high subsonic speeds.

STRUCTURAL DAMPING

No mention has been made so far of allowance for the effect of structural damping. Experiments show that this damping, in general, is proportional to amplitude of displacement and is 90 degrees out of phase with the elastic forces (Coleman, R. P.: "Damping Formulas and Experimental Values of Damping in Flutter Models," N.A.C.A. Technical Note No. 751, 1940). It can thus be readily taken into account by multiplication of the elastic force terms in the equations of motion by a complex factor. This factor is usually different for different modes and must be determined experimentally. Its importance increases rapidly with the higher modes, as a result of which these modes are, in general, hardly excited unless the external force is highly concentrated and very rapidly applied.

DETERMINATION OF STRESS FROM DISPLACEMENTS OF NORMAL MODES

Till now, we have discussed the dynamic response of the airplane to various types of rapid loading in terms of displacements of the normal modes of vibration. However, we are ultimately interested in the transient stresses in the structure. The problem is to relate these stresses to the displacements of the normal modes in a convenient manner. Two possible methods suggest themselves.

First, we may find the stress distribution corresponding to a unit displace-

ment of each of the normal modes. In order to do this, it is not necessary to use the deformation of the structure as information from which strains are to be calculated as a step in the determination of the stress distribution. Instead, we may find a distribution of load which corresponds to this deformation by calculating the inertia forces for free vibration in each mode and then find the stress corresponding to this load distribution by the conventional methods of stress analysis.

The time history of the stress at a particular point in the structure for a specific dynamic loading condition can then be written as a linear combination of the displacement functions for the various modes.

$$\sigma_j = A_j^{(1)} q_1(t) + A_j^{(2)} q_2(t) + \ldots \tag{11}$$

The coefficients $A_j^{(1)}$, $A_j^{(2)}$, etc. are functions of the particular point under consideration and are determined in the stress analysis. By selecting a limited number of points in the structure, as being those at which the stress is likely to be critical, we may calculate the time history of the stress at these points and, in that way, obtain maximum values of stress. These maximum values will not be reached at all points of the structure simultaneously. In this procedure the stress analysis would depend only upon the mode shapes and, once carried out, could be applied to any particular dynamic loading problem, without additional work other than the calculation of the displacement functions for the normal modes. The stress obtained in this way would, however, be only that part of the total stress which is due to the disturbing forces and the disturbed motion of the airplane taken as a departure from the initial steady condition. It would be necessary to add to it the stress corresponding to this initial condition.

This method is particularly well suited to the gust problem, since the aerodynamic forces are inserted as functions in the equations of motion and are not determined explicitly. A calculation of the actual loads acting on the airplane would be extremely cumbersome and is avoided here.

Another method consists in calculating first the stresses which would be obtained if the structure were rigid, which is the present basis, and then finding an additional stress due to elastic effects. This approach is convenient for the landing problem, in which the external forces are assumed to be independent of the response of the system. In this case, the additional stress at a particular point in the structure may be written as a linear combination of the acceleration functions for the various vibration modes. The total stress may be expressed as

$$\sigma_j = \sigma_{j_r} + B_j^{(1)} \ddot{q}_1(t) + B_j^{(2)} \ddot{q}_2(t) + \ldots \tag{12}$$

σ_{j_r} is the stress which would be obtained if the structure were rigid. The coefficients $B_j^{(1)}$, $B_j^{(2)}$, etc., as in the previous section, are functions of the particular points under consideration and are determined from the stress analysis.

The main advantage of the latter approach is that convergence of the series in terms of accelerations of normal modes is more rapid than the series in terms of displacement.

In conclusion, modern, large, high-performance military aircraft should not be designed by using large safety factors which replace the designer's ignorance of dynamic stresses. For many years an ultimate factor of safety of 1.5 has been used in airplane design. This factor could hardly be increased in modern military aircraft without a sacrifice in per-

formance, and some attempts have been made in recent years to decrease it. Its capacity as a catch-all has, in fact, been already severely taxed in the race between increased airplane performance and adequate design load data. It is necessary, therefore, that dynamic stress problems be solved by rational procedures if possible.

DISCUSSION

L. M. BALL, NOL: It is surprising that some of the BuAer people did not respond on the safety factor. On one hand the speaker suggested that neglecting dynamic force was tantamount to requiring a safety factor. I wonder if rates of loading of dynamic forces on material would increase the failing stresses and counteract the increased loading.

R. L. BISPLINGHOFF, M.I.T.: I cannot give a definite answer. It is a very pertinent question at the present time. We have almost no information on what we should use for allowable stresses once we have found the dynamic stresses. All we have are the ordinary static allowables. However, we hope, through research programs, to determine some information on allowable stresses under rapid rates of loading.

THE MEASUREMENT OF MECHANICAL TRANSIENTS FOLLOWING LANDING IMPACT OF A MODEL AIRPLANE

by

Walter Ramberg,

National Bureau of Standards

The problem of determining the transients in an airplane following landing impact is discussed, with emphasis on those aspects that are of general interest in determining the response of an elastic structure to impact. Methods of analysis as well as experimental methods of dealing with the problem are outlined, and their limitations are discussed.

STATEMENT OF PROBLEM

We do not like to think of the airplane as being mistreated by "shocks" such as those administered by the many diabolic impact machines that have been described, yet the airplane may be regarded as a flexible piece of equipment that is subjected to a mild shock test whenever it lands or taxis on rough terrain. The occupants of the airplane will be quite interested in having the airplane survive without a broken wing or other failure.

METHOD OF SOLUTION

The problem of landing impact has been attacked analytically, experimentally, and by combinations of analysis and experiment.

Analytical Method

Analytically the problem can be stated as follows: Regard the airplane as an elastic body; impact forces which vary with time in a known way are applied to this body by the landing gear; find the stresses throughout the body as a function of time.

Several methods have been proposed (Figure 1) to solve this problem. The choice of method to be used depends on the sharpness of impact. The sharpness of impact is conveniently measured by the ratio T_1/T of time of impact to period of structure.

Beginning with values of this ratio large compared to one, we have the impact force gradually applied to the structure. The inertia forces are negligible compared to the elastic forces. The dynamic problem reduces to the familiar static problem.

As we shorten the time of impact, the inertia forces come in first as a small, but not negligible, effect. The effect of the inertia forces may be computed as a correction term or "dynamic overthrow" as

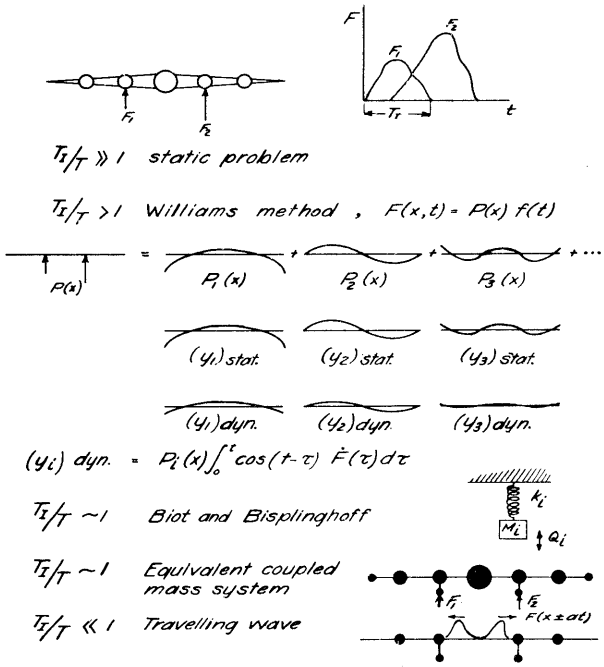


Figure 1. Survey of Analytical Methods of Solving for Dynamic Response During Landing Impact.

proposed by David Williams*. Williams limits his analysis to impacts of fixed shape and position, which can be written as P(x) f(t). He expands P(x) into components having the shape of the inertia loadings for each one of the first few modes of vibration of the structure. He then derives a simple formula for the dynamic overthrow for each mode. The dynamic overthrow becomes negligible for the high frequency modes, so that the computation need be confined usually to the first one or two modes only. We have rapid convergence.

We have less rapid convergence as $T_1/T \sim 1$. The Williams nethod does not apply if the distribution of the impact force changes with time, as it frequently does, or if the time history of the impact force is unknown. In this case we may estimate the maximum response from the Biot and Bisplinghoff statistical method described by the previous paper.

The Biot-Bisplinghoff method is a powerful method for taking into account the effect of impact forces which vary in any way in space and time; but it must be remembered that it is limited to systems whose motion can be described in terms of normal modes independent of each other. It fails when there is coupling between the modes, either because of friction or because of nonlinearity.

In that case a solution is possible, in principle, by replacing the elastic system by an assembly of elastically connected masses and then solving for the displacements of the individual masses. This method has not yet been used widely. It may become unwieldy for airplanes which cannot be approximated by an assembly of a few masses and springs.

The method of solution in terms of normal modes becomes entirely unsuited as the ratio of $T_1/T \ll 1$. In that case the impact excites many natural modes, and it appears more profitable to look at the effects in the immediate neighborhood of the point of impact. The stresses at that point will depend on the rate at which energy can be radiated away from the point. The problem reduces to one of traveling waves. The solution in terms of traveling waves has not been worked out as yet, except for the ideal case of waves traveling through long structures—such as longitudinal waves in rods or trains of railroad cars, transverse waves in beams or strings, or torsional waves in shafts. Its application to more complicated systems of masses and springs should be investigated, in my opinion, especially since it gives a very clear picture of the phenomena and allows one to bring in easily nonlinear effects caused by plastic yielding or by friction.

* *Williams, D. Displacements of a linear elastic system under a given transient load. Paper presented before 6th Int. Congr. for Appl. Mechanics, Paris, 1946.*

Experimental Method

I have said enough to make clear that the theory of landing impact is based on simplifying assumptions which should be checked by experimental landings under controlled conditions before applying the theory to airplanes that are still in the design stage.

Unfortunately, there is no way of making controlled landings of full size airplanes. The stresses set up in a full size airplane will vary from landing to landing, depending on the pilot's technique, the attitude of the airplane, the wind direction, and irregularities in the landing strip. Controlled landings to check the theory are best made in the laboratory on a model airplane.

We have attacked the problem by constructing a model which has a distribution of mass and of bending stiffness along the wings that is proportional to that in the B-24 airplane (Figure 2). The four engines of the B-24 are replaced by rigidly attached masses. One-point and two-point landings have been made with this model. The landing gear for the one-point landings was replaced by a combination of springs and a dashpot (Figure 3) with

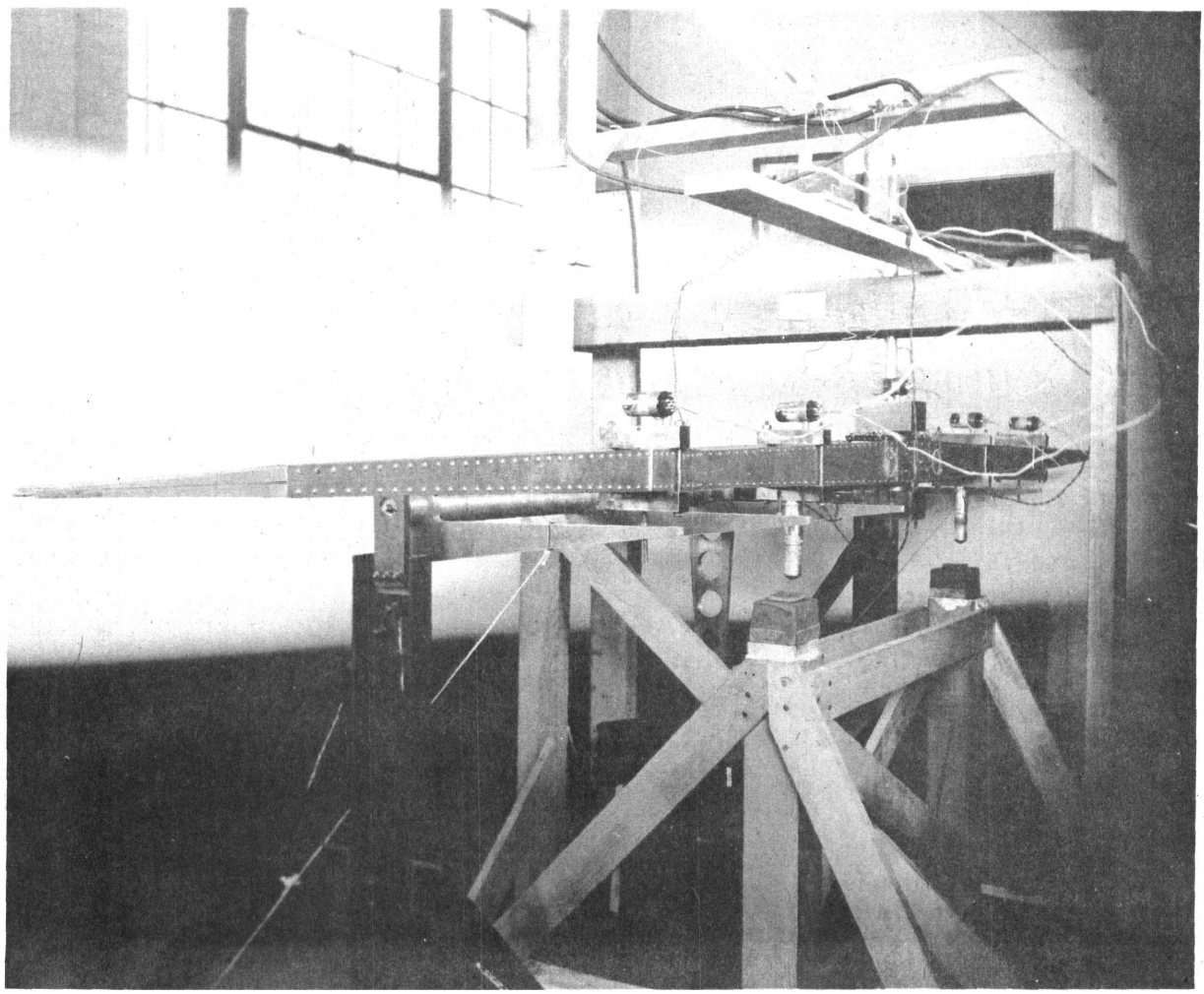
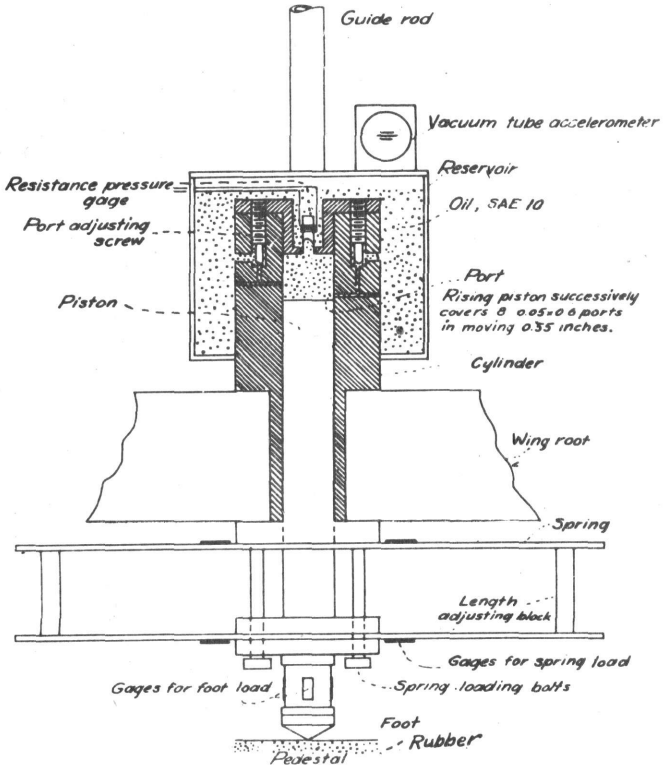


Figure 2. Model Wing on Release Gear Ready for Two Point Landing



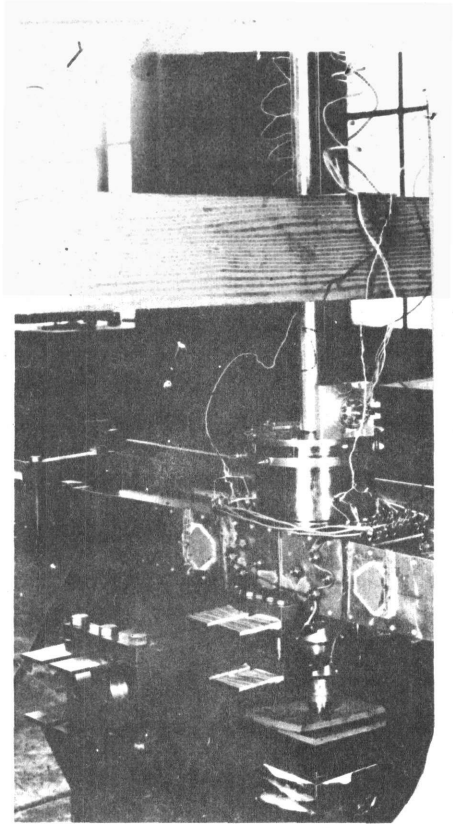


Figure 3. Alighting Gear for Central Landing

adjustable ports so that controlled landing forces with a wide range of shapes could be applied during the landing impact. The test is made by dropping the model from a given height on a synthetic landing field consisting of combinations of sheets of rubber and of plasticene. Special pains are taken to release the model in a "stress free" condition by first supporting it at a number of points (Figure 2), adjusting the position of the supports so that the bending strains produced by the weight of the wing are minimized, and then sweeping all supports simultaneously from under the model at an acceleration greater than gravity. Unless these precautions are taken, the wing will vibrate because of the sudden disappearance of the dead weight forces at the moment of release.

A number of quantities are recorded during the landing impact. The impact force itself is obtained from the output of strain sensitive wire wound around a thin walled tube (Figure 3) just above the landing foot. The spring force transmitted by the landing gear for the one-point landing is obtained from wire strain gages attached to the springs in the gear. The damping force applied by the dashpot is obtained from a pressure gage consisting of a thin walled cylinder with strain sensitive wire which projects into the pressure chamber. The acceleration at the fuselage and at the engine masses is obtained with vacuum tube accelerometers (Figure 4) which were designed at the Bureau of Standards and built by Sylvania Electric Products, Inc. The accelerometer consists of two separate flexibly mounted plates on opposite sides of a fixed cathode inside a glass envelope for a standard vacuum tube. The plates are deflected elastically by the acceleration, thereby increasing the current between one plate

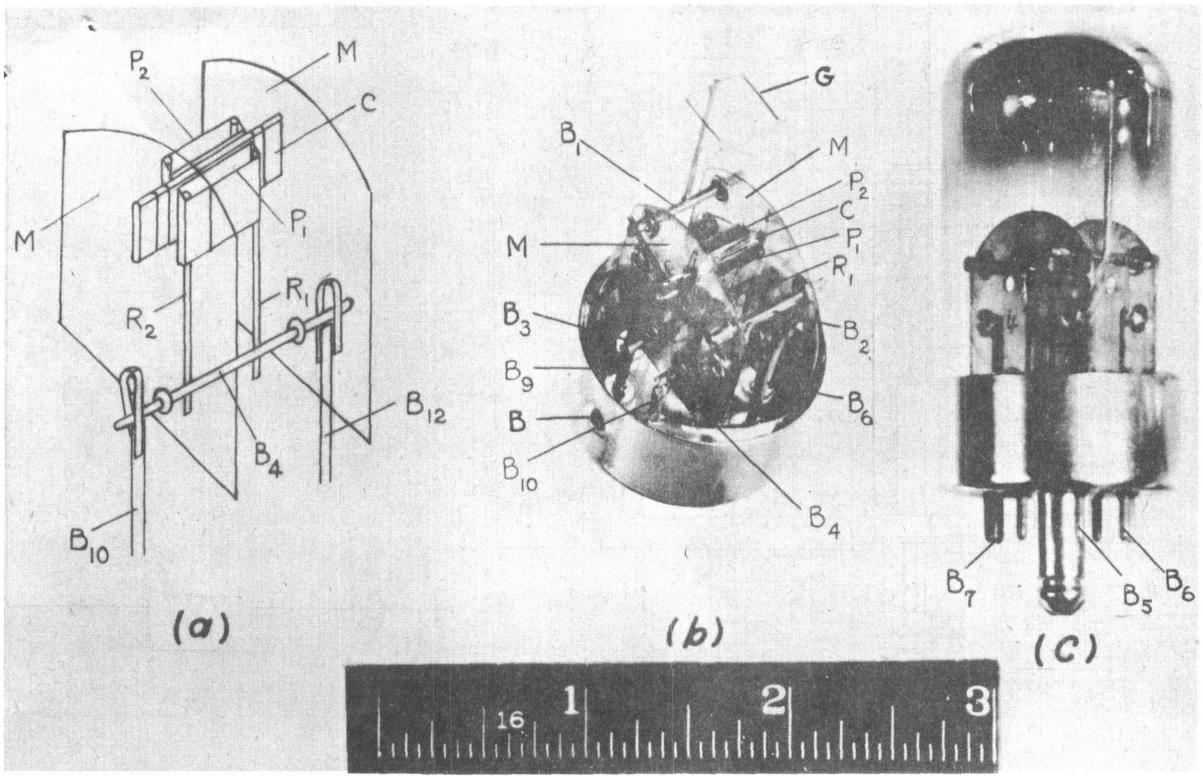


Figure 4. Vacuum Tube Acceleration Pickup

and the cathode and decreasing it between the other plate and the cathode. The total change in current is proportional to the acceleration. It is fed through a Wheatstone bridge and low pass filter into a recording galvanometer. The pickup has a fundamental frequency of about 800 cps.

The bending moments at various stations are measured by attaching pairs of wire strain gages to the top and bottom of the wing.

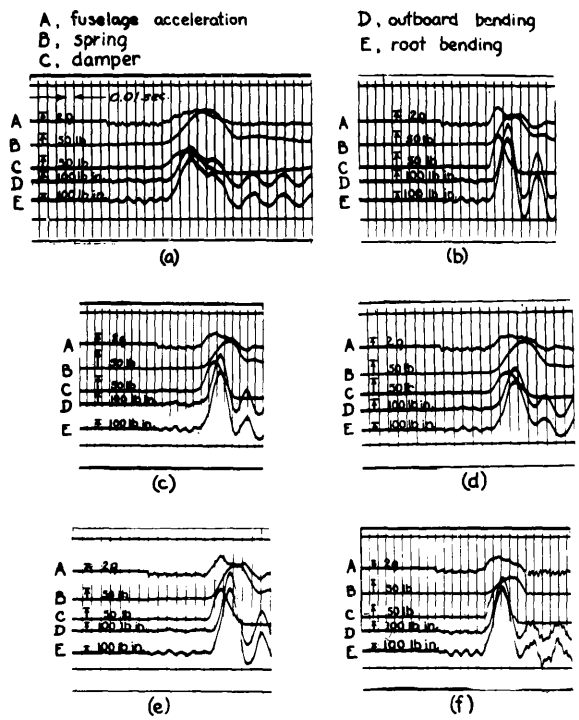
Typical results for one-point landing tests with various conditions of sharpness of impact are shown in Figure 5.

The measured tip deflections, bending moments, and accelerations at the fuselage for a one-point landing are compared in Figure 6, with values computed from the actual forcing function. We see that there is good agreement between computed and measured response.

The tests indicated that the Biot and Bisplinghoff method gives a good approximation for the response to impacts similar to those applied to the model wing, and that it is sufficient to confine the analysis to the first three flexural modes for such impacts.

Comparison of accelerations measured during actual landings with values computed from the Biot and Bisplinghoff theory have shown less satisfactory agreement. In several cases the measured accelerations were much larger than those computed. It has been suggested that this might be due to inadequacy of the envelope of response factors and that it might be due to interaction between the landing gear and the flexible airplane.

The first explanation was studied by including the effect of unsymmetrical landings in the forcing functions which lead to the envelope curve. It can be



Test	Initial spring loading (lb)	Number of rubber pads under landing foot	
		Natural	Neoprene
a	0	5	0
b	0	0	2
c	0	2	2
d	0	2	4
e	0	1	4
f	43	2	4

Figure 5. Records of Six Symmetrical One-point Landings.

shown that unsymmetrical, two-point landings will excite unsymmetrical modes of the wing with a forcing function that can be approximated by a full sine wave. The response of such a forcing function was computed with the result shown in Figure 7. It is apparent that the response may be about 50 per cent greater than that given by the Biot and Bisplinghoff envelope curve if the time of impact is approximately equal to the period of the mode considered. This provides at least one possible explanation for the observed discrepancy between measured and computed accelerations during actual landings.

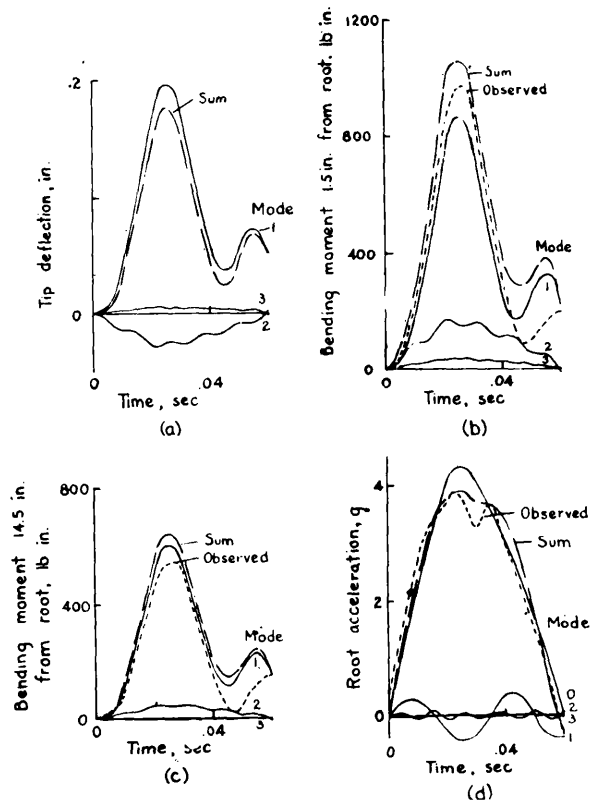
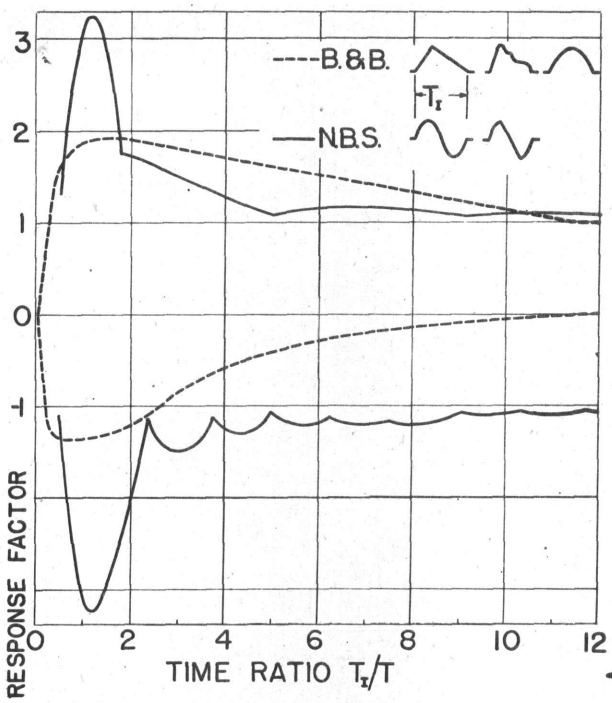


Figure 6. Comparison of Computed and Measured Dynamic Response.

The second explanation was studied by determining the effect of bending of the wing in its fundamental mode on the forcing function applied by the idealized landing gear used in the one-point landing tests of the model wing. The wing of the airplane (Figure 8) was replaced by a cantilever beam with a tip mass. The effect of flexibility was increased by increasing the proportion of mass carried at the tip. In each case the force was determined when this model made contact with the ground at a given velocity of descent. The experimental solution for the effect of flexibility was obtained by measuring the impact force for drop tests with masses at the wing tips and with all mass at the fuselage. Both tests (Figure 9) and analysis showed that the flexibility reduced the maximum force at the landing



gear. The reduction was slight (less than 10 per cent) in nearly all cases. It was concluded that the observed discrepancy between calculated and measured accelerations during service landings should not be blamed on wing flexibility.

Much more must be done to study the problem of landing impact. We should know more about the effects of unsymmetrical landings, of spin up forces for the wheels, of torsional flexibility of the wing, and of impact on water. We are planning to study these effects on elastic models. We hope that corresponding studies will be made on full size airplanes, in order to keep us aligned with the actual problem.

←Figure 7. Envelope of Response Factor for Sinusoidal Forcing Function.

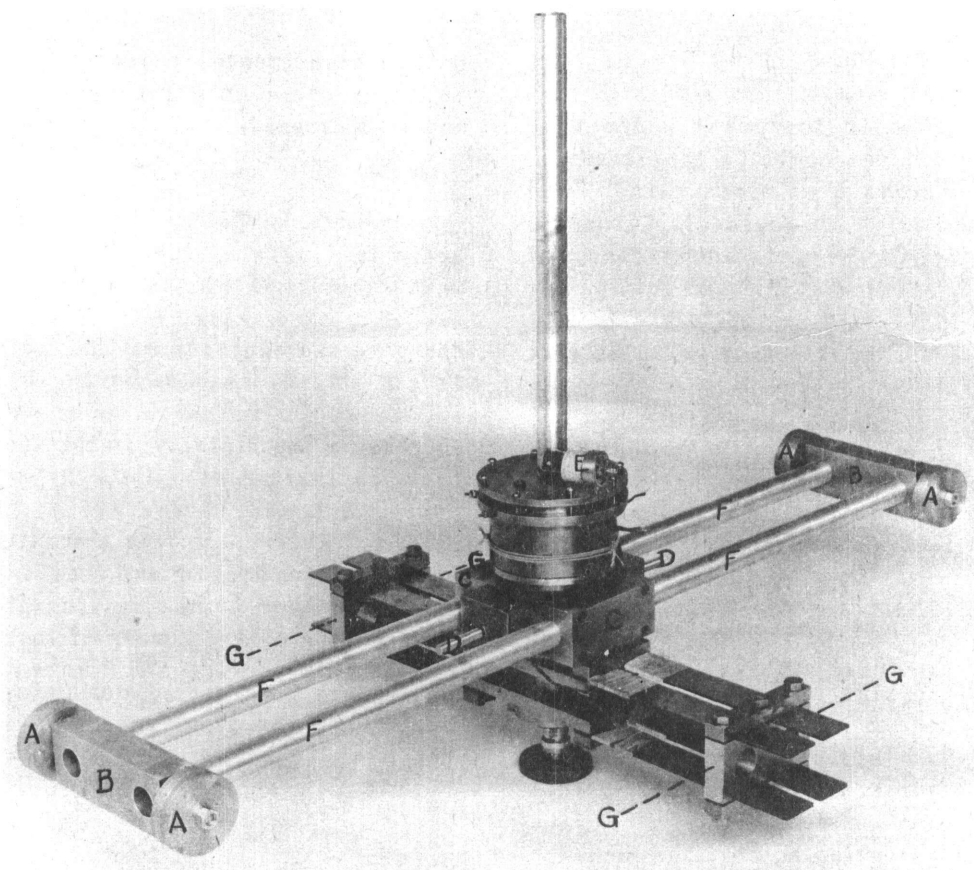


Figure 8. Model for Studying Effect of Wing Flexibility

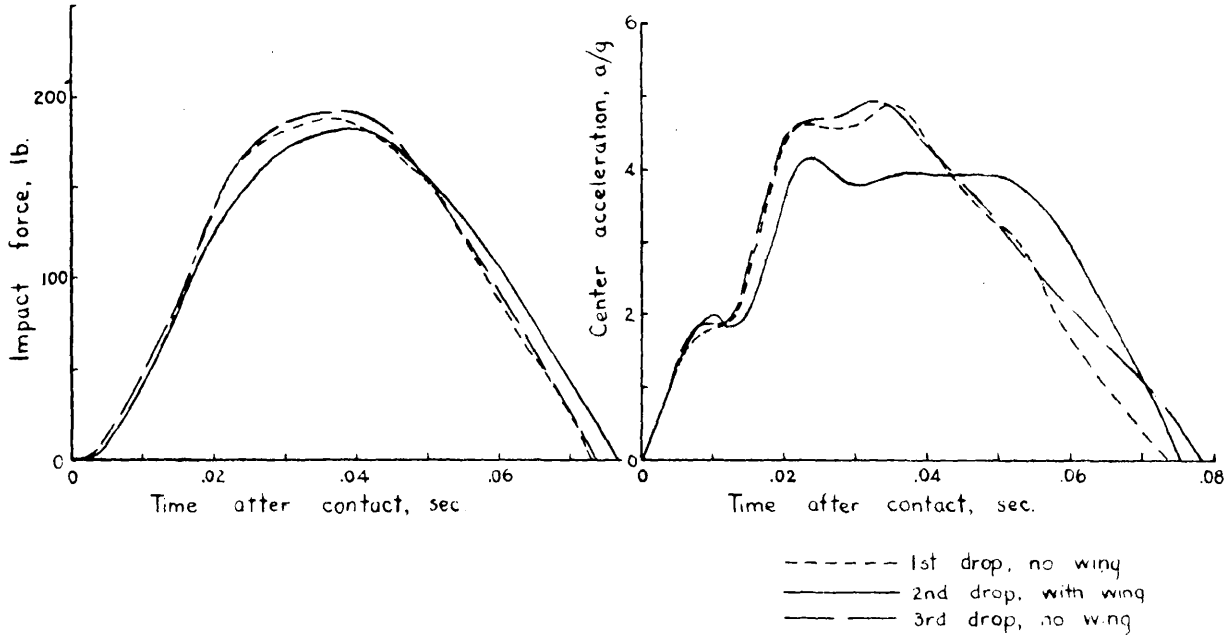


Figure 9. Results of Tests of Model

DISSCUSION

G. M. SCHROEDTER, NOTS: In this testing, it is assumed that simulation has been developed to the point where true landing conditions could be approximated. As you excite natural modes rather than flutter modes, which would give true accelerations of the wing in landing, it would appear that what you are getting now are modes that would be apt to stall. Apparently aerodynamic forces have not been introduced into the simulation.

WALTER RAMBERG, NATIONAL BUREAU OF STANDARDS: We are trying to check the methods of analysis which can be applied to actual landing. We don't include spin forces nor aerodynamic forces, but feel that we have to check the theory.

F. F. KOPTONAK, WATSON LABORATORIES: Explain how the time pulse was controlled on the experimental model of beams. How is the force-time curve varied when the model is dropped?

WALTER RAMBERG: If you will refer again to Figure 3, there are two ways in which the shape of the force-time curve may be changed. The time can be varied by changing the rigidity of the springs, and it can be decreased by moving the blocks in; and the time can also be changed by increasing the rigidity of the foundation-that is, instead of using 1/2" of natural rubber and plasticene, if you want to shorten the time, replace the natural rubber with synthetic and leave out the plasticene. This is also accomplished by closing down on the number of ports on the dashpot.

EJECTION OF PILOTS FROM AIRCRAFT

By

Wing Commander S. R. C. Nelson,

Royal Air Force

Tolerance to vertical accelerations and resistance of the body to forces of certain durations are discussed. Observations are made on the effects of air blast upon the body. Safety harness and related automatic devices are described. The problems of installing the gear in aircraft and educating the pilots in the use of the equipments are outlined.

I wish to explain that the research work treated and the conclusions drawn in this paper have received no contribution whatsoever from me. This work has been done either at or under the supervision of the Royal Air Force Institute of Aviation Medicine at Farnborough, and those of you who have seen and read Flying Personnel Research Committee Report No. 671, will discover nothing new in this paper. However, surmising that a considerable number of you have not read this report, I will discuss certain material from it in the hope that you will be interested in current British thinking on the problem of pilot ejection from aircraft, and the history of its development. In one or two places I will add my own opinion. You will be able to assess this at its proper value. You may notice that almost no mention is made of American work in this field. I have decided to do this because I feel it possible and easier to present British development as an entity. In any case you undoubtedly know more about your country's developments in this field than I do, which makes my decision tactically sound.

Our first clue to the fact that pilot ejection is a practical possibility came from reports of our fighter pilots who, after successfully mixing it with F.W. 190's, reported that as the German machines got into severe difficulties they would often see the pilot suddenly leap about 40 feet into the air like a jack-in-the-box. After some preliminary scepticism, it was accepted that the Germans had a practical ejection seat in their high-speed fighters. In addition to this, a fatal accident in a Meteor aircraft in January, 1944, showed that it was possible for the pilot to suffer very severe injury to limbs and extremities when these were exposed to a high velocity slipstream. As a result, it was recommended that a program should be initiated to investigate the problems of emergency escape at high speed. In the spring of that year, a meeting was held at Farnborough and it was decided:

(a) that any scheme of slowing down the complete aircraft by means of a parachute would be of limited use, would require very long-term development, and

would materially affect airplane design.

(b) that an upward ejection velocity of 40 feet per second should be sufficient in most cases for the pilot to clear the airplane structure. Assuming that the cockpit allowed a two-foot travel before attaining this velocity, the initial acceleration would be 12.5 g acting for one-tenth second. A longer travel would, of course, reduce the g and increase the time of application. Blower tunnel tests had also determined the flight path of a man ejected, with the seat, from an aircraft. These tests with scale models showed that for a pilot to clear the tail of a Meteor travelling at 750 feet per second, his ejection velocity should not be less than 50 feet per second if he and the seat were free to part, or 40 feet per second if he were attached to the seat; further, he might rotate in any direction around his center of gravity at rates of one-half to one and one-half revolutions per second.

The first experiments to determine the behaviour of the body under the required forces commenced at Farnborough in 1944. These were done on a rocket-propelled trolley on steel rails. The force measured was decelerative, the car being stopped in a short distance by an hydraulic cylinder. The final mean value reached was 12 g, which was applied over the first one-tenth second of the duration of the deceleration. These tests did not represent accurately the acceleration time diagram required for pilot ejection, since the deceleration took place over six feet, the total time being approximately 0.17 second and the impact speed 65 feet per second. Following this preliminary work, the tolerances to accelerations have been determined on four test rigs. Most of the work has been done on three test rigs at the Martin-Baker Company. All these were inclined at approximately 20 degrees to the vertical, and the thrust was applied to the body as shown in Figures 1, 2 and 3. The seat and the subject were propelled along rails, being brought to rest by gravity, while downward movement was prevented by the engagement of levers in slots. These test rigs have proved most reliable, and so far hundreds of live tests have been performed without failure of any part of the equipment. The first rig gave a free travel against gravity of 20 feet; the second of 65 feet; the third of over 110 feet. The fourth rig has been in use at the Armament Research Department. Inclined five degrees to the vertical, it has a free travel of 30 feet and has been used to investigate the behaviour of single charges on the complex seat-jack-roller system. The use of restraining gear enables investigation of charges giving a velocity of more than 40 feet per second. It is unsuitable for live tests above 45 foot-seconds due to danger of failure of the restraint, which has occasionally occurred in practice. Figure 1 illustrates the direction of the application of force to the human body in the Martin-Baker seat. Figure 2 illustrates the initial results on the first Martin-Baker rig. The acceleration curves are derived from space-time recording by means of a high-speed cine camera operating at 750 to 1000 frames per second. Only approximate values are shown, since this method is admittedly inaccurate. The third, and last, curve in Figure 2 proved to be acceptable physiologically, but the first and second curves produced trauma on subjects.

Following flight trials in a Defiant aircraft with a Martin-Baker installation in May 1945, it was decided the ejection velocity should be increased to 60 feet per second. Martin-Baker, therefore, developed a multiple charge system with stroke lengths of 34 to 40 inches, which proved to be acceptable physiologically to subjects on a soft, down cushion. It was necessary to develop an accurate system of recording the acceleration. The Electronic Section R.A.E. utilized for this, at the beginning, strain gauge type accelerometers with amplifiers and C.R. tubes and, later, Miller type inductance accelerometers with amplification and galvanometer recording.

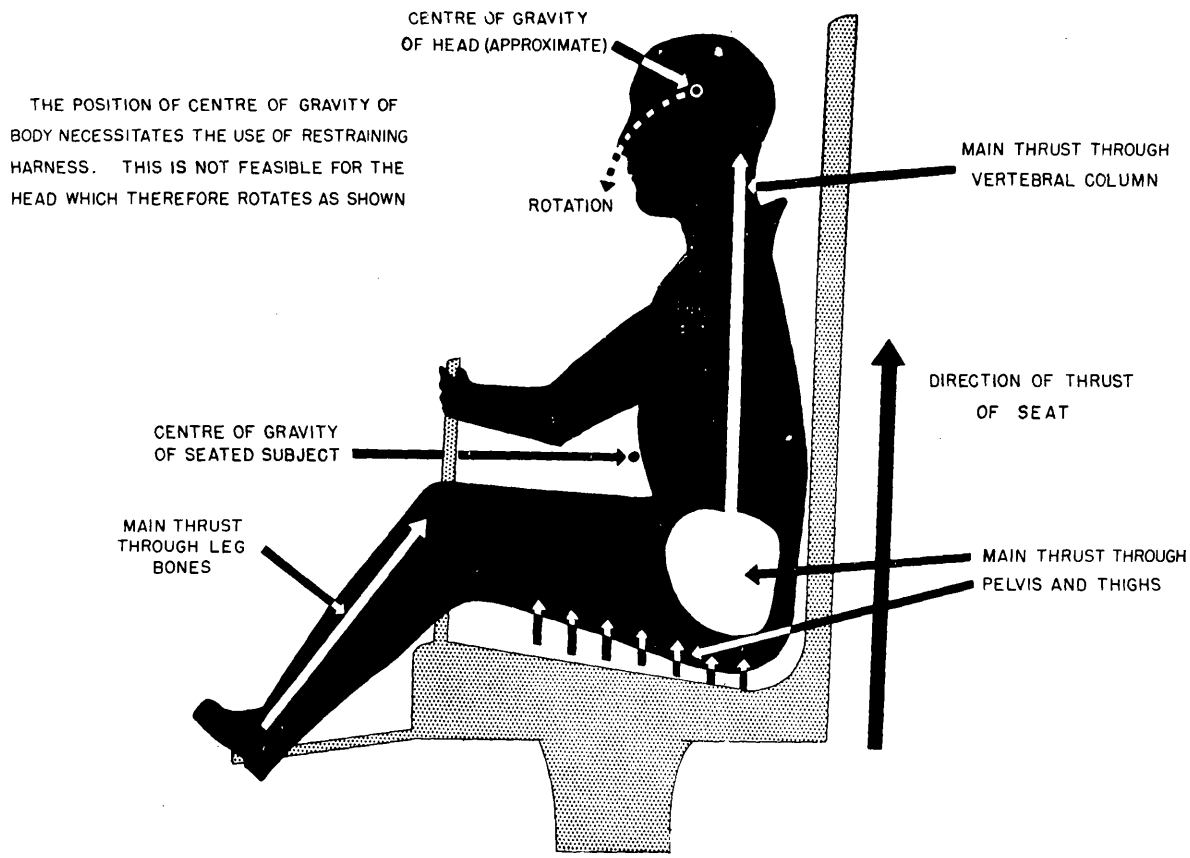
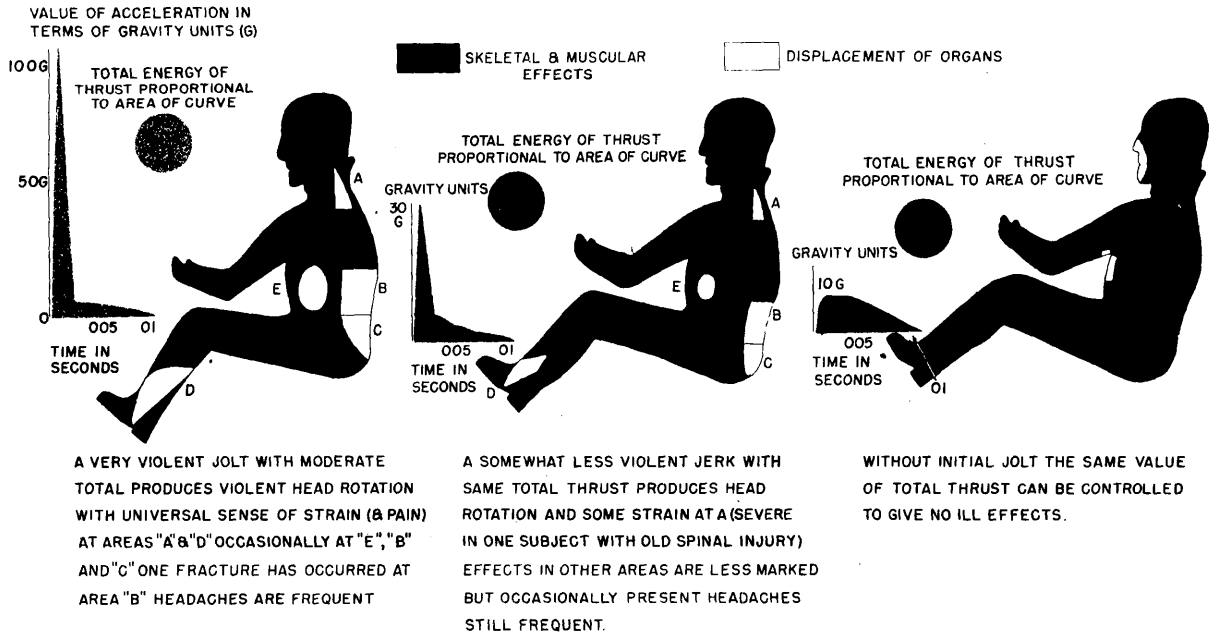


Figure 1. Investigation of Structural Strength of Human Body



A VERY VIOLENT JOLT WITH MODERATE TOTAL PRODUCES VIOLENT HEAD ROTATION WITH UNIVERSAL SENSE OF STRAIN (& PAIN) AT AREAS "A" & "D" OCCASIONALLY AT "E", "B" AND "C" ONE FRACTURE HAS OCCURRED AT AREA "B" HEADACHES ARE FREQUENT

A SOMEWHAT LESS VIOLENT JERK WITH SAME TOTAL THRUST PRODUCES HEAD ROTATION AND SOME STRAIN AT A (SEVERE IN ONE SUBJECT WITH OLD SPINAL INJURY) EFFECTS IN OTHER AREAS ARE LESS MARKED BUT OCCASIONALLY PRESENT HEADACHES STILL FREQUENT.

WITHOUT INITIAL JOLT THE SAME VALUE OF TOTAL THRUST CAN BE CONTROLLED TO GIVE NO ILL EFFECTS.

Figure 2. Investigation of Structural Strength of Human Body

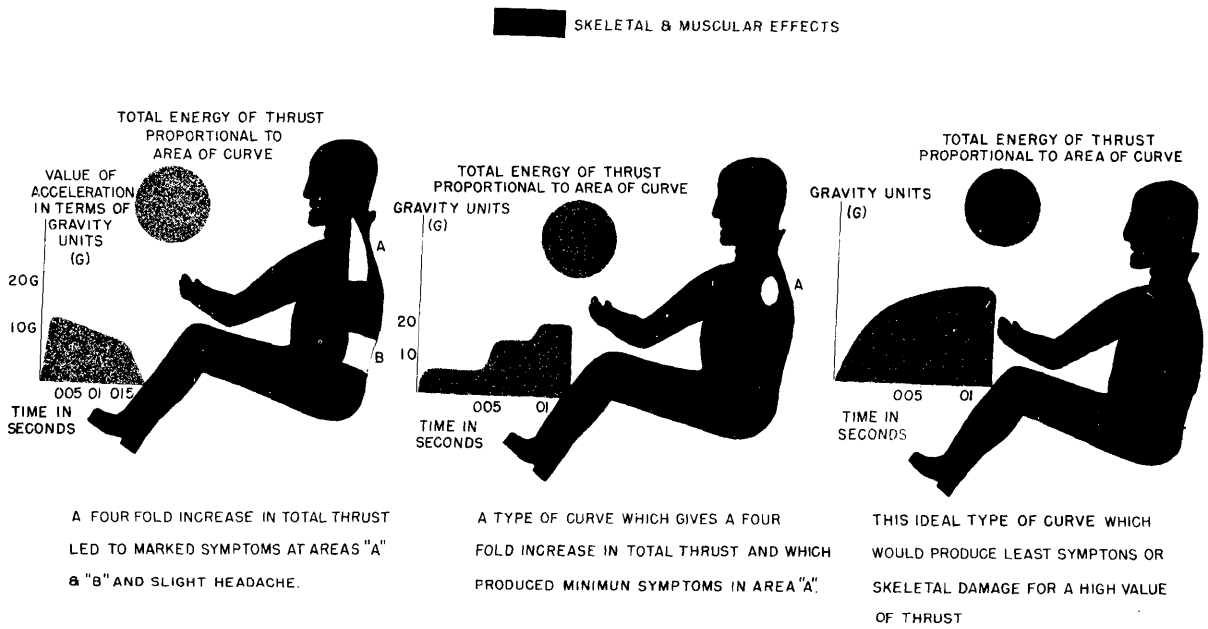


Figure 3. Investigation of Structural Strength of Human Body

An investigation of support for the upper half of the body was carried out, and it was apparent that, with ejection velocities in excess of 45 feet per second, some form of restraint, additional to a safety harness, must be applied. The development of the multiple charge led to the fundamental physiological principle that, at the higher acceleration values, the rate of onset of g should be controlled so as to take advantage of the composite elasticity of the body. A dummy for use in these experiments was produced at Farnborough, and it is approximately anatomically correct as regards centers of gravity of the whole and of its various parts. It weighs 185 pounds and has provision for either strain gauge or Miller type accelerometers in the trunk and head. From this series of experiments two conclusions emerged:

(a) It is probably unwise physiologically to subject a person to acceleration much greater than five g applied in the first one-hundredth of a second to or to final values greater than 25 g.

(b) There is an intimate relationship between the accelerations recorded on the seat and those recorded on the person or on the dummy.

Further investigations have shown that the that the natural frequency of the gun, seat, jack, roller mechanisms, and mass accelerated on the seat have a very marked effect on the accelerations recorded both on the seat or on the mass. To some extent the amount and nature of padding between the mass and the seat also affects both records. On this data a single charge system was developed by the Armament Research Department with a jack designed by R. Malcolm's Limited, which has a stroke of 36 inches. This system has characteristics which seem to be physiologically acceptable, but complete proving tests have not yet been done. Provided they are satisfactory, we will probably adopt the single charge system in preference to our present multiple charge. Additional work on the Martin-Baker test rig has demonstrated that if vertical ejection velocity in excess of

60 feet per second has to be catered for, the stroke of the jack should be four feet or over. With a stroke of four feet, velocities approaching 70 feet per second have been attained without damage to live subjects. At present, flight trials confirm that 60 feet per second will provide adequate clearance at indicated air speeds of 500 miles per hour.

The sequence of events in pilot ejection are:

(a) The pilot places his feet on the stirrups attached to the seat and disconnects any attachments between himself and the aircraft.

(b) He then reaches above his head with both hands and grasps two handles to which a shaped roller blind lined with chamois is attached.

(c) This blind is pulled down in front of the face (see Figure 4), insuring that

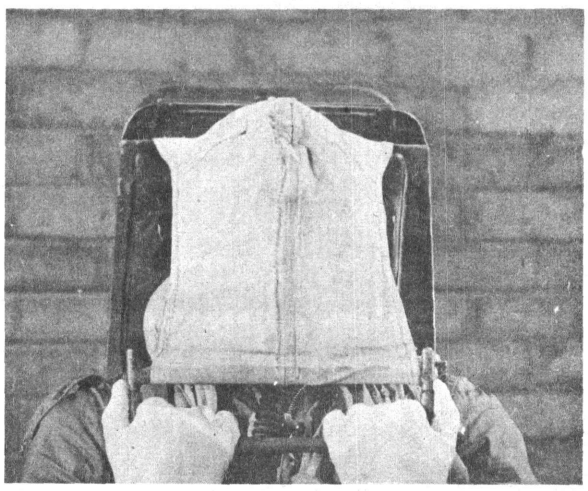


Figure 4.

the arms are supported, the face is protected, and the head is in correct position. The unrolling of the blind fires the ejection charge, and immediately afterwards a small drogue 'chute is developed. This prevents tumbling and, after an interval of seconds, when deceleration is adequate, the drogue 'chute pulls out a 28 foot canopy which supports the seat and the pilot in it.

(d) He can then release himself from the seat and descend by his pilot type chute.

Accelerations: Duration 0.2 seconds. Maximum 18 g - 20 g on occasions but never greater. Rate of build-up 150 g per second - maximum 200 g per second. Double cartridge system (cordite).

Effective stroke length: Usually 42 inches.

Angle of ejection: Usually 23 degrees from vertical but may vary slightly with individual installations; e.g., in navigator's seat in multiple seaters (medium bombers).

Clearance over tail of Meteor: Approximately 10 feet at 500 m.p.h. (indicated). Live ejection.

Apart from adequate clearance of the aircraft structure, a basic requirement for abandoning aircraft at high speed is a close approach to simultaneous exposure of all parts of the body to the airstream. In practice, a tenth of a second has been chosen for the ejection time. It is considered that this time is sufficiently brief and should cause no ill effects. Possible causes of injury due to air pressure may be summarized as follows:

(a) Variations in coefficient of drag of various parts of the body. There is, as yet, little information regarding the aerodynamics of the human body and, in the past, the coefficient of drag of the whole body has been arbitrarily taken to be 0.8. It is believed that a properly designed seat will act as a splint and protect personnel from injury, but it is to be noted that arms have been injured by sudden exposure to slipstreams at speeds in the two hundred mile per hour range.

(b) With a slow exit, differential pressures may exist between the mouth and thorax, resulting in sudden distention of the lungs and temporary or permanent damage.

Experiments have been done both in Germany and by the U.S. Navy exposing subjects to windblast in the neighborhood of 500 miles per hour without major effects, beyond inability to open the eyes and some temporary embarrassment to respiration. The highest speed at which a live ejection has yet been made by us, is 505 miles per hour. In this, the subject stated that the protection offered by the Martin-Baker blind was excellent and that he felt no more symptoms than in a previous ejection at 300 miles per hour.

(c) Rotation around the center of gravity may follow ejection. At one and one-half revolutions per second the radial acceleration at head and feet may be in the order of five to six g, and it is considered that this would be incapacitating even if of brief duration. From the various flight trials, an analysis of motion picture records does not show any rotation at a speed greater than one revolution per second and, if the parachute stowage and various ancilliary pieces of equipment are properly designed, the seat and pilot would appear to be aero-dynamically stable until they are falling free. The use of a small pilot-type 'chute to stabilize the seat has proved beneficial. In the latest series of flight trials in a Meteor aircraft, rotation has not been observed. It can be stated that the Germans did not consider rotation to be a problem. They believed, when it did occur, that the radius was sufficiently large to prevent physiological effects, the line of action of the force being transverse to the body. Exposure of the subject to an airstream of 500 miles per hour has been compared to a deceleration of 25 g. It can be confidently expected that forces of this order will not give rise to injury, provided the subject be in close contact with the seat, since the duration will be brief. There are certain modifying factors which must be taken into consideration:

(a) Apart from the possibility of displacement of helmet and mask assembly by the slipstream, the association of anoxia and high acceleration would probably induce unconsciousness at altitudes above 45,000 feet. For safety in escapes from or above this altitude, the pilot would have to be dropped in a pressurized cell, or suit, or even in his cockpit.

(b) At very low altitudes, a maximum ejection velocity would afford more time, but the effect of high opening shocks at high speed requires further investigation.

(c) In loss of control in a spin or spiral dive, considerable centrifugal acceleration may be imposed. This would tend to reduce the ejection velocity. Practice trial in flight has shown that it is possible to operate the Martin-Baker blind at three g. At four g it is still possible, but the time required is greatly prolonged and the action made will be impossible for some subjects; although, from experience one would expect a man under the stress of emergency to be capable of considerably more muscular energy than he could produce for similar movement on the ground. It should be further borne in mind that, when the seat is in top position, the foot rests may be higher than the rudder panels. Under high centrifugal acceleration, this would make it impossible to place the feet on the foot rests and thus increase the hazards of ejection. We have met this problem by keeping the foot rests below floor level in all cases and providing guiding channels for the feet from the rudder bars to the foot rests.

With regard to Safety Harness, a combined parachute-safety harness is now being developed, and when a satisfactory one is produced it will unquestionably simplify escape drill. A prime requirement of such piece of equipment would be that in automatic or voluntary detachment from the seat, all four points of attachments should be separated simultaneously. It will have an inertia lock on the shoulder harness to the seat and tensioning gear for the lower abdominal attachments.

in this connection, it should be mentioned that further development must be based upon a clear decision as to which of two methods of separation from the seat would be employed. These methods are:

(a) automatic separation of pilot and parachute from the seat very shortly after ejection. If this method were chosen, a very few seconds after ejection the pilot would automatically be separated from the seat or would separate himself voluntarily. If the pilot is ejected at a great altitude and remains conscious, he would fall freely until reaching a safe height for release of his parachute. Education and training should insure successful operation. If he were unconscious, an automatic device would open his parachute at some predetermined altitude. In this method one would not be able to take advantage of the stabilizing Drogue parachute due to rotation and tumbling which would increase the danger of loss of gloves, etc.

(b) Under this method the pilot would descend in the seat to a safe altitude. A canopy attached to the seat would open automatically and, if circumstances made it desirable, the pilot could then detach himself from the seat, completing his descent with the normal pilot-type parachute. If circumstances rendered this course undesirable, he could stay in the seat and land with it. In this connection, I might say that in one of our latest live ejections the subject remained in the seat due to having pulled and fouled his pilot-type parachute. He was unfortunate enough to land in the seat on a concrete base with the result that he fractured his lumbar spine. However, the fact that he was not killed can be interpreted as being encouraging.

As you know, the second method has been favoured in the R.A.F. because of the advantages of the positional stability on descent and the time of opening of the main canopy. In any such system in which automatic devices play a part, there must be overriding manual controls. For instance, in the case of ejection at very low altitudes, time delays built into the automatic devices for the purpose of insuring the minimum jolt on opening the parachute would cease to be advantageous and would become a positive menace. In considering the two possibilities for escape, it is quite obvious that the first method treated would impose considerable delay on the user or offer great risk (danger of entangling parachute if it were pulled prematurely). We feel that it would be better in these cases to offer the possibility of opening the large parachute canopy immediately, as, undoubtedly at high speed the jolt would be extremely high and the shock would be much more tolerable if transmitted through a seat instead of through a parachute harness. Also, in this type there might be no delay between ejection and pulling the cord, and the chances of entanglement are considerably reduced. It will be seen from the example I have mentioned that landing in the seat is not without its hazards, but I would venture the opinion that it is preferable to landing without a parachute.

Helmet-Mask Assembly

The helmet and mask may be displaced or entirely lost by reason of high accelerative forces (10 to 11 g will displace the latest R.A.F. mask downwards, even though straps are tightened to their maximum). Moreover, helmet-mask assembly might be removed by airblast. Development of a full face mask is under way, but, in the meantime, it is considered that the blind on the Martin-Baker seat offers considerable protection, at least against airblast and, to some extent, the effects of acceleration. A positive, quick disconnect for all tubular and electrical leads to the pilot is an obvious necessity. I believe that these leads should be cut as close as possible and that there should be the minimum of metal or plastic material, if any, at the point of discon-

nection. The danger of loose wires, etc., (particularly with heavy objects at their ends) flailing the pilot is obvious. Emergency oxygen must, of course be carried and a means has been devised of turning it on easily and with certainty.

Clothing

No special clothing has been developed. The light weight, one-piece overall has been worn in our ejections and has proved to be satisfactory.

Head Restraint

The function of the Martin-Baker head blind has already been mentioned. Other forms of fixing have been tried or considered. The head blind is the only method developed so far which positively keeps the head in contact with the head rest throughout the ejection procedure (See Figures 5 and 6).

Installation in Aircraft

Central coordination is necessary if progress in this field is to be satisfactory. It is of prime importance that drawings of cockpit layouts and prototype mock-ups in which ejection seats are to be fitted should be inspected at an early stage, so that adequate clearances on ejection may be insured.

Morant has derived data from measurements of a large number of pilots in relation to the important cockpit dimensions. The thigh length and shoulder breadth should have adequate clearance throughout the entire distribution range; otherwise, injury might occur by striking some part of the cockpit. The use of hand grips or arm rests involves widening the cockpit compared to the position where the arms are held centrally over the body. The minimum width of the cockpit at the shoulder-elbow region should be 27 inches, and a fore and aft length of at least 33 inches is necessary for thigh clearance, provided a position is assumed so that the feet do not project beyond the knees. The actual fore and aft dimension of the cockpit will, therefore, depend upon the additional dimensions of the seat, jack, and rail attachments, and whatever padding or cushions may be added for seat comfort.

It is clear that back type parachutes or emergency packs could not be used unless designers are willing to increase fore and aft dimensions of cockpits considerably. Ideal dimensions for a cockpit, accommodating pilots of all sizes and allowing adequate clearances in ejection, have been worked out. The seat adjustment, which has to be parallel to the ejection rails, has a range of 5 inches, and the rudder bar adjustment has the unusually large range of 13 inches on an arc rising as it approaches the pilot. In all cases the feet are slightly higher on the rudder bar than on the seat rests used for ejection. This work has been reported on in Flying Personnel Research Committee Report No. 689.

The only alternative to a large fore and aft dimension is preselection of pilots in bodily size so as to exclude those with long thigh lengths.

In an emergency it is not possible to guarantee the position of the control column, and some redesign of the handgrip may be necessary to avoid injury to the inner aspect of the thighs during ejection in retrospective installation. The control column recommended for future design has a horizontal column control, and will be required to be positively moved forward during ejection. It is apparent that the application of maximum acceleration to pilots of 200 pounds weight or more will require a charge which might cause injury to pilots in the lighter weight ranges. It should be noted that a restriction in weight to 172 pounds (nude) implies a total penalty of approximately only four percent. The question of seat adjustment is most important from the aspect of seat comfort. One British manu-

SUBJECT WITH HEAD RESTRAINT.

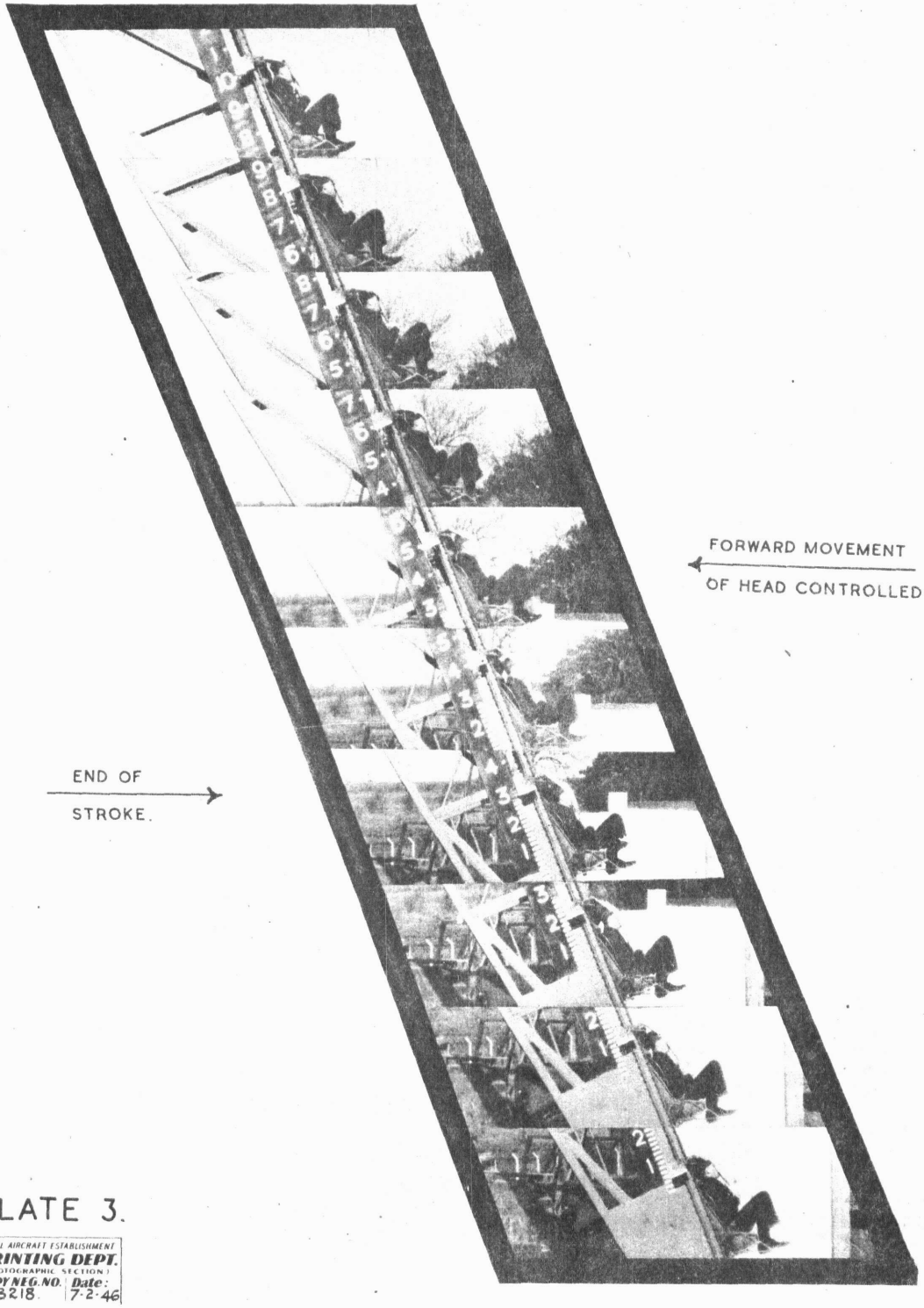


PLATE 3.

ROYAL AIRCRAFT ESTABLISHMENT
PRINTING DEPT.
(PHOTOGRAPHIC SECTION)
COPY NEG. NO. 68218.
Date: 7·2·46

Figure 5.

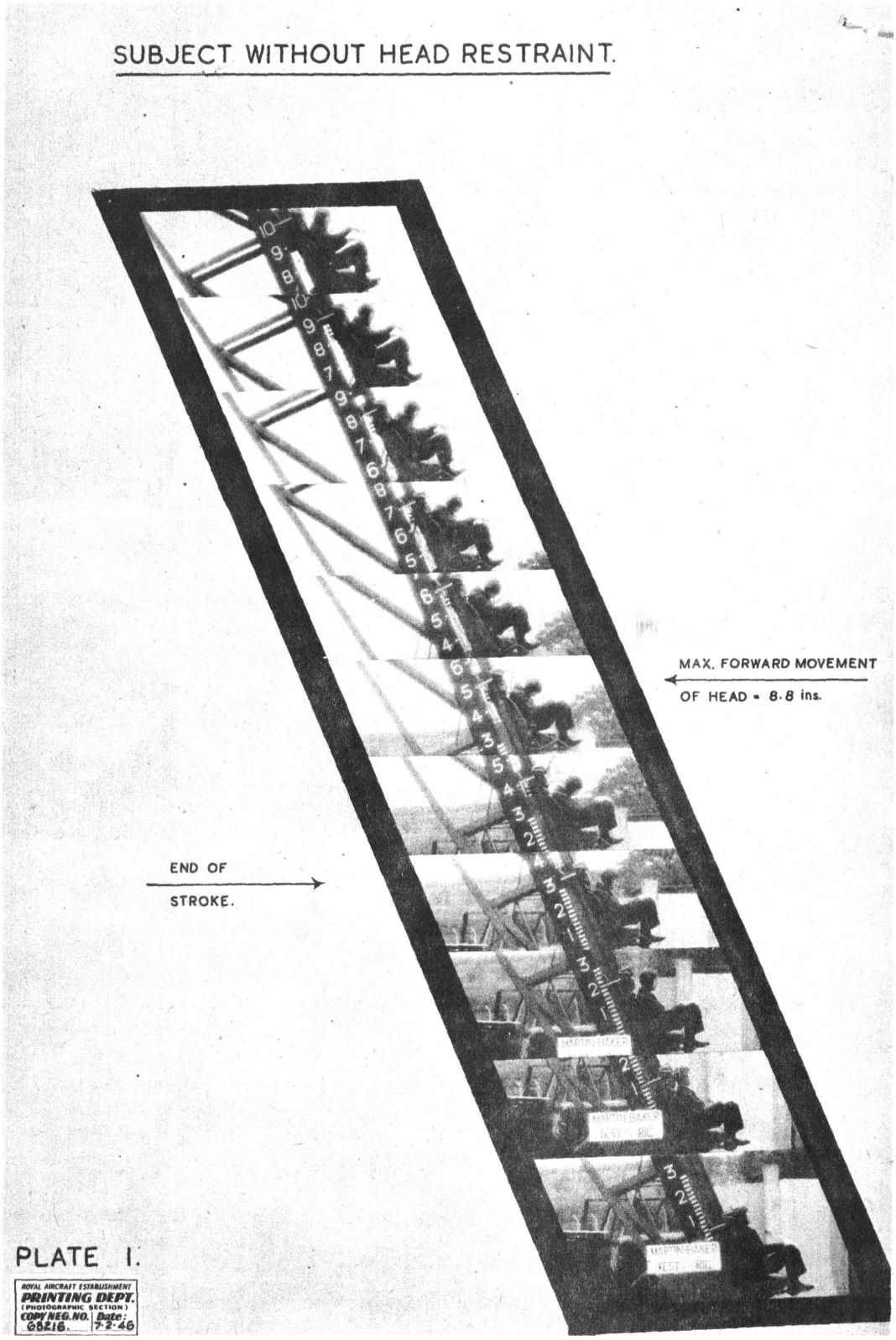

SUBJECT WITHOUT HEAD RESTRAINT.
END OF
STROKE.
MAX. FORWARD MOVEMENT
OF HEAD = 8·8 ins.
PLATE I.
ROYAL AIRCRAFT ESTABLISHMENT
PRINTING DEPT.
(PHOTOGRAPHIC SECTION)
COPY NEG. NO. 68216.
Date: 7·2·46

Figure 6.

facturer produced a prototype which had movable rails and jack. It is considered that the seat which can be tilted is capable of being adjusted to give greater comfort than one which can be raised or lowered only. However, the principal disadvantage of the movable rails is that the pilot might fire the seat when it is tilted and so suffer severe injury if clearances are insufficient. The solution to the problem seems to be that the rails should be fixed but that the back of the seat should be adjustable. However, in this connection investigation should be done as to the maximum tolerable angle between the spinal column and the line of ejection for the accelerations used. A final and most important requirement is instantaneous jettisoning of the hood. If the hood should remain in place, the pilot would probably suffer severe injury, notwithstanding the possibility of protection from the projection of the seat. Jettisoning of the hood must be positive and instantaneous and might possibly be linked to the firing of the seat by suitable time delay. If it is necessary to have separate control, it must be mounted in such a position to avoid possible injury to the arm if it were swept into the windstream.

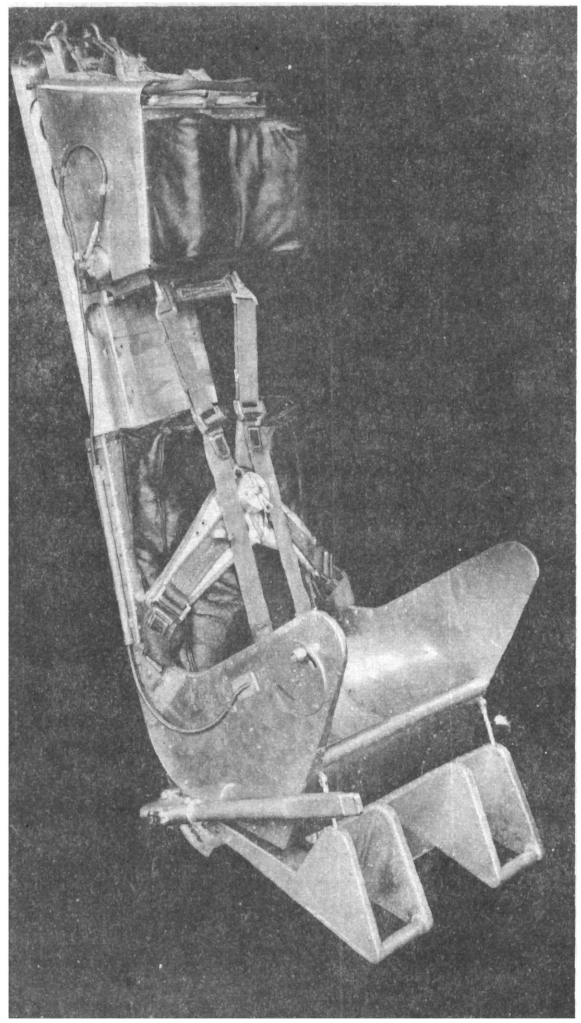


Figure 7.

Present Position

The seat with the ejection system (Figure 7) is to be designated the Mark I ejection seat and will be fitted in all Meteor IV aircraft and all subsequent prototype aircraft capable of a true air speed of 400 miles per hour or more in level flight. Instead of the old tubular welded structure, the new seats will be made of riveted sheet metal. The seat pan is movable up and down over a six-inch range by means of a hand operated lever at the right hand side. The rest of the seat remains stationary in the rails, that is, the head rest position is fixed and thus the eye sighting line remains constant with different sizes of pilots. The pilot will sit on a seat type parachute and a specially designed felt cushion incorporating a water cushion. Telescopic foot rests to accommodate different sizes of pilots have been designed and may yet be used. The head rest is dished and has been proved sufficient in depth to cater for sagging under accelerations of all sizes and subjects.

The head blind is still used as the method of firing for the other advantages already mentioned. Knee guards on the seat are provided to prevent displacement of the knees in a narrow cockpit and to prevent forcible abduction or swivelling of the body from effects of air blast.

Education of the Pilot

Familiarization to the physiological effects of the accelerations occurs after severe ejections on the test rig. Muscular strains are not felt to the same degree, and some degree of adaptation appears to take place physiologically and psychologically. This process appears to be similar to physical conditioning. It has, therefore, been thought that for purposes of education a series of runs on the test rig to heights of about thirty feet, with mean maximum acceleration of approximately 9 g, would be more beneficial than single runs with the maximum or operational charges. A most important point is that the pilot should be trained to go through in detail all the motions he would require in an actual ejection, and that he should be trained to assume the position best suited to insure adequate clearance of the cockpit aperature. It is suggested that the seat could be mounted on a device operated electrically so that the pilot could be raised through an adjustable opening which would be fixed to the size of the aperture of the cockpit under consideration. By such a device, it could be determined whether any particular pilot could be safely ejected from any particular aircraft. If a pilot were found to be unsuitable for any particular type, because of his size, his log book should be endorsed accordingly.

Conclusion

The problems of escape from high-speed aircraft, at very high indicated speeds or at very high altitudes, is extremely complicated and demands a specialized team of investigators under central direction.

The mechanical, aerodynamic, and physiological requirements are so integrated that it is difficult to assess any one aspect of the problem (e.g. the physiological) as an entity, and the correct solution in any given case is undoubtedly a compromise between what is mechanically or aerodynamically possible and what is physiologically desirable.

It is clear that future requirements of escape from aircraft demand much greater consideration from designers than has been the case in the past.

For seat ejection, two general stages are envisaged. Firstly, ejection from the aircraft, which in itself is a great advance but implies a conscious pilot for preservation of life; secondly, development of ejection with auxiliary automatic mechanism to insure that an unconscious pilot will avoid severe injury.

THE MEASUREMENT OF FORCES ACTING ON PILOT DURING CRASH LANDING

By

A. E. McPherson

National Bureau of Standards

This paper describes the development of a dynamometer for recording the maximum loads reached in a pilot's lapstrap and shoulder harness during a crash landing. The work is sponsored by the Airborne Division of the Bureau of Aeronautics as part of their program to determine the force acting on pilot restraining harness during a crash.

About three years ago the Bureau of Standards was asked by the group which is now the Airborne Equipment Division of the Bureau of Aeronautics to assist in the development of instruments for measuring the forces acting on an airplane pilot during an accidental crash.

Information regarding the magnitude of these forces, measured in actual service crashes, would be of great value to the designers of pilot restraining harness, seats, carry-through seat structure, etc. From the medical angle, the value of such information is obvious. It should be stated at this time that the crashes expected to yield the most useful information are of the types which frequently occur in training and do not result in collapse of the cockpit.

At the time when this program was started, one of the common features of a severe training crash was the tearing loose of the pilot's seat with the pilot securely attached thereto. Consequently, it was felt that measurements of the maximum forces in the pilot's harness would, in many cases, be limited by the strength of the seat carry-through structure.

In view of this condition, it was decided that the best approach to the measurement of the forces on the pilot would be to measure the deceleration of the plane near the pilot seat and from this calculate the forces on the pilot, his harness, his seat, etc.

After considerable study, it was decided that the first decelerometer should be capable of recording the maximum deceleration accurring along a given line.

The instrument finally constructed is shown in Figure I with its protective cover removed. Deceleration in the direction A tends to move the scriber S over the chrome-plated target by an amount proportional to the deceleration, provided the natural frequency of the mass and spring system are much higher than that of the deceleration. In order to prevent motion of the scriber due to deceleration encountered during normal operations of the plane, the stop B was pushed against the

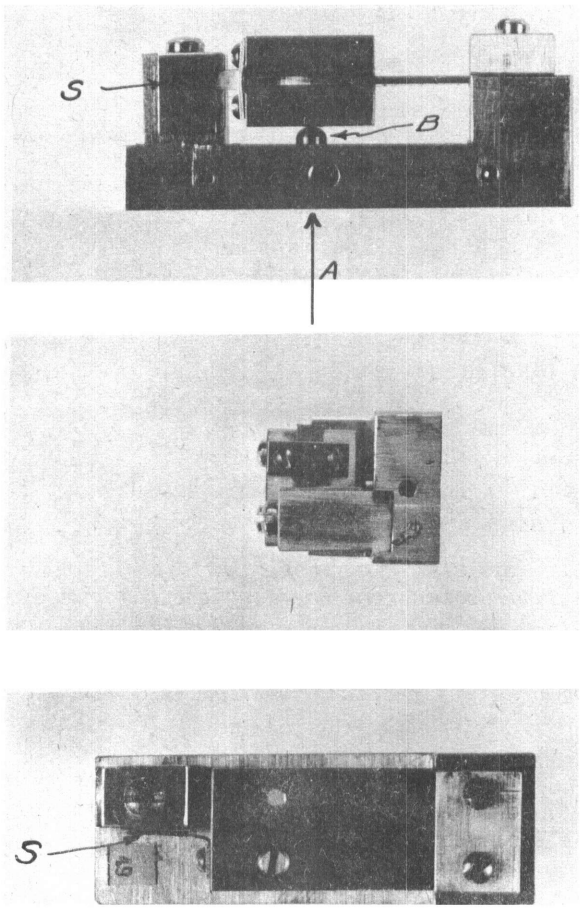


Figure 1.

mass so that a deceleration of about 10 g was necessary to move the mass from the stop and to start recording. The mass spring system of the instrument had a natural frequency of about 160 cps which was considered well above the 10-20 cps estimated equivalent frequency of the acceleration of the pilot during a crash. Fifty such instruments were manufactured and calibrated. Twenty-four planes were fitted with pairs of the instruments set so as to record forward and upward deceleration.

Several crashes occurred in planes so equipped, and the decelerometer records were examined. The results were very disappointing, since it was found that the instruments had responded to high frequency acceleration to such an extent that the targets were badly blurred and yielded no reliable data. This response was also found on instruments of intact ships, in which case it was attributed to the shocks set up by the extremely hard tail wheel of the planes used. Short flight tests at Anacostia, in another type of plane, had shown that the stop worked satisfactorily.

At this time, it was decided that the Bureau should devote its efforts to development of instruments suitable for measuring the maximum forces in the pilot's harness in planes by now equipped with much stronger harnesses and seats. This instrument was to be inserted in series with the piece of harness at its attachment point and remain there ready to record the maximum load reached during a crash.

Several elastic dynamometers using scratch recording systems were considered, and the most promising one was built and tested. This instrument was satisfactory for recording slowly applied loads but was unsatisfactory for dynamic loads, due to resonant response of the recording system. Attempts to eliminate this response were unsuccessful.

Crash dynamometers, ring type I and II, were then developed to record the maximum load applied to a piece of harness. This dynamometer is believed to be practically free from natural frequency response of parts. The ring type II instrument described here is the second form of ring type instrument developed. It is a development of the original single ring dynamometer to fit into less space, and it is of more simple construction.

Two forms of the instrument have been made; one for insertion in the lapstraps and the other for insertion in the shoulder harness. Since the instruments are practically identical, the discussion will, in general, be limited to the lapstrap instrument.

The principle of the dynamometer can be described by reference to Figure 2. The end pieces A and B divide the load between the rings C which are loaded across a diameter by the bolts as shown in the assembly at the top of the Figure. When the rings are loaded beyond their elastic range, the permanent deformation, measured as the "final diameter" of the ring perpendicular to the direction of loading, has a definite relation to the maximum load applied.

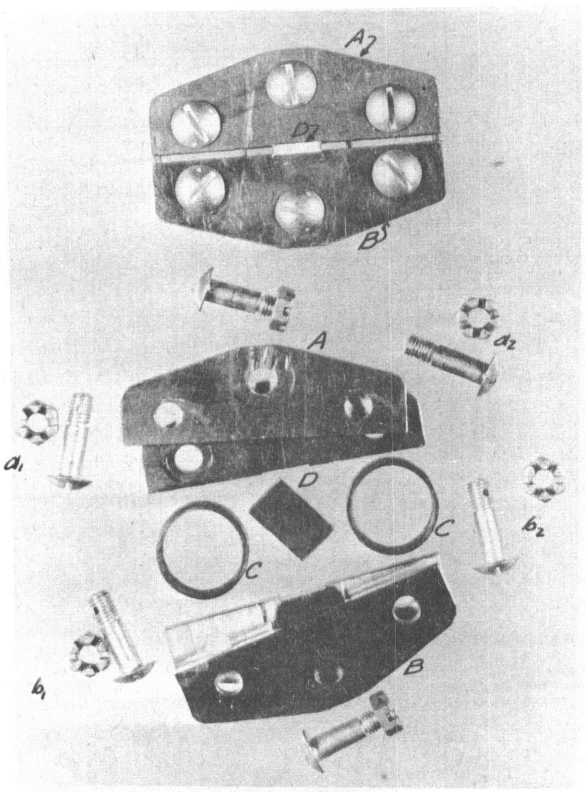


Figure 2.

The assembled lapstrap instrument shows the keeper D clamped between the ends A and B. This keeper is inserted while the dynamometer is under a load of about 500 pounds. When the load is removed, the rings, stressed slightly beyond their elastic limit, close up to clamp the ends firmly together across the keeper. The dynamometer now acts as though it were one piece and will not separate and record until a load higher than the preset load is applied. The preset load is chosen so that the instrument will not separate and record during normal operations of the plane.

The relationship between maximum applied static load, applied with a testing machine, and "final diameter" for 1/4 inch long lapstrap rings is shown by vertical crosses on the calibration curve Figure 3.

Dynamic calibrations were made by arresting the hammer of a modified impact testing machine with a half lapstrap in series with a ring type II dynamometer and an electric recording dynamometer. Each point plotted is half the peak load from the electric dynamometer plotted against the average "final short diameter" of the two rings in the dynamometer which in no case differed by more than 0.010 inch. During tests of both the single and double-ring types of dynamometers, the time required for the load to reach a maximum varied from about 0.02 sec to 0.06 sec. The faired line, which we call the calibration curve, satisfactorily represents both the static and dynamic behavior of the rings. This was also true for the single-ring instrument.

The curve just considered carries the calibration up to a maximum applied load of 2250 pounds per ring, which is equivalent to a total load of 4500 pounds on the instrument. This gives a working range well above the specified strength of the current 40 g lapstraps, namely, 3750 pounds.

A few tests were made on the single-ring dynamometers to indicate the effect of low temperature and fire. For the low-temperature test four rings were loaded dynamically to loads ranging from 3000 - 4000 pounds while at -40 degrees. The maximum difference from the faired calibration curve was about eight per cent. Another ring was proof loaded to 5500 pounds while at -40 degrees without showing any signs of distress. At this time the rings were proof loaded to 5500 pounds proof load rather than ultimate load. The effects of fire on the apparent maximum

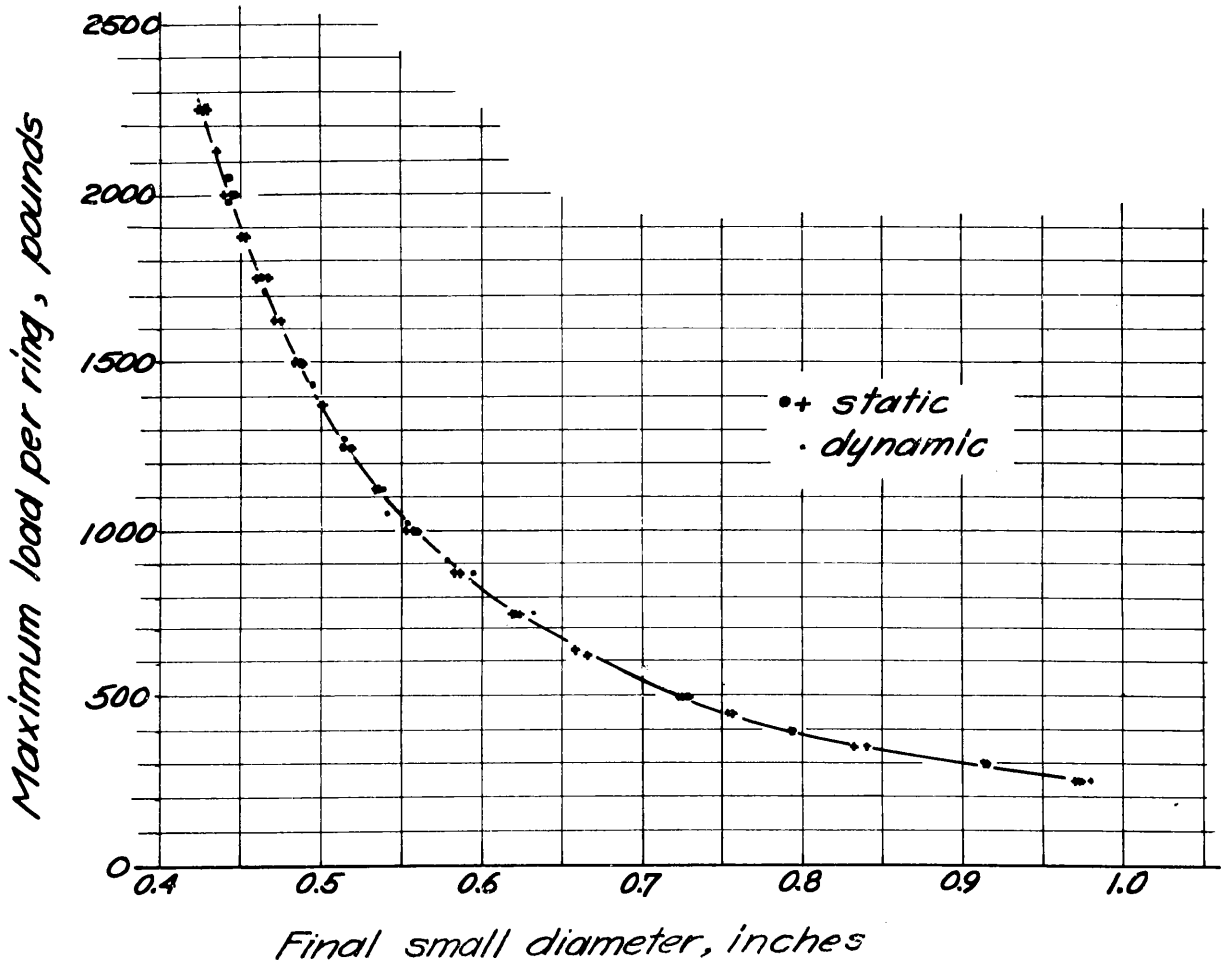


Figure 3. Calibration of Rings for Lapstrap Dynamometer Ring Type II Rings OD = 1 in, length = 0.25 in 16 gage, x 4130 stock

load recorded from the deformed rings was indicated by two tests. A deformed but unloaded ring was heated "cherry red" and cooled. The change in diameter was negligible, corresponding to similar negligible error in the indicated maximum load. Deformed rings carrying 150 pounds of dead weight were heated to "cherry red". The deformation of the rings while hot was so great that evaluation of the load was impossible.

Thus far we have described a simple instrument which appears satisfactory for our problem. It is obvious that when such a device is made the attachment point of a safety device, the strength of the instrument must be as closely controlled as possible. During the development of the instruments, several samples of NE8630 and X4130 normalized steel were used for rings. It was found that for the one-inch O.D. 16 gage tubing employed, the ultimate strength when tested as a ring was of the order of 95,000 pounds per square inch. This corresponds to an ultimate load on a 1/4-inch ring of about 3000 pounds. The current requirement for control or sample rings is an ultimate load not less than 2700 pounds which is arbitrarily 90 percent of the nominal 3000 pound ultimate. Since two of these rings are used per instrument and two instruments are used in the lapbelt link-

age, the margin of strength of the dynamometer rings over the lapbelt strength is about 44 percent. For shoulder harness dynamometers, the rings are to be 0.180 inch long and have an ultimate load not less than 2000 pounds, which is about 43 percent greater than the half harness strength. The preset value for shoulder harness dynamometers is about 300 pounds.

It is planned to fit a large number of airplanes with these dynamometers, one at each end of the lapstrap and one in the shoulder harness attachment member. All of the parts, except rings, for the required number of instruments have been obtained from the Naval Aircraft Factory and will be assembled and preset as soon as rings are available. Rings are being made at the Bureau of Standards and, at present, are being selected for strength. Every eleventh cadmium plated control ring from a given stock length of tubing is tested and must have an ultimate static strength of not less than 2700 pounds for lapstrap or 2000 pounds for shoulder harness.

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