THE APPLICATION OF PULSE EXCITATION TO GROUND AND FLIGHT VIBRATION TESTS

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Abstract

A discussion of the relative merits of sinusoidal versus non-harmonic excitation for flight flutter testing is presented. It is concluded that the use of transient excitation is rapidly becoming a necessity. The application of small-scale rocket motors to the excitation of the aircraft is suggested. The design and development of rocket motors specifically for flight flutter testing is described. Methods of measuring and analyzing the transient response of the aircraft are discussed, and the techniques of theoretically predicting the structural response are described.

INTRODUCTION

In considering the multiplicity of problems associated with the development of adequate flight flutter testing techniques, ones attention is immediately focused upon the initial problem of exciting the aircraft. Since there are basically only two methods of exciting the aircraft; namely - sinusoidal or non-harmonic, it would appear at first inspection that the choice would be simple. It becomes rapidly apparent to the experimenter however that each of these methods has associated with it a unique series of both theoretical and experimental problems which must be solved in order to insure the success of the flight program.

A large number of experimental methods have been employed in flight flutter testing in the past and improved methods are constantly being developed. Common to all of these, however, is the basic necessity to determine the effect of varying flight conditions on the damping characteristics of several of the lower aircraft vibration modes. A wide variety of techniques for experimentally determining the modal damping characteristics from either a transient or steady-state structural response have been devised. Nevertheless, the measurement of the aircraft modal damping characteristics, even on the ground, represents a not in-considerable experimental effort both in time and in the accuracy of the experimental techniques required. Thus, it is not surprising that considerable difficulty should be experienced in any attempt to determine the modal damping in flight.

The technique most frequently employed in ground vibration testing is to excite the aircraft in a natural vibration mode using external sinusoidal excitation. By rapidly removing this excitation and causing the structure to decay exponentially the structural damping can be measured. With careful experimental techniques it is possible in this way to measure the structural damping during ground tests with reasonable accuracy.

It is quite reasonable when first contemplating flight vibration testing to attempt to extend this sinusoidal testing technique to the determination of the aircraft vibration and modal damping characteristics in flight. This has, in fact, been done with varying degrees of success. By varying the forcing frequency it is possible to determine the damping of the system from a knowledge of the frequency response characteristics of the structure. However, attractive the sinusoidal excitation may be conceptually, it presents many serious problems practically, which in many instances preclude its use. Not the least of its limitations is that the airborne equipment required to provide the sinusoidal excitation is extremely heavy and requires considerable space for installation. In the case of small aircraft this single factor may be sufficient to preclude the use of this technique.

With the size of sinusoidal excitation equipment is alšo associated a high degree of complexity which reduces reliability and increases the cost of the program. Existing aircraft power sources are frequently inadequate and it becomes necessary to install supplementary power supplies. In many cases it is necessary to install major portions of the excitation equipment during the construction phases of the aircraft. Further, in order to provide the required force levels, the actual shaker itself may be sufficiently massive to compromise the free vibration characteristics of the flight surfaces being studied. In the practical use of sinusoidal excitation it is necessary for either the pilot or a suitable servo-mechanism to vary the forcing frequency over a prescribed frequency range. By measuring the response of the flight surface, the modal damping can be determined. If the forcing frequency is varied too rapidly, the response is no longer simple harmonic and the test becomes transient in nature. Therefore, there is a finite time required to sweep the desired frequency range during which steady flight conditions must be maintained. The pilot's complete attention is required during this period in maintaining the flight conditions constant and in some cases in actually performing the frequency sweep. In high performance aircraft, where quite often the flutter-critical flight condition can only be achieved momentarily, these requirements are impossible to meet and a transient testing method is required.

Thus, for many reasons (light weight, installation simplicity, minimum requirements for pilot's attention and the ability to obtain data during transient flight conditions) the flutter engineer is led to a choice of transient testing techniques. Basically, in transient flight flutter testing, the response of the structure to a non-harmonic forcing function is studied to deduce the modal damping of all significant vibratory modes. One possible source of non-harmonic excitation is the onmipresent aerodynamic turbulence. This is an ideal forcing function in the sense that it required no airborne equipment for its generation. However, it is necessary to determine the exciting force in order to interpret the meaning of the response using this technique. This alone is a problem which could easily consume several careers in its solution. Due to the present technical difficulties encountered in attempting to exploit this means of excitation no further discussions of this form of transient excitation will be pursued.

Two other basic types of transient excitation however are considered sufficiently practical to be useful at this time. One of these has been aptly described as "stick-banging" or "rudder kicking", according to the surface under investigation. It has seen considerable use in the past by several flight flutter experimenters. This technique does not normally require special airborne equipment for generating the impulse except for a robust pilot. In this respect it provides a minimum weight, maximum simplicity installation and is suitable for tests conducted on short notice. This technique is ideally suited to many types of testing and no further sophistication is required. However, it is frequently impossible to adequately excite the aircraft vibration mode desired by pulsing a control surface. For example - symmetric wing bending modes are extremely difficult to excite by any abrupt control input. The increasing, and now almost complete, use of powered or boosted controls further decreased the usefulness of this technique. "Stick-banging" will continue to be a frequently used tool but it is not cabable of meeting all the requirements for a completely general technique which will handle all problems which arise.

The second method for providing transient excitation to the aircraft is by attaching a suitable "disturbance generator" to a lifting surface. This basically can be any device which is capable of storing energy and releasing it rapidly, thus applying an impulsive force to the structure. This might be accomplished in any number of ways; such as releasing a high velocity liquid or gaseous jet or by releasing a concentrated mass from the surface. The optimum design of such a device would require that the unit be simple, light, small, reliable and self-contained - that is, not require extensive aircraft installations. A small solid propellent rocket motor attached to the structure satisfies these requirements nicely. Further, a rocket motor is easily designed to provide a variation of force-time histories to suit varying test requirements.

The idea of using rocket motors (ballistic impulse units) to provide an impulsive excitation to an aircraft structure for flight flutter testing purposes is not at all new. Although no published record of such experiments is known to the authors, it is apparent that many experimenters in this country and abroad have used this technique with varying degrees of success. Two major difficulties can be expected in using ballistic impulse units for in-flight excitation; namely - the difficulty in obtaining simultaneous ignition of multiple rocket motors and the difficulty of exciting all flutter significant vibration modes with a limited number of impulse units. Since the prime danger in flight flutter testing is that of not observing the modal damping of the least stable flutter mode, it is mandatory that whatever technique of excitation is employed provide adequate knowledge of the damping characteristics of all flutter-significant modes. The decisions as to what mode is significant must be made in advance by the flutter engineer.

In the following sections the development of ballistic impulse units specifically designed for flight flutter testing is described, as well as the associated instrumentation and supporting analytical and data reduction techniques.

OPTIMIZATION OF IMPULSIVE FORCING FUNCTION

On the basis of the reasoning in the previous section, it is concluded that the use of transient flight flutter testing techniques is inevitable and that the use of airborne impulsive excitation is a practical means of providing the required transient force. The application of rocket motors (ballistic impulse units) to this purpose offers a practical engineering approach to the accomplishment of transient excitation. It is recognized that past use of such devices has met with some difficulties, however, it is felt that by designing special rocket motors for their special task and by utilizing them in an efficient manner that many, if not all, of the previous problems can be eliminated or ameliorated. Specifically, it was initially felt that by careful design of the rocket motor's ignition system utilizing the lastest technological advances available to the ordnance engineer, simultaneous ignition of multiple motors could be accomplished. Recently it has been demonstrated in actual tests of several prototype motors, that excellent repeatability of ignition times is realizable. For all practical purposes it can now be stated that simultaneous ignition of several motors is a readily accomplished fact. Details of the actual ignition system design are presented in a later section.

The problem of exciting all flutter significant modes by an impulsive force has been given considerable study. By optimizing the force-time history of the impulse unit and the location of the motors, the required force level to excite the desired mode can be minimized (and thus the size of the motor). Thus optimization increases the probability of getting a pure modal response to transient excitation.

It can be shown analytically that the maximum response of an undamped second order system can be obtained by a step function input. More specifically, when considering an impulsive forcing function, the maximum dynamic response of the system (twice static deflections under the applied loading) can be achieved by applying a terminated step-function of period equal to the half-period of the vibration mode being sought. If the period of the forcing function is less than the half-period of the vibration mode being excited the dynamic response will be less than maximum. The maximum response will be constant for periods greater than the vibration mode half-period. For all impulsive forces other than terminated step-functions (greater than half-period), the dynamic response is less than twice the static deflection under the applied load.

The dynamic response of an undamped second order system has been studied when the impulsive force is a semi-sinusoid (i.e., the first half cycle of a sinusoid). This represents approximately the force-time history that can be rather easily obtained from a ballistic unit. Figure 1 shows a comparison of the system response characteristics when excited by either a terminated step-function or a semi-sinusoid of varying duration. It is observed that the maximum dynamic response is achieved when the period of the forcing function is approximately 1.6 times the half-period of the mode which is to be excited. The dashed curve of Figure 1 shows the

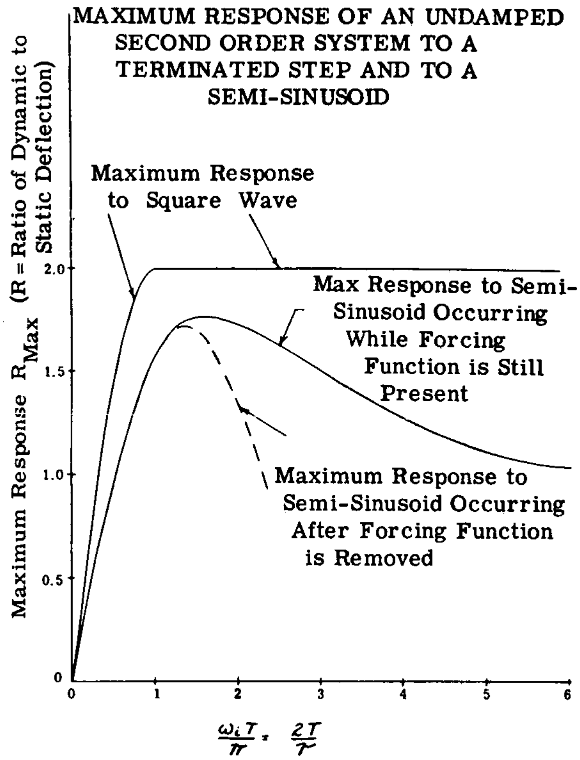

Figure 1. Maximum Response of an Undamped Second Order System to a Terminated Step and to a Semi-Sinusoid

maximum amplitude response after removal of the transient forcing function. It is noted that the optimum time duration for this impulse is somewhat less than for the response during the time the forcing function is applied to the structure. A brief study has shown that the mere accomplishment of a maximum response is not necessarily the optimum for flight flutter testing purposes. It can be shown that a considerable improvement in the purity of the desired mode can be achieved by proper selection of both the impulse shape and duration. Analyses to date have been confined to a comparison of terminated step-function and semi-sinusoid inputs. Appendix I shows typical examples of the modal purity as effected by the time duration for both shapes of inputs. It can be concluded that the square-wave input behaves like a high pass filter and the semi-sinusoid like a bandpass filter.

Assuming the duration of both the semi-sinusoid and the terminated step-function impulses to have a duration which will provide maximum response, it can be seen that all frequencies above the desired mode will have maximum response (assuming the force is fed into the mode optimally - not at a node line) when excited by the square-wave. The response of higher modes to the semi-sinusoid become attenuated. The lower frequencies of both are attenuated approximately equally. Even though the square-wave will produce a greater response than the semi-sinusoid, the added advantage of high frequency attenuation offered by the semi-sinusoid leads one to a selection of this form of excitation.

A further improvement in the purity of the structural response can be achieved by deviating from the "amplitude-optimum" period of the semi-sinusoid. By increasing the period the high frequencies are further attenuated, but not without amplifying the low frequencies. Since generally the lower vibration modes are more likely to mark the desired modal response, it is more desirable to lower the period of the forcing function to attenuate the "lows". A slight increase in the response of the higher frequencies will accompany this, however, the response characteristics are such as to produce a much more marked effect on the "lows" than on the "highs". The exact period of the semi-sinusoid which will produce the purest possible wave shape must be determined for each case as a function of the ratio of the frequencies to be suppressed to the desired frequency.

It appears that further improvement in the purity of the response could be realized by suitable design of the force-time history - the final objective being to provide an impulsive shape which would give a large response in the mode desired and a minimum response in all modal frequencies, either higher or lower. For the development program being described, this refinement was not considered warranted. Accordingly, a semi-sinusoid of one-half the period of the mode to be excited was selected. This, as can be seen from Appendix I, gives substantially greater response purity at all frequencies than the square-wave. The reduction in absolute response can be compensated for by approximately a 25% increase in force level.

Further improvements in the response purity can be achieved by careful location of the rocket motors on the aircraft structure. In general, the maximum purity would result if the ballistic unit could be located simultaneously at an anti-node of the desired mode and on the node lines of all other modes. This would at the same time maximize the generalized force provided to the desired mode and minimize the generalized force in all other modes. Since it would be an extremely unique structure that would meet the above conditions, carefully selected locations, which will come as close as practical to this ideal, should be sought. Practical considerations will further dictate that the rocket motors be located on major structural elements - not on skin panels. A typical installation pattern is shown in Figure 2. It should be noted that charges are located on both sides of the structure. This is to allow the application of force in directions compatible with the modal deflections.

Practically, it is impossible to manufacture a ballistic unit which terminates as abruptly as a semi-sinusoid. In truth, an unavoidable trailing off of a force-time history over a reasonably long time period, as compared to the characteristic time, is observed. However, by careful design it has been possible to achieve a very close approximation to the semi-sinusoid (see Figure 3). Details of this motor design are discussed in the following section.

DESIGN DETAILS OF NAA ROCKET MOTORS

The actual details of the NAA rocket motor design and their physical installation is worthy of further discussion. In particular, those aspects of the design which give repeatability of ignition periods deserves special mention. Also a discussion of how

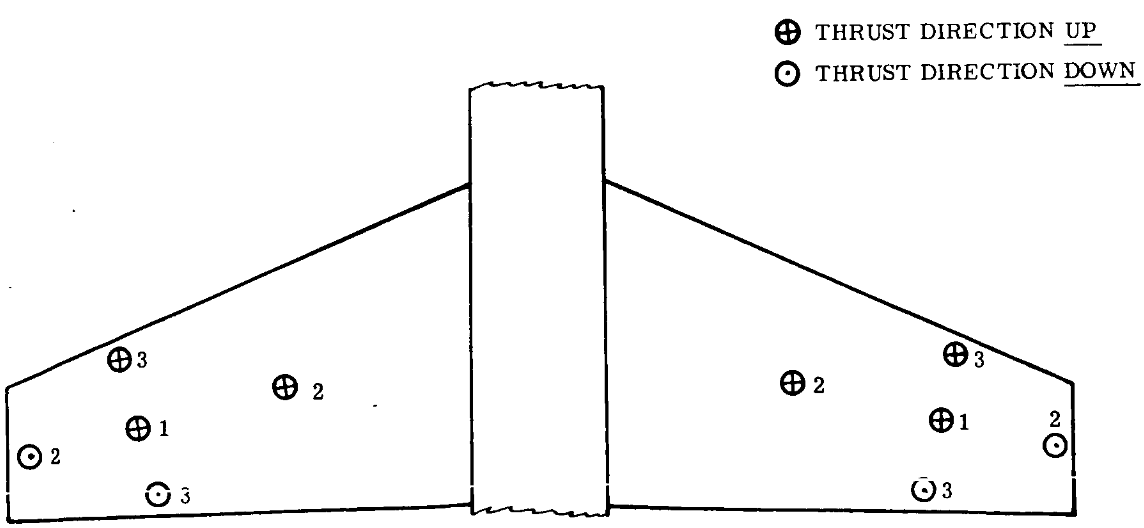

Figure 2. Typical Placement of Ballistic Impulse Units on an Airfoil to Excite the Usual First Three Symmetric Modes

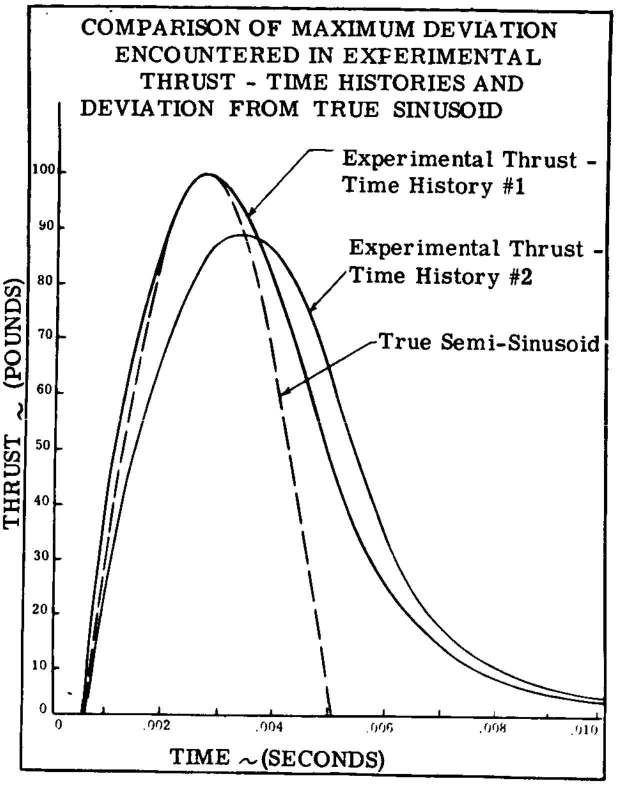

Figure 3. Comparison of Maximum Deviation Encountered in Experimental Thrust — Time Histories and Deviation from True Sinusoid

the force levels and time duration are controlled is pertinent.

The basic cartridge is fabricated out of 4140 steel in two pieces; - namely, a base unit which is bonded directly to the aircraft structure and the motor unit which is attached by means of screw threads to the base. This two-piece design minimizes the exposure time of both the aircraft and personnel to the live rocket motors and provide a high degree of interchangeability. Further, since the ballistic units must be replaced after each firing, it allows replacement of the rocket motors without disturbing the airplane attachment. The base of the two-piece unit is externally bonded to the aircraft structure using a polysulphide type bonding material. A curing period of two hours at a temperature of 140°F is required.

The base unit includes the electrical contacts to which the electrical fire control system is attached. A drawing of the rocket motors and attachment pads are shown in Figure (4). A suitable aerodynamic fairing is placed around the motors to minimize drag. Due to the small volume of the charges it was impractical to design the steel case to withstand the "lock-shut" pressures. This is the pressure which would build up within the cartridge were the exit orifice plugged. Normal operating pressures of the internal ballistic unit range from 4000 to 10,000 psi. A typical "lock-shut" pressure ranges between 40 and 50,000 psi. Internal temperatures during detonation are of the order of magnitude of 3000° Kelvin. The

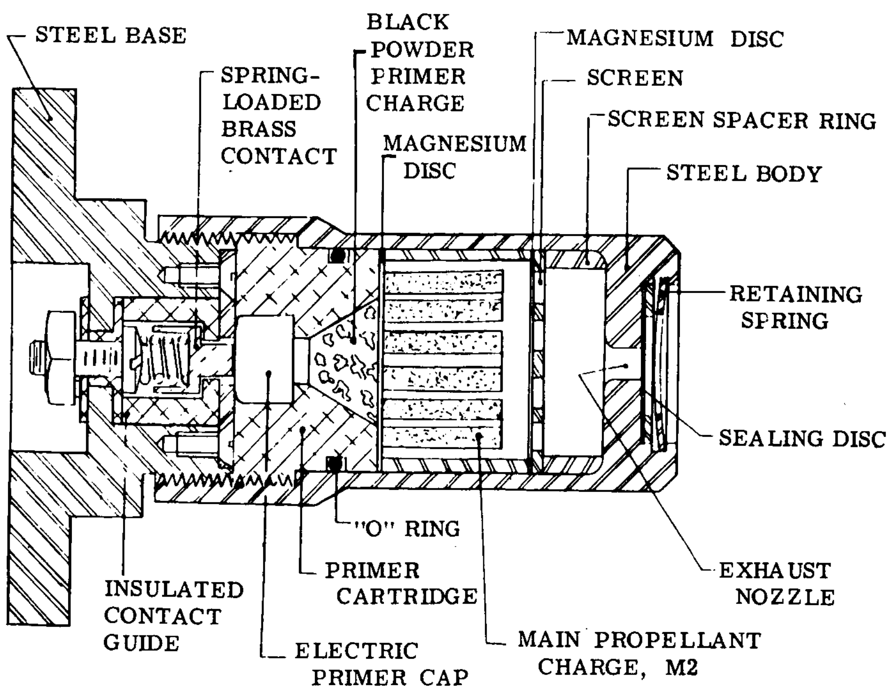

Figure 4. Cutaway of Ballistic Impulse Units

total rocket weight varies from 0.6 to 0.8 lbs and produces a thrust of 50-200 pounds as required. The units are approximately 2-1/2" long and 1" in diameter except for the base.

The ignition system consists of two parts: A M52A3 electric primer (Lead Styphnate), which becomes unstable when an electric current is passed through it, triggers a black powder igniter charge, (type A4BP) which in turn ignites the main propellant. A thin magnesium disc separates the igniter charge from the main propellant. By delaying release of the energy generated by the igniter until a more complete burning of the charge occurs, this disc serves to improve the repeatability of ignition time. This disc also serves the function of providing a moisture seal for the black powder igniter. When this seal is ruptured, the igniter triggers the main propellant (M-2). This propellent consists of several cylindrical single-perforated grains. The total charge weight varies from approximately 1.1 grams for short duration impulse units (7 to 9 milliseconds) to 2.8 grams for longer duration impulses (28 milliseconds). This compares to approximately 3 grams of propellent in a typcial 12-gauge shotgun shell.

The propellent grains are each individually selected by hand to minimize burning irregularities. Approximately 10% of the grains are rejected in this hand selection process. In order to obtain a sharply terminated long duration impulse (28 milliseconds) each individual propellent grain is oriented in a special direction in the rocket motor. The main propellant is sealed from the combustion chamber by an aluminum disc. This is done to achieve a maximum burning rate of the propellent prior to the release of the energy. This provides a maximum repeatibility of the characteristic rise time and improves control of the force amplitude. A screen is provided between the aluminum disc (which is ultimately ruptured) and the exhaust nozzle. This screen prevents plugging of the nozzle by propellent particles, thus achieving a clean force-time history by minimizing higher order disturbances as well as reducing the possibility of explosion. The volume of the combustion chamber is carefully designed to achieve the desired internal pressure and hence force level. A nozzle is located in the end of the combustion chamber of the rocket motor. Very careful hand reaming techniques are necessary to get good repeatibility of both force amplitude and time duration from the rocket motor. A retaining ring and blowout seal are provided over the nozzle to prevent the intrusion of foreign objects.

The burning rate of the M-2 propellent, which is being used in the prototype rocket motors, is approximately a linear function of the internal combustion chamber pressure. Since the internal pressure is critically dependent upon the temperature of the propellent at the time of ignition, it is necessary to confine the operation of the prototype ballistic units to a narrow range of temperatures. They are designed for a normal temperature of 70°F and reasonable repeatibility can be expected over a range of ±10°F. With special propellents which possess the unique characteristics of having a range of combustion chamber pressure over which the burning rate is constant, it is possible to successfully increase the temperature range within which reproducible force-time histories can be achieved. Since the aircraft operates over a wide range of temperature this is an absolutely necessary design condition. All rocket motors for use in flight testing must have reasonable temperature insensitivity. Since the burning rate is independent of the combustion chamber pressure for this special propellent, it is then possible to control the time duration of the impulse by the quantity of propellent provided and the force level by the nozzle design. With the M-2 propellent these two design requirements are inseparable. Thus, using the special propellent it is within the realm of practicability for the flutter engineer to maintain a storehouse of rocket charges to which he can fit a variety of nozzles; thus he can construct a force-time history at the test site without recourse to further ballistic testing. Such a kit of motors and nozzles is one of the final aims of this development program.

By the above design procedures and by paying careful attention to details, it has been possible to achieve virtually simultaneous ignition of several motors. The time elasped between receipt of the electrical impulse to the electric primer and the start of the pressure build-up in the rocket motor is less than 0.1 milliseconds. Figure 3 shows the repeatibility of the force-time history. The deviation between the two traces of Figure 3 is the maximum deviation observed over a large number of tests on prototype units. It has further been possible to tailor the force-time history to very nearly approximately a semi-sinusoid. This is a much easier task for short duration impulse units than it is for the larger duration units.

Certain safety considerations were observed throughout the design of these rocket motors. In particular the two-piece design minimizes the personnel hazard by allowing the actual propulsion units to be stored in a magazine until just prior to the test flight. For indoor firing, an inexpensive personnel shield can be provided at a distance of approximately 15 to 20'. This shield can be constructed of 1/4" to 1/2" plywood or plexiglass and provide adequate safety. The only personnel hazard at a reasonable distance from the charges is that of explosion. The normal firing of the charges, except for the danger of explosion, could be observed from as close as 5 feet. The charge produces a flame pattern of approximately 2' with flame temperatures considerably less than 1500° Kelvin. The charges are capable of operating or being stored in an environment of up to 160°F with very adequate margins of safety.

The only auxiliary equipment required to be used with the rocket motors is a fire control console. This unit provides the required triggering voltage to the electric primer. This is accomplished in most cases by a condenser discharge across a resistor. The actual airborne fire control circuit provides for sequential selection of multiple rocket motors. For example, it will fire units in the following sequence:

(1) 2 units to excite first bending
(2) 4 units to excite second bending
(3) 4 units to excite first torsion

This sequence can be either at the pilots discretion or can be done automatically. In order to minimize pilot-attention during the flight flutter program the automatic feature is recommended. The fire control console will draw its power from the aircraft electric system, the output of which will be rectified and filtered to provide the desired electrical impulse to the electric primer.

ANALYTICAL METHODS OF PREDICTING TRANSIENT RESPONSE

In many instances flight flutter programs have been conducted without benefit of any concomitant theoretical analysis. In fact, many times flight programs have been performed specifically in lieu of an analytical program. For low-speed aircraft with reasonably straight-forward aeroelastic configurations, there is practical engineering justification for this approach. However, when flight flutter testing is being conducted on a modern, high-performance aircraft, a thorough analytical program becomes an absolute necessity. At every phase of the flight program, a correlation of theoretical predictions with the measured data is necessary before proceeding to probe untried flight regimes. A flight program improperly supported by theoretical analyses is a highly dangerous experiment!

The theoretical tools required to support a flight program are straight-forward extensions of the basic critical flutter analysis. The flutter analyst has already at his disposal the homogeneous set of equations which he is accustomed to solving. These are of the same form whether based on a matrix or assumed mode approach. The only modification to the basic equations is the addition of an external time-dependent forcing function which renders the equations non-homogeneous. The solution of the resulting set of equations although elementary mathematically, can be extremely laborious even on the most modern of computing machines. However, it has been demonstrated that the transient response of complex elastic structures can be obtained satisfactorily. The resulting transient response, consisting of the individual responses of each mode can be compared directly to the recorded structural response at a given location on the aircraft. The damping associated with each vibration mode can be separately determined if desired and a series of velocity-damping plots constructed for each root of the equations. (The damping determined at each airspeed for a given altitude represents the true damping and bears no relation to the familiar V-g curves used in "critical" flutter analyses). This plot provides the analytical equivalent of the flight flutter test. The possession of such an analytical result can well save the flutter engineer the embarassment of watching the wrong mode with possibly disastrous results.

AIRBORNE INSTRUMENTATION

The entire paper has been centered so far on a discussion of the techniques of providing the excitation to the aircraft structure. Equally important is the necessity of measuring the structural response and reducing this data to obtain the modal damping of the flutter-significant vibration modes. The transient nature of the response substantially increases the degree of sophistication of airborne instrumentation required.

The structural response can be observed by several types of transducers; either accelerometers or strain gauges can be used to measure the deflection, phase relationship and frequency of the structural response. Strain gauges are more difficult to calibrate; however, accelerometers pick-up high frequency structural noise and require the use of an auxiliary low-pass filter network. Either pick-up can be made to provide a signal to a recording device. The conventional recording oscillograph is not practical for high speed data reduction. It is virtually a necessity that the structural response signal be available in electrically retrieveable form for automatic data reduction purposes. Thus, it is necessary to use a multichannel airborne tape unit. This is preferable to telemetering all structural data to a ground stationed tape recorder, since it minimizes the data transmission problems. If the number of channels required exceeds the number of channels available on the airborne tape recorder the analog form of the structural response can be preserved by frequency modulating the data to be recorded using conventional telemetering subcarrier oscillators. In addition to using an airborne tape recorder as the primary recorder, it is necessary to telemeter selected channels of information to the ground for monitoring by the flutter engineer. The telemetered signals are received, recorded on tape in singly-modulated form and passed through suitable band pass filters onto a direct writing recorder for immediate observation by the flutter engineer. By recording the received telemetered signals immediately, a permanent record is available which has been unaltered by any filtering techniques and thus contains the raw data from the flight program. Immediate discrimination (demodulation) and display of the telemetered data to the flutter observer is necessary to minimize the hazard of flight flutter testing. The signal after being demodulated and prior to being displayed on the direct writing recorder is run through a series of variable-width band pass filters so that all frequencies which are not of interest in the immediate test are eliminated, thus the purest possible trace is presented to the flutter engineer.

During the entire flight program direct radio communication must be maintained between the pilot and the flutter observer on the ground, both to minimize flight time and test reruns as well as to provide the best possible technical advice to the pilot during the test program. In addition, the response of a single selected transducer is presented to the pilot on a miniature Cathode-Ray oscilloscope. The pilot can observe the decay envelope and is advised prior to flight of the anticipated envelope and of the safe operating limits. He is obviously at liberty to discontinue flight testing at any time within his judgment.

It would be very desirable to measure the force-time history of the input to the structure to verify that the rocket motors are performing as predicted. However, the design of a force transducer with adequate response characteristics to accurately monitor the force input would be extremely complex. It has been repeatedly demonstrated in ground tests of the motors that the pressure-time history is quite dependable. Therefore, no provision has been made for measuring the forcing function during flight.

Thus, in summary, the instrumentation provides the following information:

(a) Selected data display to the pilot.
(b) All data recorded on airborne tape (including flight conditions).
(c) Selected data is telemetered to the ground, filtered and displayed to the flutter engineer, in addition to providing a permanent record of the transmitted data in case of accident.

DATA REDUCTION

The basic data, obtained in its entirety on the airborne tape and partial form on the ground-stationed tape recorder, will initially contain varying degrees of signal noise. Some of the noise will arise from the technical problems of data transmission and recording and be basically on an electrical nature. However, a substantial degree of "structural noise" will also be present in the recorded data. This will come from random vibration and acoustic inputs to the airplane. The "structural noise" will be minimized as much as possible by seeking still air in which to conduct the test program. Nevertheless, it is to be expected that there will be some residual noise which will have to be removed by filtering techniques. This will be accomplished after the data has been taken. The basic data including "structural noise" will be recorded. The filtering will be performed upon playback and will pass a sufficient bandwidth so that the basic structural response being studied will be preserved.

A direct comparison of the structural response data with that predicted theoretically can be made. However, it is anticipated that sufficient disagreement will result between this data that a comparison of more basic quantities will be required. Thus, the measured transient response will be passed through a series of variable width bandpass filters. By suitably adjusting the width of the filters, it will be possible to isolate a response at a single frequency and to subsequently determine its decay characteristics. Since several different modes will be decaying simultaneously it will be necessary to perform this operation several times using different filters bandwidths. Finally, by this technique a progressive record of the measured damping of all flutter significant modes can be obtained as a function of airspeed at a given altitude. This then, when compared to the predicted damping will aid the flutter engineer in extending the flight boundaries.

DEVELOPMENT PROGRAM

The design and present state of development of special rocket motors for use in flight flutter testing has been described above. The force-time histories of these prototype units have been designed to be compatible with the known vibration characteristics of a full-scale prototype flight surface of an operational transonic aircraft. Conventional ground vibration tests have been conducted on this stabilizer removed from the aircraft. Transient tests using the rocket motor impulse units will be performed to demonstrate the ability of transient testing to determine the known modal frequencies, shapes and damping ratios of the flight surface.

The basic difficulty of evaluating any method of flight flutter testing is that, if successful, the aircraft did not flutter. After the program is successfully completed, it is impossible to say whether this was because the aircraft would not have fluttered anyway or whether it was truly a good technique. To honestly evaluate a method of flight flutter testing it is advantageous to have an aircraft which has fluttered in a prototype configuration. Such an aircraft configuration is available and prototype flight surface will be tested following successful completion of the ground test of the individual components. Prior to flight, the lifting surfaces will be subjected to transient ground tests on the aircraft and the structural response recorded on the airborne tape and telemetered data transmitted to a remote receiving station. This will be used both to verify the steady state ground vibration test results and to checkout the entire airborne instrumentation system.

Theoretical subcritical response analyses will be performed for the flight conditions investigated to determine in advance the anticipated modal damping characteristics. A point to point correlation will be made between theoretical and experimental data during the flight program. Any discrepancies between the theory and experiment will be resolved prior to proceeding with the flight program. The test will be carried to within 10% of the known flutter boundary.

CONCLUSIONS

On the basis of the ideas put forth in this report, it is concluded that transient flight flutter testing has become a necessity. Steady state flight flutter testing although adequate in some instances, cannot meet all requirements due to the complexity, size, weight and the necessity of maintaining steady state flight conditions for extended periods of time. It is concluded that small-scale rocket motors are a practical means of proving a transient excitation to an aircraft. The problem of providing multiple ignition has been solved. The difficulty in exciting higher modes, can be solved by careful rocket motor design and sensible location of the impulse units.

The instrumentation techniques required are extremely complex but not novel. No basic development of instrumentation techniques is required, mainly an application of existing techniques. The data reduction techniques are complex but are not impractical. Any flight flutter test method must have a careful analytical program to accompany experimental program or it is doomed to failure at start. The analytical techniques required by this method are reasonably straightforward to develop and do not present any unsurmountable obstacles.

ACKNOWLEDGEMENTS

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APPENDIX I - COMPARISON OF MODAL RESPONSE - TERMINATED STEP-FUNCTION VS SEMI-SINUSOID EXCITATION

Reference: North American Report, NA56H-562 "Dynamic Response of Airplane Structures" - F. E. Nagel - 11/20/56

In the above reference the basic equations for the dynamic response of an undamped second order system to a terminated step function and a semi-sinusoid were developed and studied. Figure (1) presents the maximum response in terms of the period of the impulsive excitation. It is seen that the terminated-step-function provides maximum response for a period of impulsive force equal to the half-period of the free vibration mode being excited. The following simple examples have been carried out to demonstrate the relative purity of the transient response which could be expected from excitation by either forcing function:

The following quantities will be defined:

T - period of forcing function

ω_i - ith natural frequency $(\frac{rad}{sec})$

f_i - ith natural frequency (cps)

τ_i - period of ith natural mode

R_{max} - maximum response

r_i - ratio of modal response i to response of desired mode

The parameter $\frac{\omega_i T}{\pi}$ can be rewritten as:

$$\frac{\omega_i T}{\pi} = \frac{2\pi f_i T}{\pi} = 2f_i T$$

$$\frac{\omega_i T}{\pi} = \frac{2T}{\tau_i}$$

For study purposes, consider a three degree-of-freedom system with coupled frequencies:

ω_1 = 10 cps $\quad\quad \tau_1$ = 0.10 sec.
ω_2 = 50 cps $\quad\quad \tau_2$ = 0.02 sec.
ω_3 = 100 cps $\quad\quad \tau_3$ = 0.01 sec.

Case I:

Impulsive excitation of the fundamental mode: (by either a terminated step-function or semi-sinusoid with the period, T selected for maximum response)

	Square-Wave			Semi-Sinusoid		
Mode	$2T/\tau$	R_{max}	r	$2T/\tau$	R_{max}	r
1	1.0	2.0	1.0	1.6	1.76	1.0
2	5.0	2.0	1.0	8.0	1.0	.57
3	10.0	2.0	1.0	16.0	1.0	.57

Case II:

Impulsive excitation of a higher mode: (by either a terminated step-function or semi-sinusoid with the period, T selected for maximum response)

	Square-Wave			Semi-Sinusoid		
Mode	$2T/\tau$	R_{max}	r	$2T/\tau$	R_{max}	r
1	.1	.3	.15	.16	.30	.17
2	.5	1.45	.725	.8	1.35	.77
3	1.0	2.0	1.0	1.6	1.76	1.0
higher modes	>1.0	2.0	1.0	>1.6	$(1<R_{max}<1.76)$	$(1<r<.57)$

It can be concluded from a comparison of the above two cases (forcing period T set for maximum response) that the semi-sinusoid behaves like a bandpass filter; it attenuates all modes, both higher and lower than the mode desired. The square wave behaves like a high pass filter, attenuating only frequencies less than that of the desired mode. Although slightly improved low-frequency attenuation is offered by the square wave, the lack of high frequency attenuation is serious. Thus the semi-sinusoid is to be preferred.

By reducing the period, T, of the semi-sinusoid it can be seen that a substantial additional attenuation of the lower modal responses will result. This will be accompanied by a slight amplification of the higher frequencies. Since the basic problem is in exciting higher modes while rejecting the strong responses of lower modes, the increase in response of the higher modes is tolerable. The following example will demonstrate the possible gains in purity of response by shortening the period to one-half of the period of the mode being sought.

Case III:

Semi-Sinusoid excitation of higher mode $(T = \tau/2)$

Mode	$2T/\tau$	R_{max}	r	r (case II)
1	.1	0.2	.128	.17
2	.5	0.96	.615	.77
3	1.0	1.56	1.00	1.00

It can be seen that a marked improvement in rejection of the lower frequency was obtained by this technique. It is possible to optimize the period of excitation to obtain maximum rejection of the lower modes. The optimum period will be a function of the ratio of the frequency to be suppressed to the frequency desired.

It is obvious that by using semi-sinusoidal impulsive excitation and further by not using the "amplitude-optimum" period, that a reduced absolute response has been the price paid for increased wave purity. This is easily compensated for by increasing the basic force level - in this example, by only 25%.