DOUGLAS EXPERIENCE IN FLIGHT FLUTTER TESTING

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Abstract

Douglas Aircraft Company experience in flight flutter testing is reviewed briefly, with comments on state-of-the-art excitation and instrumentation techniques used up to the present time. The limitations of previous techniques are discussed with emphasis on the problem of:

(a) Establishing a flutter margin of safety for predicted marginal flutter modes.

(b) Resolving instances of flutter not predicted by theoretical calculations in advance.

(c) Delaying the airplane demonstration by time consumed in acquisition and reduction of flutter data.

Current Douglas philosophy in flight flutter testing is presented and a description given of:

(a) Steady-state vane excitation system development.

(b) An automatic data handling system.

(c) The potential application of automatic computing methods for increasing flutter data yield.

INTRODUCTION

The development of high performance aircraft of various configurations with increased flexibilities and concentrated weight items at structural extremities has made the consideration of flutter not only a design criterion but also an important flight demonstration item.

The Douglas Aircraft Company has required extensive flight flutter tests on all aircraft models and versions which have been produced since 1954. The objectives of these demonstrations have been 1) verification of analytical predictions, and 2) demonstration that unpredicted instabilities do not exist. The responsibility for these demonstrations is shared jointly by the Design Engineering and Testing Divisions. A policy, based on the airplane type, performance capabilities, and the aero-elastic characteristics predicted by theoretical analyses and flutter model tests, has been established for the flight conditions, airplane configurations, instrumentation, and the data reduction techniques to be used for these flight demonstrations.

Experience has shown that neither the theoretical predictions nor the flight test techniques used to date have been infallible. The intent of this paper is to show the shortcomings of earlier techniques as revealed by flutter experience obtained from tests of current aircraft.

EVOLUTION OF TECHNIQUES

The initial flutter programs were conducted by monitoring the decay of structural motion excited by manual control surface pulse inputs. Instrumentation consisted of strain gage type accelerometers installed at the aircraft extremities or at locations having large response amplitudes in the predicted flutter modes. Control surface positions were measured using electrical potentiometers to define the character of the input pulses and to detect coupling of control surfaces in the flutter mode. Data were usually obtained on airborne oscillographic recorders; however, direct writing pen type recorders have occasionally been used to allow immediate monitoring of the data as obtained.

Sharp control surface inputs were made at incremental airspeed and Mach number as the flight envelope was extended. The tests were run at a relatively low altitude to minimize Mach buffet effects during airspeed advances, and, conversely, at a higher altitude to minimize rough air effects during Mach number extensions. It was also found advantageous to schedule flutter flight tests in the early morning and/or over the ocean to minimize atmospheric turbulence.

Although this approach to flutter testing required a minimum of test equipment and installation, the quality of the data obtained did not always provide consistent stability indications. Data scatter resulted primarily from 1) the manual pulsing depended on pilot ability for repeatability of pulse duration and magnitude, 2) the pulse energy was not directed to the desired mode, that is, symmetric wing modes were poorly excited by elevator pulses and not at all by conventional aileron inputs, and 3) the tranducer outputs were often masked by buffet and other extraneous vibration.

Various harmonic analysis methods were used to extract information from the recorded data. The Fourier analysis and transfer functions proved useful for separating frequency components which could be used to follow flutter trends.

The results of several flutter programs illustrate many of the above difficulties. As an example, Figure 1 shows an oscillograph record obtained during an aileron input while investigating a symmetric wing bending-torsion flutter case on a twin jet airplane. The initial asymmetric response degenerates to the desired symmetric mode after approximately four cycles; however, in view of the background noise, it was extremely difficult to obtain accurate structural damping from the decay in the required symmetric mode.

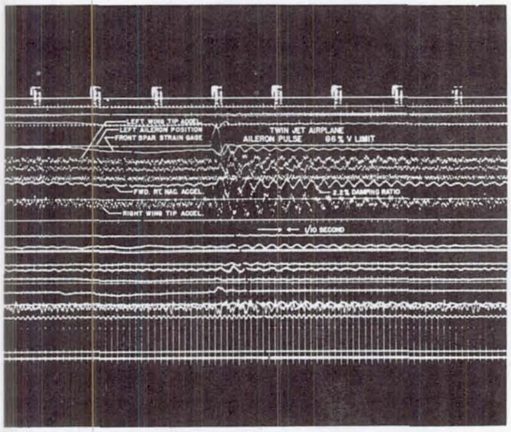

Figure 1.

The next figure (Fig. 2) shows the damping trends as indicated from the above aileron input investigation. Data scatter and failure to excite the symmetric flutter mode lower than about 85% of the required demonstration speed did not allow extrapolation to the zero damping speed or instill much confidence in investigating this flutter case further. It is obvious that a more efficient excitation method would be desirable in this case.

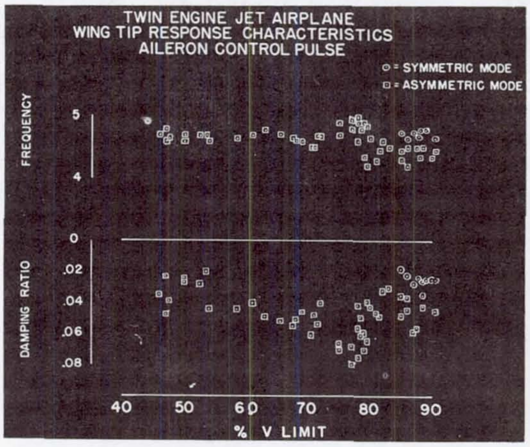

Figure 2.

Figure 3 shows the structural response of a single jet airplane following a rudder pulse. The excitation in this instance was adequate for exciting the aft fuselage torsion-vertical stabilizer bending mode; however, the airplane had been previously flown beyond the flutter speed where rough air was sufficient to precipitate an instability which had not been excited during the initial pulsing program. Fortunately, the flutter, although severe, was non-destructive and

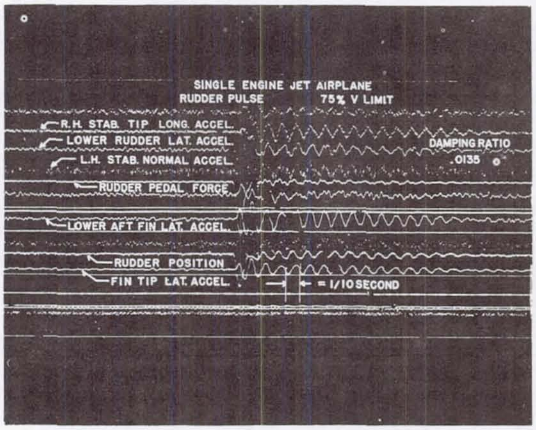

Figure 3.

the pilot had an opportunity to perfect his rudder pulsing technique by using sharper and harder inputs. Subsequent investigation using the perfected rudder pulsing provided consistent stability data which allowed a definite extrapolation to the flutter speed. This trend is shown in Figure 4.

Manual control surface pulse excitation has been adequate for certain flutter flight testing; however, in many instances, its use was restricted by pilot ability, response of the control system, and poor pulse energy transfer to various parts of airplane (i.e., elevator to wing). Except for control systems with extremely slow response rates and the cited difficulties, structural modes with frequencies below 10 cps can be excited by manual pulsing techniques.

The shortcomings, as noted above, of manual pulsing have led to the investigation of auto-pilot inputs, ejection of bombs and stores, and devices to pulse flight controls. The low frequency response of auto-pilots (below 5 cps) and the inadequate energy transfer from control surface inputs have, in general, negated this method of excitation. Bomb and store ejections have been satisfactory in some instances; but, usually, the sharp input, limited bomb carrying capacity, and cost of ejected items have made this excitation method prohibitive. Devices for control system pulsing have extended the input capabilities but are still subject to the limitations as cited for manual pilot inputs. The need for a consistent pulse input that could be applied at a discrete structural point has led to development of an impulse generator unit. These units are essentially small rocket motors having a specific impulse and burning time dependent on the amount and type of propellant used. The size of these devices has allowed installation in fairly limited spaces and has provided excellent pulse inputs. The details and usage of the impulse generator excitation method were presented in a preceding paper * at this symposium.

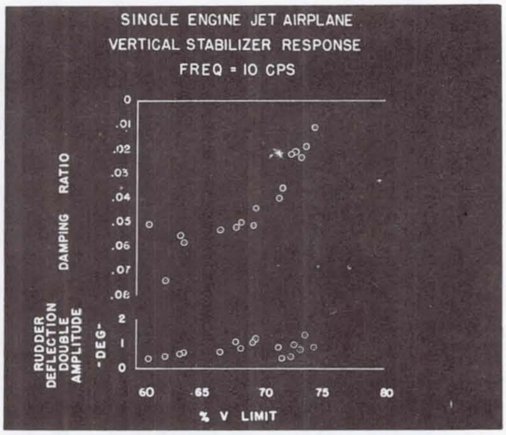

Figure 4.

Sinusoidal excitation from manual elevator inputs has proved successful for exciting structural response at frequencies below five (5) cps. The input for single frequency and frequency sweeps was controlled by having the pilot synchronize his input rate to the response of tuned reeds. In one instance, a photograph of a rather voluptuous lady encased in a plastic projector had the exact mass required to tune a reed for a particular frequency. Airplane and pilot response to this device was excellent. For some unknown reason, the reed was lost on the last flight of this flutter program.

Instrumentation for flutter flight testing has always posed a problem. The frequency response and output of most commercially available transducers require some compromise to cover the required flutter acceleration and frequency ranges. The strain gage type accelerometer has been an useful device from the standpoint of size, calibration, and maintenance. Strain gages for load and stress measurement in oscillating components provide cleaner data than the accelerometer; but the installation, calibration, and maintenance of gages is much more difficult. Control surface positions from electrical potentiometers are fairly reliable, but frequency response and lack of sensitivity at low amplitudes limit their usage. Greater resolution and frequency response are possible from strain gage bending beams operated by a cam on the rotating member. The output and linearity of these items can be adjusted by their physical geometry.

Extraneous vibration at frequencies above the flutter range tends to mask the accelerometer outputs. Several types of electrical filters have been developed. A unit package in a case similar to the standard 350 Ω galvanometer shunt has proved most useful and provides a 6db/octave attenuation or can be seriesed to give multiples of this attenuation. The units have been designed for roll-off frequencies of 20, 30, 40, and 60 cps.

Airborne recorders have been utilized for flutter data recording. The standard 18, 36, and 50 channel CEC oscillogarphs have been used mainly for their frequency response, adaptability to the transducer outputs, and the analog presentation of the record. The photographic developing the oscillograph record has been a delaying factor in some flight flutter programs. The currently available direct writing oscillographs and magazines have largely eliminated this problem.

In an effort to increase the airspeed range per flight and to provide simultaneous flight coverage, FM/FM telemetry has been used during recent flutter testing. Eight (8) standard sub-carrier frequencies from 5.4 to 30 KC combined and transmitted on 230.0 megacycle carrier has been used. The composite signal is received at a ground station where it is tape recorded, discriminated, and displayed as an analog record. One or two flight test engineers can reduce the flutter data from these records and keep a running plot as the flutter test progresses. Portable FM/FM telemetry stations and relay stations have been used to extend the receivable test area.

Occasionally, the manner in which the flutter test is conducted does not reveal the existence of a critical flutter case. Figure 5 illustrates a flutter incident of this type. The initial data obtained during 10,000 and 35,000 foot altitude airspeed - Mach number extensions indicated adequate stability in the horizontal stabilizer yaw - aft fuselage roll case. Subsequent data obtained at intermediate altitudes showed an adverse Mach-airspeed combination with an instability within the required flight envelope. Based on this result, flutter flight programming has specified that tests be accomplished at three altitudes. The intermediate altitude is chosen at an estimated maximum "q" - Mach number combination.

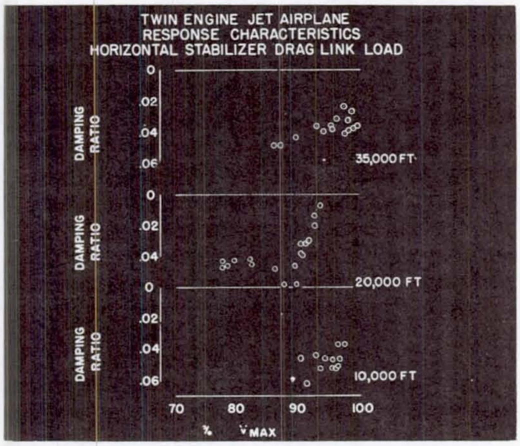

Figure 5.

The various flutter programs have shown that the excitation methods, data availability and reliability, and the necessity for a complete airspeed-Mach number build-up for each airplane configuration and/or flutter fix have been the primary sources of airplane demonstration program delays. The cost of flight test time and the hazards involved on current airplanes provide sufficient justification for a determined effort to eliminate the items cited above.

FUTURE PLANNING

For a number of years steady state excitation has been advocated for flight flutter testing. Autopilot cycling of control systems and rotating weight devices have been used; however, the low frequency response of auto-pilots and the indefinite cut-off of rotating inertia devices have made these excitation methods undesirable.

The Douglas Aircraft Company is presently evaluating the use of auxiliary airfoils for steady state flutter excitation. The first system was developed by Electrosystems, Inc., Burbank, California, and consists of two vanes to be mounted at the airplane wing, horizontal stabilizer, and/or vertical stabilizer tips. The vanes are driven in pitch by hydraulic servo valves and actuators which are controlled by an electronic programmer.

The vane system is designed to provide symmetric and antisymmetric excitation in the frequency range from 1/2 to 15 cps at a maximum input force of 250 pounds (vector). Individual mode tuning, automatic and manual frequency sweeps, and instantaneous cut-off for decay monitoring are possible. The equipment will operate with 3 square feet vanes to an airspeed of 300 knots and with 2 square foot vanes to above 400 knots. The system is schematically shown in Figure 6.

The vanes are hinged and mass balanced forward of the 25% chord to maintain a stable aerodynamic trail position when inoperative or following an emergency shut-off. The emergency shut-off will be accomplished by a by-pass valve in the actuator. Viscous damping can be introduced for vane stability by varying the restriction in the by-pass valve and line.

Airplane protection is afforded by a force feedback system which maintains the mean vane position at the zero force angle of attack. Automatic shut-off is provided for in the event that the input force or airplane structural response exceed a

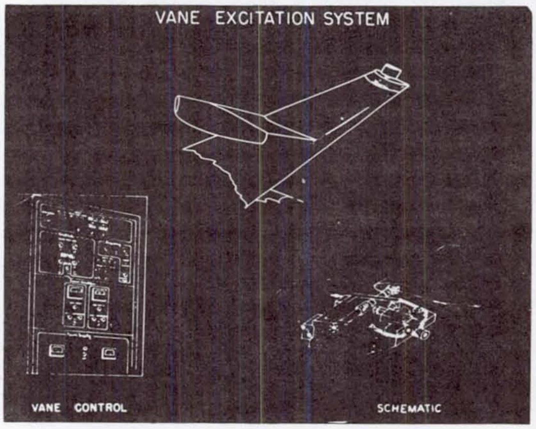

Figure 6.

pre-selected value. In the event that the automatic shut-off items do not operate, a fracture joint in the vane torque tube is designed to fail and shed the vanes at an input load below the airplane structural limit.

The vane system provides a means for exciting airplane vibration modes in-flight and will allow mode surveys for comparison with the calculated and ground vibration modes. The system also allows excitation of the modes deemed flutter critical for monitoring frequency shifts and damping trends during Mach-airspeed advances.

It is expected that the vane excitation system will conserve flight flutter test time, as compared to previous methods, by providing a more positive excitation of the flutter modes, increasing the data confidence factor, and allowing an evaluation of configuration changes or flutter fixes from data obtained from a single flight.

In conjunction with a general effort to improve overall flight test procedures, the Douglas Aircraft Company in conjunction with the Consolidated Electrodynamics Corporation is currently developing an automatic data handling system (ADHS) to expedite the acquisition, handling, and reduction of flight test data. Although the ADHS was not designed specifically for flutter flight testing, the flutter data requirements were integrated in the design specification.

The ADHS consists of an airborne system, a ground station at the test site, and a computer station. The airborne system will sample the analog voltage outputs of the various test data transducers, convert these outputs to binary digital form, record the digitized information on magnetic tape, telemeter the digitized information to the ground station over a PCM (pulse code modulated) link, and provide in larger airplanes, a "quick-look" facility for a flight test engineer's control information. The sampling rate and accuracy allow frequency resolution up to 100 cps and to 1 part in 1000 for 100 data channels. Super and sub-commutation of the input channels allows either higher frequency resolution or an increased number of input channels, respectively. By modular design, the physical size of the airborne unit can be tailored to the aircraft size by restriction of number of data channels. The maximum uncommutated high frequency capacity (100 channels) can be utilized in the larger transport and bomber airplanes and approximately thirty (30) channels in an airplane of the A4D size.

The ground station is mobile to permit coverage of many test sites and contains the telemeter receiver, a tape recorder, and a "quick-look" analog presentation to allow safety monitoring of the flight test data. The compatibility of the ADHS with a digital computer has been one of the design premises.

The computer station is somewhat similar to the ground station; however, it will not be mobile. Quick-look, playback and editing facilities are included in the computer station for scanning and editing flight test data. The required flight data, transducer calibration data, and the analysis program are fed automatically into the digital computer allowing analysis of flight test data in greatly reduced time.

In addition to the above, further savings in the time required for flight flutter testing may be possible with multiple mode excitation using mixed input signals with the flutter excitation equipment previously mentioned. The composite response signal is compared to the frequency components of the input signal through an analog-integrator, which rejects the frequency components different from the selected period of the integral. The chief advantages of this technique are: 1) various modes can be simultaneously tracked throughout the airplane speed range, 2) modal response can be extracted in the presence of noise. The most serious disadvantage of this approach is the long integration time necessary to establish the response of a lightly damped mode in the presence of noise or another mode at nearly the same frequency; i.e., a number of integration processes are necessary to reject the close sideband frequencies. Evaluation of this technique and efforts to overcome the cited disadvantage are being continued.

Separation of the structural response of modes of small frequency difference may be improved by selecting locations for pickups such that each pickup will discriminate against one or more modes and enhance others. By feeding the selected pickup outputs into an analog-type computer, the read-out will be several independent signals, each corresponding to a single degree of freedom representing an orthogonal mode of the airplane. A simplified example of this approach would be a sum and difference of the outputs of pickups located at opposite wing tips of an airplane. Summation of the pickup outputs would magnify symmetric mode response and minimize anti-symmetric response. The selection of pickup locations and the analog circuitry and constants necessary would be accomplished either during ground vibration tests or while surveying the in-flight vibration modes. The combination of pickups and analog to accomplish this function has been termed a "modal pickup."

A combination of the "modal pickup" and multi-frequency excitation techniques may be used to follow the amplitude and phasing of several airplane modes. This could be accomplished by driving a common excitation system from several oscillators, each of which is tuned to a different modal frequency, and by cross-correlation integration of the modal pickup outputs with the proper input signal the sine-cosine component and frequency of each mode will be obtained.

Although the above equipment and concepts have not been fully flight demonstrated, their preliminary evaluations appear promising.

CONCLUSIONS

Although the validity of analytical predictions and flutter model tests have not been discussed, it is apparent that the character of the flutter coupling (catastrophic or otherwise) must be known for the safe execution of a flight demonstration program. Similarly, adequate instrumentation, excitation methods, data analyses, and coverage of design flight envelopes must be provided to insure valid flight test results.