STABILIZER FLUTTER INVESTIGATED BY FLIGHT TEST

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Abstract

Flight flutter tests were conducted on an experimental airplane which resulted in the successful prediction of a limited amplitude stabilizer flutter at supersonic speeds. The flutter obtained was unusual in that fore and aft bending of the stabilizer carry-through structure contributed to the flutter condition. During flight tests the impending flutter condition was observed from force per unit amplitude, damping coefficient, and frequency measurements. A description is given of the physical and operational characteristics of the test equipment and telemetering facilities. A flutter analysis using measured modes and incompressible two-dimensional strip air forces yielded a conservative flutter speed. Sled tests of a similar stabilizer configuration had lead to the conclusion that flutter would not be encountered. Certain overall conclusions are reached regarding this particular flight flutter testing program and the need for a concerted research effort in this field.

INTRODUCTION

Development of higher performance aircraft with reduced flutter margins has increased the need for early and accurate determination of an aircraft's flutter characteristics and establishment of its safe flight envelope. The resulting emphasis on flutter investigation during the initial stages of the flight test schedule has produced considerable advances in flutter testing equipment and techniques.

Two apparently contradictory requirements are paramount in the flutter flight testing of present day aircraft. The tests must be conducted with full assurance of maximum safety, yet must be satisfactorily completed in the minimum time. Further, the test program must provide a comprehensive coverage of important parameters for all configurations over the complete speed and maneuver envelope. The recorded data from such tests must be adequate to enable prediction of incipient flutter at subcritical speeds, and to indicate the source and nature of any existent flutter. These requirements are especially important in the testing of current aircraft that are designed to probe into high Mach number, temperature, and dynamic pressure regimes where many unknown parameters must be defined.

The testing procedures that were used in investigating the flutter problems encountered in the transonic speed transition of our F9F-6 and F9F-8 airplanes were direct and simple. The excitation medium consisted of transient inputs of rudder pedal kicks and control stick lateral and longitudinal jabs to force primary surface oscillations. An airborne oscillograph was used to record the data. The results obtained from these tests were also direct and simple and merely served to show the absence or presence of flutter without indicating the build-up to or margin from the critical speeds. These tests also showed that considerable refinement of the flutter flight test program would be necessary to permit a rapid, yet safe, evaluation of future aircraft throughout speed envelopes that were expected to be almost twice the ranges previously investigated. Consideration of these refinements along with the experience gained in the production and flight testing of previous aircraft played an important part in the design of the Grumman F11F-1 Navy supersonic fighter that has been demonstrated to be flutter free to its maximum EAS of 848 knots, a dynamic pressure of 2456 PSF.

These refinements and the present methods, techniques, and philosophies applied to the flutter flight testing of the Grumman F11F-1F high performance airplane are discussed in the following text.

These procedures are familiar to all flutter specialists, however, there is little evidence to establish their accuracy, validity, and scope. The primary objective of this paper will be to examine an application of these techniques in the investigation of stabilizer flutter.

The techniques and equipment used for the F11F-1F flutter tests were essentially the same as those developed on the F11F-1 airplane. The data link used in the conduct of the flight tests is shown in Figure 1. Accelerometers were appropriately mounted on the wing, stabilizer, fin, and fuselage to sense the excitation from an unbalanced mass shaker mounted in the afterbody. The accelerometer outputs were relayed to an FM/FM telemeter package, amplified, and transmitted to the ground station, a mobile van. The signal received at the van was appropriately discriminated and sent to several simultaneously displaying mediums for immediate and rapid analysis by flight test and flutter engineers. These flight data were compared to calculations and model test results. Through the use of appropriate charts and overlays, frequency, amplitude, and decay rates were plotted as functions of airspeed and Mach number and the results relayed to the pilot along with recommendations for continuance of the flight.

The compact shaker assembly shown in Figure 2 is approximately eight inches high, seven inches wide, and fifteen inches long. This unit was designed to fit into the tail skid compartment of the F11F-1F and consequently was ideally suited to excite all of the critical stabilizer modes as well as many of the

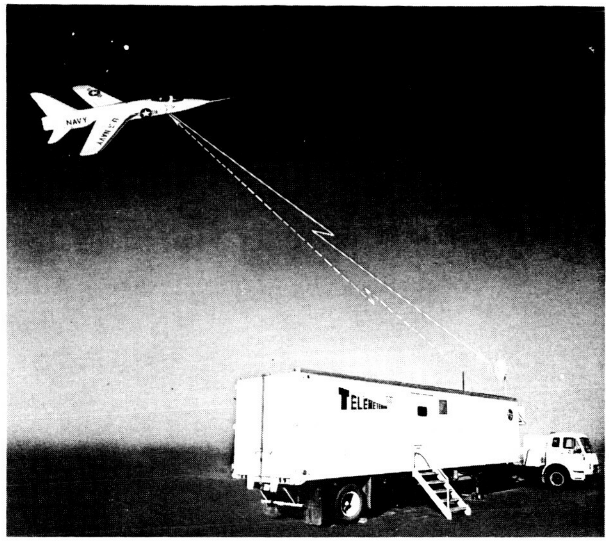


Figure 1. Airplane-Telemeter Data Link

fin, fuselage and wing modes. The shaker consists of a rotating unbalanced mass which is driven by a hydraulic motor. An unbalance of 2.5 in. lbs. was used for the flight tests. This weight was the minimum that could satisfactorily excite the required modes and the maximum excitement that the pilot wanted to tolerate. Motor speed and consequently excitation frequency is governed by a cam positioned flow valve. The cam and valve are integrally designed to provide optimum frequency sweep characteristics for the

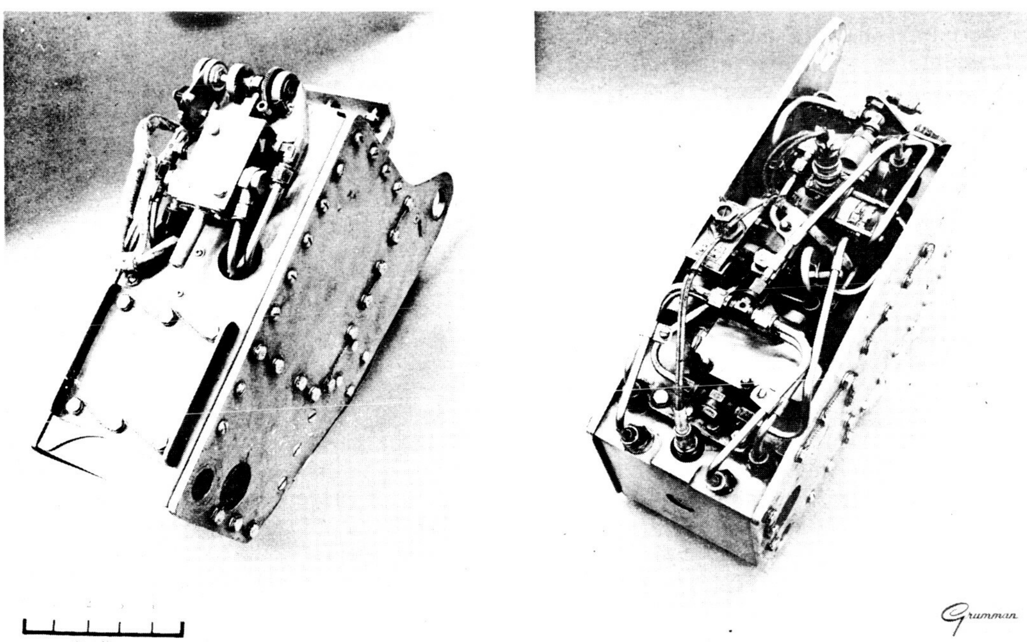


Figure 2. Eccentric Mass Shaker

particular phase under consideration. For the subject tests the frequency programming started at 10 cps, linearly progressed to 28 cps in 30 seconds, more rapidly advanced to a maximum of 35 cps within 5 seconds, and returned to the initial frequency in about 7 seconds where the cam motor was automatically stopped preparatory to another start signal from the pilot. The pilot was also able to stop or reverse the cam motor at any point of the cycle and thus maintain constant frequency shaker operation. This was usually done at a resonate mode of particular interest. A set of hydraulically actuated brakes within the shaker could also be used by the pilot to stop the mass rotation within 3/4 of a cycle at 60 cps and even faster at lower frequencies. Brake actuation also closed two solenoid valves which trapped the hydraulic fluid within the shaker motor thus increasing braking effectiveness. This was followed by cutoff of hydraulic pressure to the shaker system. The pilot was thus able to:

a) Sweep the unbalanced mass through a prescribed frequency cycle.

b) Select and maintain a specified shaker frequency.

c) Rapidly start and stop the shaker at any required frequency.

These several shaker operations, surprisingly enough, required a minimum of pilot attention and effort to accomplish. Throughout the design and development of the shaker components considerable coordination between design engineers and flight test pilots evolved a rather simple operations system. Pilot requirements ultimately resulted in:

a) Pressing a thumb button on the side of the control stick to start the shaker and program it through one frequency sweep.

b) Pressing another button on top of the control stick to stop the shaker immediately.

c) Actuating a switch near the throttle quadrant to maintain constant frequency or reverse cam rotation.

The pilot was informed of shaker frequency by a dial gage located on the instrument console adjacent to the airspeed, Mach number, and altitude gages.

A unique component of the shaker system, and one that sometimes worked too effectively, was the shaker controller. This unit was an automatic safety device that stopped the shaker through actuation of the shaker brakes when and if the wing, stabilizer, or fin oscillations exceeded pre-determined accelerations. When so stopped, the shaker could be restarted by the pilot's depressing the start button. However, the shaker would operate only if the surface oscillations were below the controller cut-off limits.

A data recording system revolving around telemetry has been successfully developed for the high risk flutter flight testing of the F11F-1 and F11F-1F aircraft. A small twelve channel, self calibrating telemeter package translates the D.C. voltage outputs of eleven data transducers and one communications channel into a frequency modulated signal which is amplified and transmitted on an FM carrier. For the flight testing of the F11F-1F at Edwards Air Force Base, the signal was received in the Grumman designed and build telemetering van. An interior view of the van is shown in Figure 3. This van was designed with special attention to the incorporation of features that would optimize the data recording and analysis. Particular emphasis was placed upon the rigid requirements of flutter flight testing. The present system includes:

a) Two receivers

b) Complete signal monitoring equipment to insure the validity of the data

c) Two tape recorders

d) An automatic sequencer

e) Analog computer for direct and immediate data processing such as addition, subtraction, multiplication, integration, filtering, and other applications.

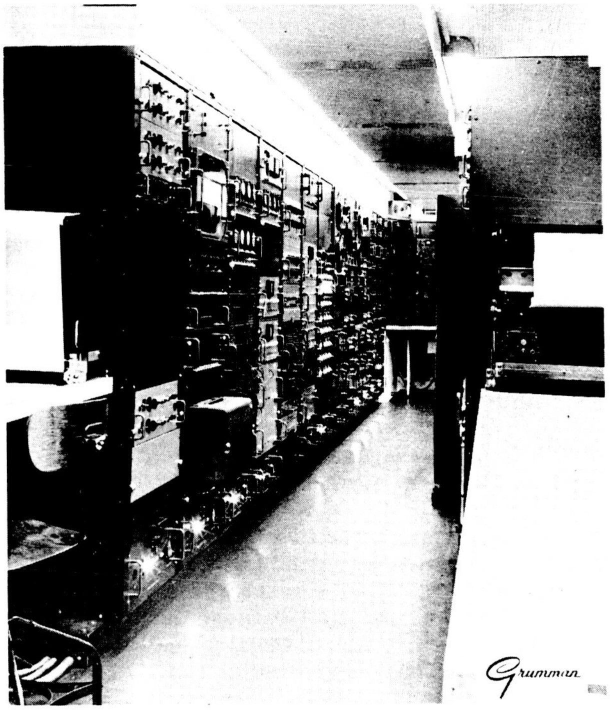


Figure 3. Interior of Telemeter Van

f) A single channel long persistance oscilloscope for x-y data presentations

g) A 50 channel oscillograph

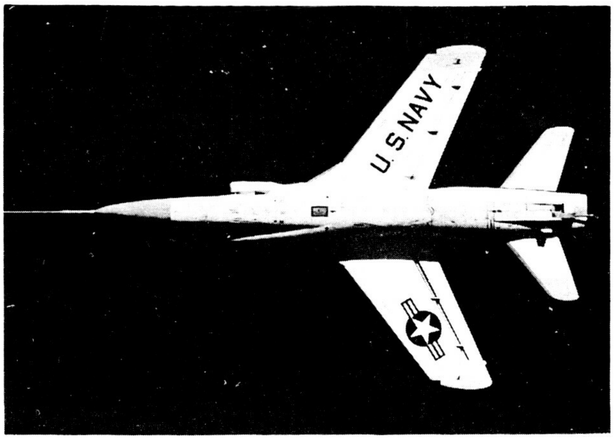
h) Two banks of Sanborn recorders of eight channels each for immediate and direct time history display of vital parameters

A special two speed feature, ten to one in ratio was built into the Sanborn recorders to permit accurate recording of higher frequency flutter data. Paper speed could be controlled either by ground personnel or remotely by the pilot through the telemeter link. Another feature added to these recorders consisted of two tables, seven feet in length, especially constructed to permit viewing and analysis of a large quantity of data. Special take-up reels allowed stopping of the paper while the pens continued to transcribe the telemeter signal at the proper paper speed.

The validity of the techniques developed for flutter flight testing with the shaker and telemetering was determined by a flight investigation of the F11F-1F stabilizer flutter problem. The second aerodynamic prototype F11F-1F airplane is shown in Figure 4. This airplane is a modification of its predecessor, the F11F-1 Tiger, and has the same wings, fin, and fuselage center section. The stabilizer planform, which is also shown in Figure 4, is also unchanged but the airfoil section was decreased from a varying 6-4% section to a constant 3% thickness and the weight increased by 45%. The major changes were necessitated by the installation of a more powerful J-79 engine in place of the J-65. The larger diameter of the J-79 required increasing the afterbody cross-section and in turn the breadth of the stabilizer yoke. These revisions to the stabilizer and its yoke have changed the surface's vibration characteristics by lowering the first symmetric mode, primarily vertical bending, from 20.0 to 12.7 cps and the second symmetric mode, primarily yaw, from 25.4 to 17.8 cps to produce a limited amplitude stabilizer oscillation that has been encountered in flight throughout a wide Mach number and altitude range. The node lines for this revised stabilizer-yoke combination are shown in Figure 5. No structural damage has resulted from the oscillations and the mild onset of the vibration permitted an investigation of this flutter through flight test with relative safety.

Prior to the first flutter incident transient inputs of aft stick jabs had been made from 200 to 510 knots as a cursory check of the overall stability characteristics. These test failed to indicate any incipient flutter and in some instances actually showed increased damping. The results of these tests led us to delay the planned flutter flight test program until after a flight evaluation of the airplane had been completed and to extend the initial restrictions of 450 knots to speeds in excess of 500 knots. During the extension of these restrictions the flutter condition that had been predicted by theoretical calculations but had

THE GRUMMAN F11F-1F AIRPLANE



STABILIZER FROM THE F11F-1F AIRPLANE

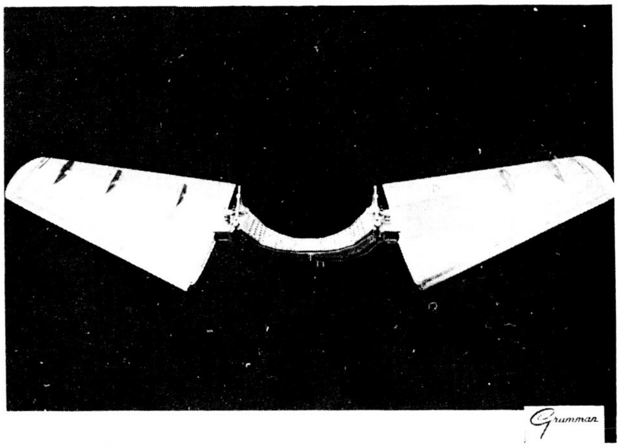


Figure 4. The Grumman F11F-1F Airplane Stabilizer from the F11F-1F Airplane

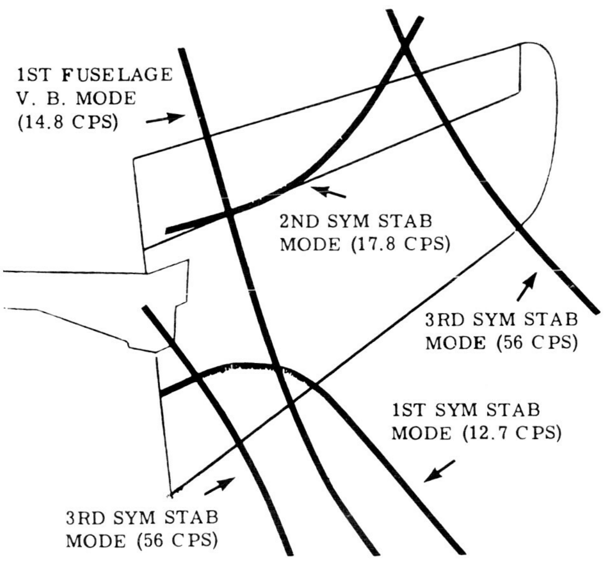


Figure 5. Stabilizer Vibration Node Lines

not been totally substantiated by model or sled tests was first encountered at a speed of approximately 530 knots, 80 knots in excess of the initial restrictions and within about 10 percent of the predicted critical speed. Appropriate restrictions of 475 knots below 35,000 feet were imposed.

The speed capabilities of the F11F-1F airplane permitted these restrictions to be exceeded easily. As a result stabilizer flutter on the F11F-1F has been encountered a total of nine times, twice by Grumman pilots, and the remainder by evaluation pilots. In all cases the onset of the vibrations were noted on telemetering records and the pilots were told to decrease speed. They all did so immediately.

The oscillations have occurred in a narrow airspeed band, 500 to 580 knots EAS from 5000 to 38,000 feet and from Mach .95 to 1.80 as shown in Figure 6. In only three instances were they of sufficient magnitude to be felt by the pilots. These particular oscillations imposed a maximum acceleration of about ±15 g normally and ±5 g fore and aft on the stabilizer.

Shortly after the completion of the flight evaluation program the delayed formal flight flutter program was conducted with extremely encouraging results. Within five flights, through use of the unbalanced mass shaker and the telemetering, we were able to define the problem area, extrapolate the test results to the critical speeds, and define the flutter modes.

This flight test investigation was conducted over an area of .45 to 1.52 Mach number and 200 to 500 knots at the altitudes of 35,000, 27,500, and 20,000 feet. The test points that were attained are shown in Figure 6. The initial flights started at the highest altitude and scheduled shaker sweeps from approximately 200 knots to the maximum safe speed based upon flutter considerations. The results of these sweeps served to define the critical resonate frequencies and their variation with air speed and to indicate the regions of decreasing stability. A more accurate definition of the decay rates was accomplished by having the pilot attain a given speed and Mach number and operate the shaker at the prescribed frequency by referring to the cockpit indicator. The indicator

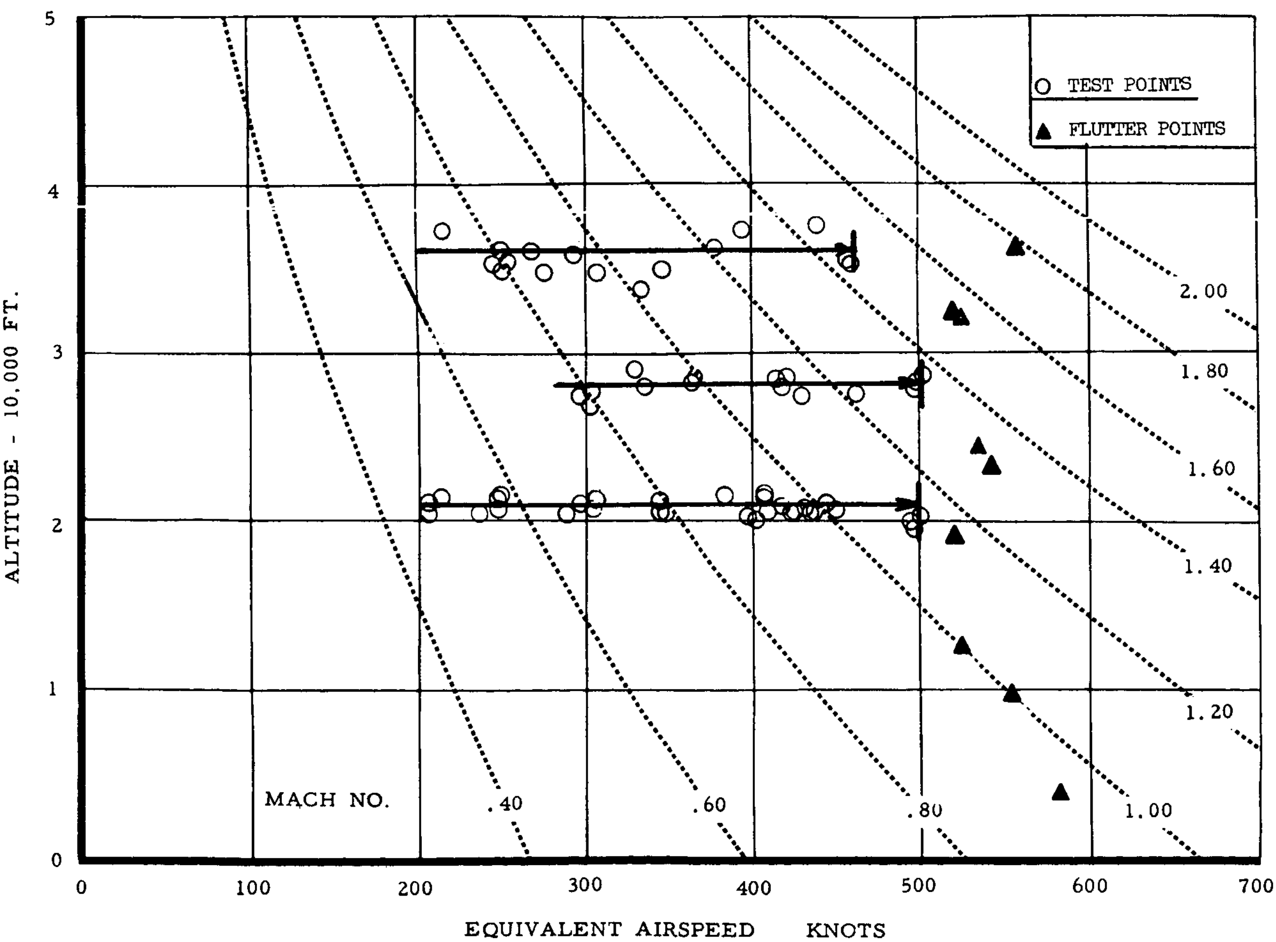


Figure 6. Flight Flutter Points

accuracy of about ±1 cps, however, was inadequate for the tests and the actual resonate frequency was attained by having a ground observer guide the pilot in selecting the true resonance. This was accomplished rather simply by comparing the frequency and amplitude of a particular telemetered data channel with a preset oscillator frequency on a dual channel scope. After a bit of practice with the airplane on the ground the actual resonance could be attained in flight within five to ten seconds. Once the resonate frequency was attained the pilot stopped the shaker then restarted it at the same frequency to define the decay rates three times. The damping characteristics of three modes were investigated by the technique. Aft stick jabs were made on the last flight to show the trends that could be determined by this transient input method.

In these five flights a total of 31 shaker sweeps, 37 resonate stops, and 11 stick jabs were made to define rather completely the mechanism of the flutter problem. Through the use of telemetering and immediate data evaluation the airplane was tested to 95% of the critical speed at the three altitudes investigated where in each case the tests were discontinued when the monitored data indicated marginal damping.

Identification of the critical modes from flight data was made through use of accelerometers mounted in the fuselage as well as the stabilizer tips. The results of a theoretical flutter analysis for the F11F-1F stabilizer as shown in Figure 7 indicated a possible coupling between the stabilizer first symmetric mode, primarily vertical bending, and either the stabilizer second symmetric mode, fore and aft bending, or the fuselage first vertical bending mode with either of the latter modes increasing their frequency with increasing airspeed. The telemetered data, however, as indicated in Figure 8, showed that the fuselage mode frequency remained relatively invariant with airspeed whereas the stabilizer first symmetric mode frequency increased with airspeed from 12.7 cps on the ground to 17 cps at 500 knots to couple with the second symmetric mode which itself varied but little with airspeed. These results along with the marked increase in amplitude of these modes at speeds in excess of 400 knots focused our attention on the stabilizer modes as the fundamental problem.

In this method of testing with forced harmonic excitation the amount of damping in the modes can be examined in two ways. First, the loss of damping may be evidenced by the sharpening of the resonant peak

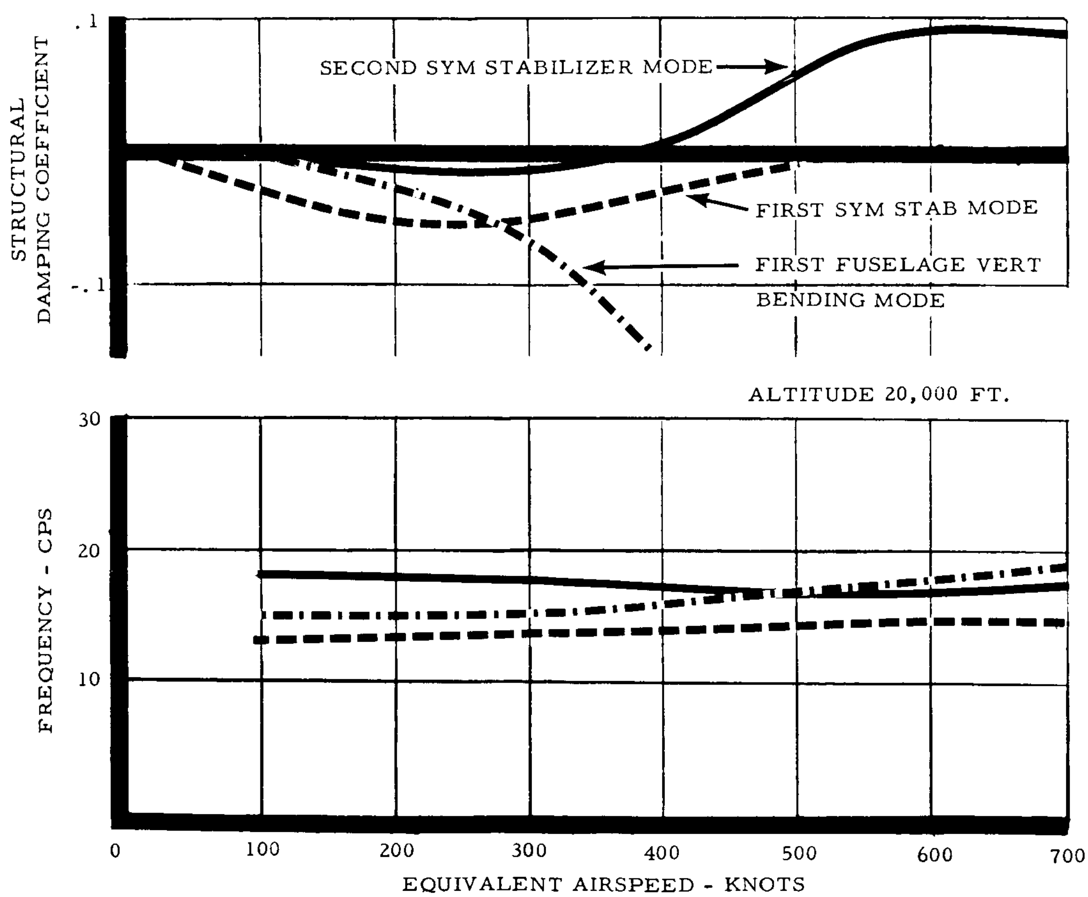


Figure 7. Results of Theoretical Flutter Analysis

accompanied by amplitude increases. A sharp peak is defined as one which has a pronounced amplitude peak occurring over a narrow frequency range. The amount of damping may thus be expressed by the ratio of the incremental frequency that defines equal amplitude boundaries of the resonate mode. Qualitatively this is a good indication of damping but because of the sensitivity of the ratio to frequency inaccuracies it becomes impractical for use in the analysis of flight data. The second method permits a rapid and direct indication of the damping in the modes by determination of the amplitude of surface vibration at a particular resonance. The data accumulated from shaker sweeps is summarized in Figure 8. These data show a rapid reduction in the magnitude of the reciprocal of the stabilizer tip vibrational amplitude, 1/A, for both stabilizer modes as the flutter speed is approached. This reduction of 1/A for both modes is in good agreement with the theory which predicts that the damping of both modes will decrease at higher speed.

Extrapolation of these frequency and 1/A data to predict incipient flutter and the critical speed may not be done with absolute certainty. Definite indications of problem areas are certainly evident from both plots and the fact that an adventuresome extrapolation would yield a predicted flutter speed of about 520 kts., in excellent agreement with the flutter that was actually experienced, is quite encouraging. In fact monitored telemeter data of shaker sweeps made on the first flight were used to limit the speed of the flutter program well below the maximum capabilities of the airplane.

Post flight analysis of these data was conducted to determine a more precise indication of the critical speeds. The ratio of shaker force input to unit velocity of the stabilizer oscillation was plotted as a function of airspeed and Mach number. The results of this analysis are presented in Figure 9. Since the numerical values of the test data for both modes closely coincided the individual test points are omitted and the resulting faired curves are separated by applying an appropriate weighing factor. These results agree relatively well with the 1/A data and a mathematical extrapolation yields a critical speed of 560 knots.

The measured values of damping coefficient which were obtained once the modal frequencies had

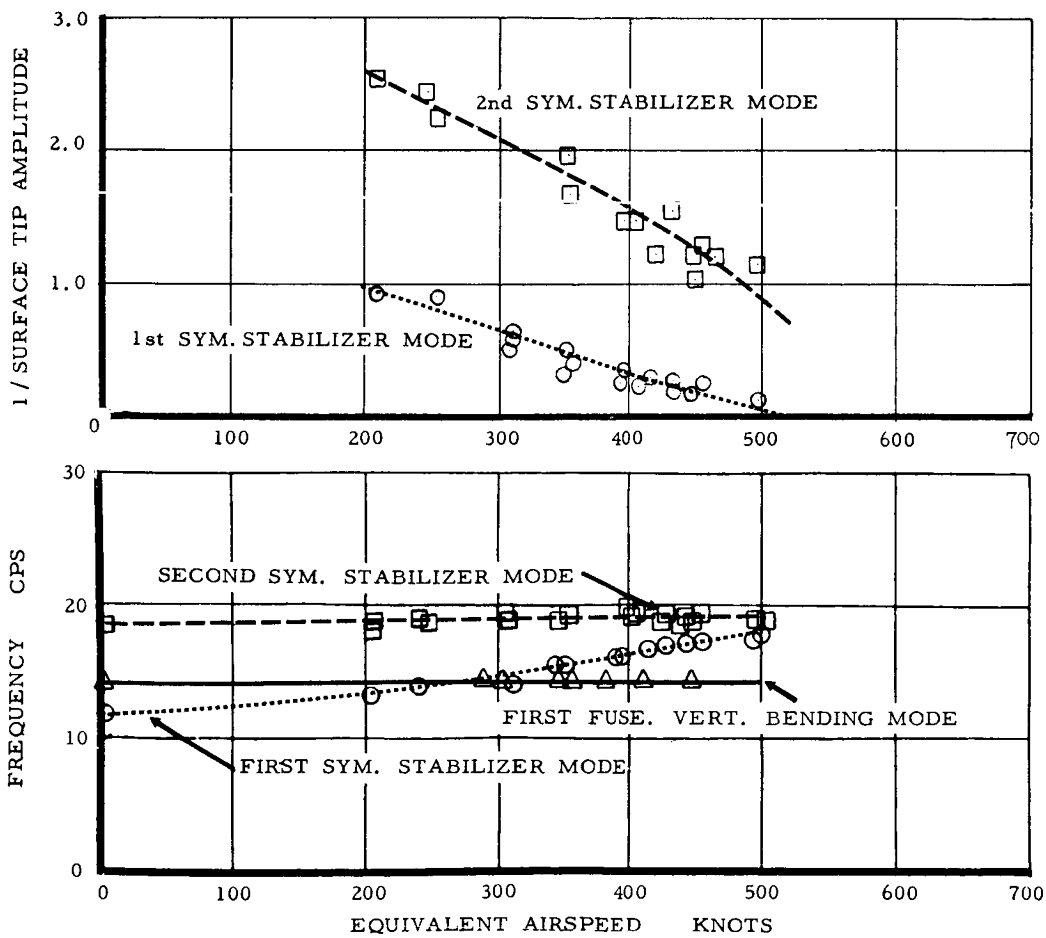


Figure 8. Results of Flutter Flight Tests

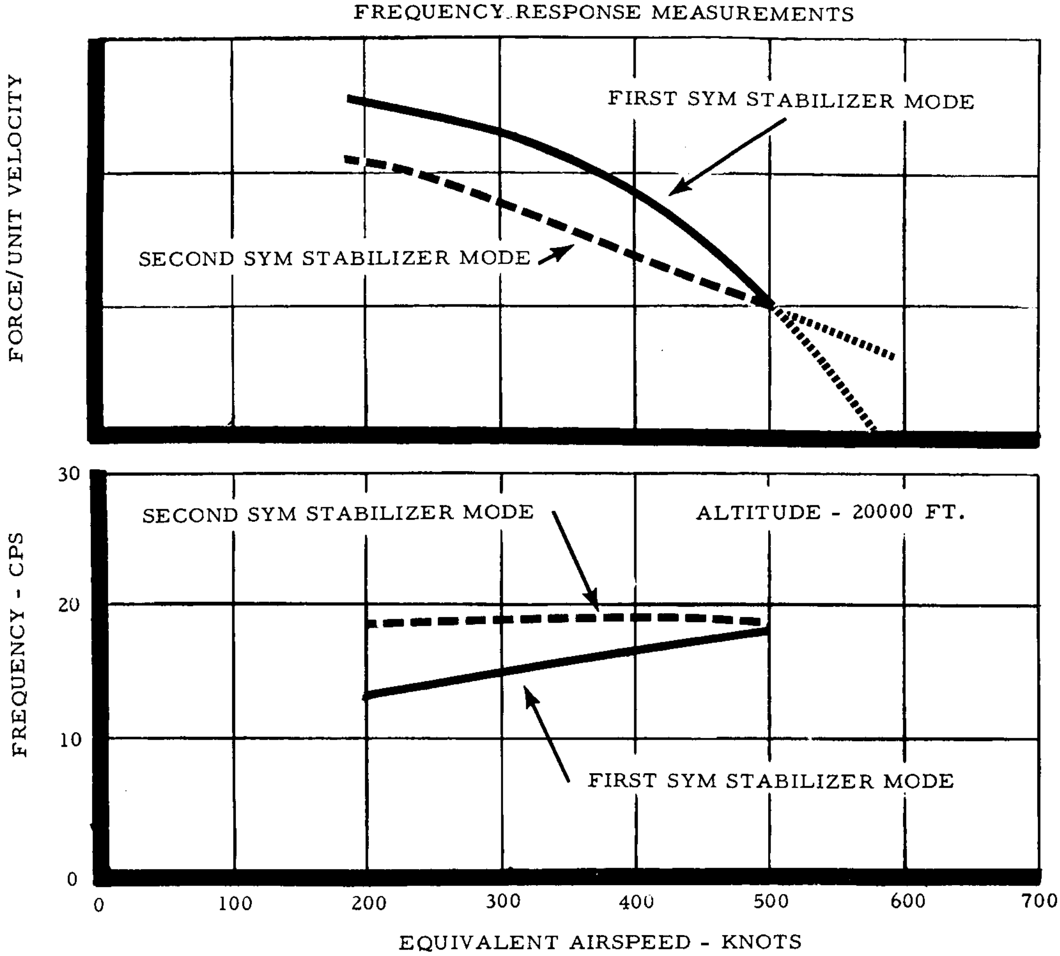


Figure 9. Results of Flutter Flight Tests Frequency Response Measurements

been defined reflect the gradual deterioration of damping with airspeed as shown in Figure 10. The reduction near the flutter speed, however, does not seem to be compatible with the 1/A and the F/A curves where the stability had decreased to one-fourth its value over a 300 knot span of airspeeds while the damping coefficients from decay measurements only decreased by one-half. This variance of data may in part be explained by the changes in mode shape with increases in airspeed which effect the output of stabilizer tip

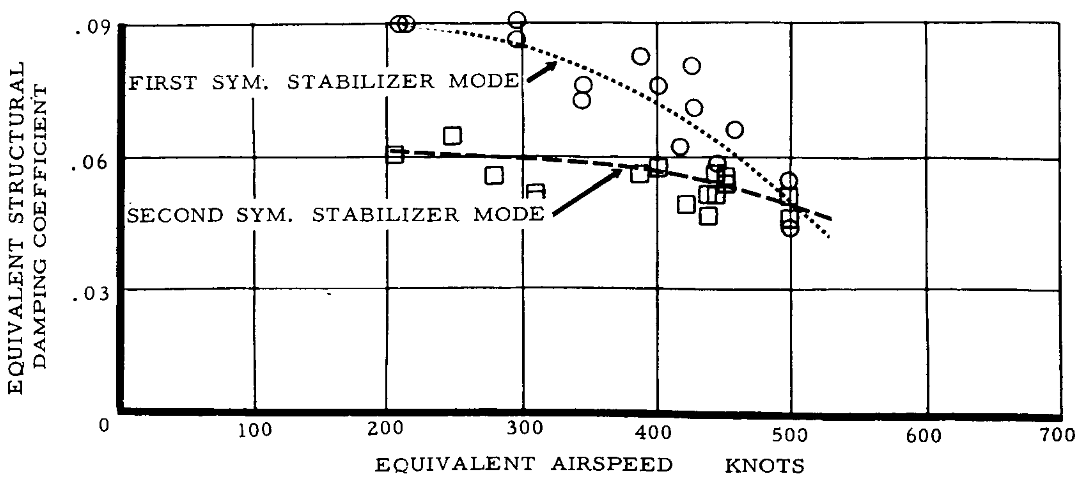


Figure 10. Results of Flutter Flight Tests Decay Measurements

accelerometers and by the possibility that the resonate peaks and frequencies were not always attained during the decay maneuvers.

A comparison of damping coefficient data obtained from aft stick jabs with the shaker excited decays showed that transient inputs were unable to excite adequately the critical modes, yielded a great deal of random scatter, and allowed no proper prediction of the critical speed. Even a rough extrapolation of the damping coefficients excited by the transient induced oscillations would show a flutter speed 50% higher than that predicted from shaker decays. In fact, a series of aft stick jabs was made prior to the initiation of this flutter program at 20,000 ft. and at 15 knot increments from 300 to 520 knots. These tests showed absolutely no evidence of impending flutter.

The results of this F11F-1F flutter program corroborated the theoretical calculations and identified as well as partially explained the mechanism of mode coupling. Since the restrictions imposed by the stabilizer oscillations do not hinder the F11F-1F flight test program, no major effort has been undertaken to eliminate the problem. However, a simple change to the stabilizer yoke which increased the fore and aft stiffness and raised the second symmetric mode frequency to 24.5 cps was flight tested. The results from this second series of flutter tests indicated that the critical speed of this configuration was substantially increased.

Certain limitations in the testing techniques and data analysis were quite evident at the conclusion of this flutter program. First, the means of determining stability criteria are far from adequate and may be classed as being part of the current state of the art; second, the methods of establishing adequate margins from incipient flutter and predicting critical speeds are rather difficult to define; third, the mechanics of exciting a structure at a desired resonate frequency needs improvement; and fourth, a single tail shaker does not excite all of the wing modes required for complete definition of the flutter spectrum.

To overcome some of these limitations, we, at Grumman Aircraft, have developed a resonance detector to obtain, automatically, excitation cut-offs at resonances that are determined during shaker frequency sweeps. This device will shut off the shaker for a predetermined interval at a prescribed resonate mode then will allow the shaker to continue the sweep until a new resonance is excited. To excite wing modes more adequately a reciprocating mass shaker, three inches in depth has been developed. The shaker weight contains integral cylinders which are hydraulically actuated by an electro-hydraulic valve. The oscillation of the mass can be controlled both in frequency and amplitude and programmed to any desired frequency sweep. In addition, a theoretical development program has been undertaken using an analogue computer that is set up to describe a discrete mass representation of an aircraft wing. Some objectives of this program are:

1) To determine stability criterion which can be applied to subcritical response data and extrapolated to predict critical speeds.

2) To examine physical behavior of a surface in the vicinity of critical speeds in order to understand more fully the reasons for the sudden decrease in damping for small speed increases.

3) To evaluate the effects of configuration changes.

Our experience from the F11F-1F and other flutter programs has indicated that:

1) A controlled well defined excitation force is necessary to permit a thorough evaluation of all pertinent modes.

2) Incipient flutter may be predicted at subcritical speeds from the results of flight tests.

3) By the use of shaker excitation three related indications of incipient flutter are readily available for rapid analysis. The first, the reduction of frequency ratio, and the second, the decrease of 1/A and F/A, proved to be more effective than the third, the deterioration of damping coefficient.

4) Telemetering flight data for analysis by ground personnel greatly reduces the time required to complete the tests, increases the safety of the program, and permits a wide latitude of data processing techniques.

The limitations and problems in the testing techniques and equipment realized at the conclusion of the program are currently being investigated. Appropriate modifications to future flight flutter tests will be made based upon our findings, the experience of others, and the information acquired at this symposium.