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N250 PROTOTYPE-1 FLIGHT FLUTTER TESTING DEVELOPMENT

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ABSTRACT

Modern Flight Flutter Testing of aircraft requires application of artificial excitation. This paper presents the development of N250 Prototype-1 Flight Flutter Testing using an aerodynamic vane.

An important consideration in aircraft Flight Flutter Test is the use of controllable aerodynamics vanes to generate a well defined shaking force. The force has to be high enough to excite the aircraft structure beyond its normal flight vibration level. The response of the aircraft structure to the exciting force is analyzed to determine the vibrational stability parameters.

The best exciter locations are chosen to excite the symmetrical and anti-symmetrical bending and torsion modes of the lifting surface beyond its normal flight vibration level. Sine-sweep and sine dwell excitation types yield higher structural response levels as compared to random or impulse step excitation. The former is less complicated to analyze.

The instrumentation to measure the vane forces and responses are located at positions where the aircraft responds best to the excitation. The flight test procedure starts with test points from a safe initial condition and proceeds with small speed increments up to the ultimate speed, Mach condition, V_D/M_D. Theoretical predictions in combination with the resonance frequencies and the corresponding damping and transmissibility factors, as a function of speed, provide an estimation of the critical speed beyond which vibrational instability can occur.

The paper concludes that the vane, developed by Dynamic Engineering Inc. (DEI), is easily operated for in-flight excitation. Flight Flutter Testing of the aircraft is accomplished in a quick, accurate and safe way. Higher excitation frequencies are reached than were possible with stick raps.

1. INTRODUCTION

Modern Flight Flutter Testing of aircraft requires artificial excitation. This paper presents the development of N250 Prototype 1 Flight Flutter Testing excitation using an aerodynamic vane.

An important element in aircraft Flight Flutter Testing is the use of controllable aerodynamic vanes to generate a well defined shaking force. The force has to be high enough to excite the aircraft structure beyond its normal flight vibration level. The response of the aircraft structure due to the excitation has to be analyzed to determine the vibrational stability parameters.

The Flight Flutter Testing is carried out for a series of test points starting from a safe initial condition and progressing with small speed increments up to the ultimate speed, Mach condition, V_D/M_D. A brief overview of the new vane application for the N250-Prototype-1 is presented and some test results are highlighted.

The Flutter Clearance Testing should be completed early so that:

a. Other Flight Testing may proceed safely
b. Maximum reaction time is available to correct problems.

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The paper consists of five sections. Section 1 presents a brief description of the aircraft, flutter test objectives, and scope of tests. Section 2 describes general methods and test procedures as well as those specifically used for the N250 Prototype 1 Flight Flutter Testing. Section 3 covers methods to analyze Flight Flutter Test data. Finally, Sections 4 and 5 present, respectively, the test results and conclusions.

1.1 General Description of Aircraft

N250 Prototype-1 Aircraft is a turboprop commuter short haul aircraft for 50 passengers, high wing and T-tail (See Figure 1). The aircraft is powered by Allison AE-2100C turboprop engine with six bladed Dowty-Rotol propellers that are mounted on the inboard wing structure. The retractable tri-cycle Messier Bugatti that is mounted in the fuselage supports the aircraft. The flight control system is a fly-by-wire design.

Each control surface is actuated by two actuators: one is active while the other is stand by. The design of the flight control system insures that the stiffness and damping of the actuators are adequate for normal and failure conditions. This implies that mass balance is not allowed on any control surface for flutter prevention. The active actuator provides the stiffness while the stand-by actuator generates the damping force.

The general technical data of N250 Prototype-1 Aircraft are as follows :

Wing Span	28000	mm
Total Length	26629	mm
Height	8787	mm
Max. Take-Off Weight	22000	kg
Max. Landing Weight	21800	kg
Max. Cruise Speed at Sea Level	250	knots
Max. Dive Speed at Sea Level	300	knots
Max. Operational Ceiling	25000	ft

1.2 Objectives of Flight Flutter Tests

The main objectives are :

a. To confirm and demonstrate the aircraft freedom from flutter in its flight envelope.
b. To validate the methodology of theoretical flutter analysis.
c. To meet the airworthiness requirements. FAR/JAR/CASR Part 25-629.

To successfully attain these objectives, the following are essential:

a. reliability of the theoretical flutter analysis predictions
b. verification of the dynamic characteristics by ground vibration test
c. an efficient and reliable excitation system
d. on-line and post-flight flutter test data evaluation
e. good correlation between predicted values and test results data

The remainder of the paper shows that the use of controllable aerodynamics vane provides definite advantages over conventional excitation methods. In particular, the use of the DEI vane for the N250 Prototype 1 Flight Flutter Testing accomplishes all of the above objectives.

1.3 Scope

The flight flutter test of N250 Prototype 1 using flutter exciter is performed up to V_D at altitudes of: 25000 ft., 10000 ft., and 17000 ft. Two mass configurations are considered, namely:

a. Max. Weight - most forward CG
b. Light Weight - most aft CG.

2. N250 PROTOTYPE 1 FLIGHT FLUTTER TESTING DEVELOPMENT

2.1 Vibrational Stability Parameters

In the frequency range of interest, the vibrational stability parameters of the aircraft are :

a. the resonance frequencies
b. the accompanying damping value for each resonant frequency
c. the accompanying complex transmissibility factor for each resonant frequency. This value represents the ratio of the vibration mode response and the modal excitation force .

For each test point , the vibrational stability parameters are determined from the excitation forces and the corresponding responses.

2.1 Excitation System

2.1.a General Methods of Excitation

The acceptable approach to demonstrate flutter stability requires that the structural modes important for flutter can be excited in flight.

The best exciter locations have to be chosen so that both the symmetrical and anti-symmetrical bending and torsion modes of the lifting surfaces can be excited beyond their normal flight vibration level. Sine-sweep and sine dwell excitation types yield higher structural response levels as compared with random, impulse or step excitation. The former is also less complicated to analyze. The following is a brief summary of various conventional excitation methods and their limitations:

1) Control Pulses (Stick Raps and Servo Control Input) can be used to shake the aircraft by its own control surfaces and thereby avoid the installation of special devices shown in Figure 2. However, the frequency range is usually limited to low frequency (maximum about 10 Hz) and the quantification of the excitation forces generated by the control surface deflections is not possible. There is, therefore, a poor repeatability in generation of forces.

2) The low quality impulse excitation with Pyrotechnics (Bonkers) is applicable to supersonic airplane Flight Flutter Testing and Control Surface Testing, where the installation of vanes or inertia shakers is not allowed. This type of excitation is very good for higher frequencies (about 65 Hz). However, this excitation is poor for lower frequencies and, furthermore, the excitation forces are not measurable.

3) The excitation by air turbulence is still currently in use. The determination of the vibrational stability of the aircraft for the entire flight envelope using air turbulence is not accurate. The method requires making certain assumptions about the spectral contents of the natural source. This cheapest excitation source is not always available wherever and whenever needed and is, therefore, limited in practical application.

4) The advantages of the use of excitation by the controllable aerodynamic vanes are: the lower and upper frequency range of the excitation can be enlarged and accurate measurements of the excitation forces are possible. At present, three types of aerodynamic vanes are applied :
   a) Rotating vane with adjustable width (Lockheed application, Figure 3[Ref. 1])
   b) Pitching vane, Figure 4
   c) Fixed vane with rotating slotted cylinder along trailing edge Figure 5 [Ref. 2]

2.1.b Excitation Methods Used for N250 Prototype 1

Two methods of excitation were used in sequence at each test point in the flight flutter testing of the N250 Prototype 1 :

1) The first method is the use of control surface pulses by stick raps and rudder kicks. This method has the benefit of being able to excite the low frequencies and to quickly anticipate the occurrence of the low decay rate of the aircraft structure. After the aircraft structural vibrations due to the control surface pulses are damped out, the second method of excitation is activated.

2) The second method of excitation uses a flutter exciter system with slotted rotation cylinders. (See Fig. 5) It was developed by Wilmer H. Reed III and is distributed by Dynamic Engineering Inc. (DEI). The exciters are mounted on the Wing Tip and Horizontal Stabilizer Tip, both left and right hand sides. The advantage of using this flutter exciter is that it can sweep all modes in the frequency range of interest. In this case the structural modes that are important for flutter can be excited.

The basic flutter exciter unit is a pair of rotatable concentric cylinders. Each cylinder has a slot that allows the air to pass through. As the cylinder rotates about its axis the airstream is alternately deflected upward and downward at a frequency twice that of the cylinder's rotation frequency. The amplitude of the excitation force depends upon the dynamic pressure and the degree of slot opening.

Because the cylinder rotates at a constant or slowly varying frequency the torsional force that is necessary to surmount the inertial forces is not present. The drive motor, therefore, only needs to overcome mechanical and aerodynamic friction forces that are relatively small. The power required to rotate the slotted cylinders is minimal, allowing the use of a low wattage electric motor. This can be mounted together with the rotating cylinders and the fixed airfoil to a simple compact flutter exciter system.

The DEI flutter exciter uses a digital control system to maintain the proper cylinder speed under varying loads. The control system is packaged in two separate units. One unit, the cockpit control interface, is a small cockpit-mounted box housing all the interface switches and controls for the pilot's operation of the system (See Figure 6). The second unit is the avionics box which contains the principal control system components and motor amplifier necessary to drive the brushless motors used in the exciter assembly (See Figure 7).

2.1.c Modes of Operation for the N250 Prototype 1

The system allows three principal modes of operation which can be selected by the pilot:

1) Sine Dwell
2) Linear Sweeps
3) Logarithmic

Linear sweeps in the range of 25 Hz is used with 60 seconds duration time for the N250 Prototype 1 Flight Flutter Testing. Shorter duration sweeps and logarithmic sweeps did not always sufficiently excite the structural modes above 20 Hz.

The system also provides the choice of two force outputs: High or Low level. These levels correspond to the opening and closing of the outboard cylinder. Closing the outboard cylinder results in a 50% reduction in force. An additional blockage plug is included which allows the inboard slot to be half-closed for an additional 25% reduction in force. This inboard plug is attached on the ground prior to flight. Thus, it can not be modified while in flight.

The N-250 Prototype-1 flight flutter testing used 75% of maximum force (the slotted cylinder is 75% open) in order to obtain adequate excitation for important flutter modes in flight.

The control system also maintains phase control over the two exciters. The pilot can choose to operate the units either in-phase or 180 out-of-phase, allowing symmetric or anti-symmetric excitation, respectively.

The induced sinusoidal forces and bending moments are calculated from measurements by strain gauges mounted at the root of the exciter vane. The amplitude and frequency of excitation are displayed on the operator's control panel and are also available as analogue voltage inputs for data recording systems; similarly with the control panel switch positions.

2.4 Instrumentation

The essential instrumentation for flight flutter tests are the accelerometers distributed over the aircraft for the determination of structural vibrations, and the induced forces of the flutter exciters. The vane forces and the responses have to be measured. For that purpose the aircraft has to be instrumented at locations where the aircraft responds best to the excitation. In general, this will be at the extremities of the lifting surfaces of the aircraft, namely: the tips of the wing, the stabilizer and the fin.

Thirty five accelerometers and potentiometers are distributed over the N250 Prototype-1 aircraft and 4 strain gauges are located on the four flutter exciters as shown in Fig. 8.

Also important are the instrumentation to determine Speed, Mach Number, Altitude and Fuel Condition. All these signals were recorded on an On-board Pulse Code Magnetic (PCM) tape recorder. In addition, they were sent via telemetry to the Mission Control Room for real time quick-look monitoring on stripcharts and for a quasi on-line analysis of frequency and damping values of dominant modes (See Figure 9).

2.5 Flight Test Procedure

2.5.a General Aspects of Flight Test Procedure

The Flight Test procedure starts with test points from a safe initial condition and proceeds with small speed increments up to the ultimate speed, Mach condition, V_D/M_D. To reduce the complexity of the analysis, the symmetrical and the anti-symmetrical behaviour are considered separately. At each test point the sweep excitation is performed for symmetric and anti-symmetric excitation by which the vanes acts, respectively, in phase and in counter-phase sequence. The length and the number of repetitions of the sweep excitation can be regarded as an acceptable compromise to simulating the non-steady flight test conditions at the high speed descending flight path. The progress of a flight flutter test depends strongly on the test procedure, on previous experience with similar aircraft configurations, and on the results of reliable flutter calculations.

The general philosophy of testing is that such test points are scheduled for each flight which allowed expansion of the flight envelope to higher speeds only after extrapolation of the damping trends. If the analysis of the flight records at lower speeds showed no evidence of the flutter on-set, a clearance for the next airspeed increment was given. Maximum use is made of real time analysis techniques to reduce as much as possible the number of flight trials required.

The basis for the test is the availability of a comprehensive flutter analysis of the aircraft in all possible configurations. Starting from an initial flight envelope, cleared from a flutter point of view by analysis , the flight envelope expansion is made in progressive steps. At each progressive step the in-flight damping and frequency of all important structural modes of the aircraft and its control surfaces are determined.

2.5.b Implementation of Test Procedures to N250 Prototype 1

An efficient Flight Flutter Test Program of the N250 Prototype-1 of clean configuration (retracted flaps) for Maximum Weight - Most Forward CG and Light Weight - Most Aft CG were performed up to Vd for 25000 ft, 17000 ft and 10000 ft and up to 170 KEAS with flaps down.

The flight testing was conducted at three altitude levels, 25000 ft, 10000 ft and 17000 ft with a velocity range of 160 KEAS to 250 KEAS and a Mach number range of 0.28 to 0.63 (see Fig. 10, Test Points of N250 -PA1 Flight Flutter Test). For each test point control surface pulses and flutter exciter were both used to obtain frequency and damping data

First, the impulses were applied sequentially to the aileron, elevator and rudder control surfaces. This operation was used to clear each test point qualitatively and to obtain a rough approximation of decay rate.
The 8 selected parameters were displayed on stripchart for 'Quick-look' monitoring (See Fig. 11)

After completing the application of the impulse forces described above the flutter exciters were activated to obtain better frequency and damping calculation. This is done by activating the symmetric and anti-symmetric wing flutter exciters in sequence. When this is completed the symmetric and anti-symmetric tail flutter exciters are activated similarly. Because of the limitation of altitude tolerance, only control surface impulses were done at dive speeds.

The linear frequency sweeps were performed from 1. to 25 Hz at 60 sec. duration. This frequency range covers the primary modes of interest for the N250-PA1.
The accelerometer response data were telemetered to a mission control room for real-time data collection and monitoring. Thirty nine (39) parameters were telemetered and 2 parameters (one on wingtip and one on horizontal tip) were selected for a quasi on-line analysis of frequencies and damping values for dominant modes to clear next test point. The other 8 selected parameters were displayed also on stripchart for 'Quick-look' monitoring .(See Fig 12)

These 39 parameters were recorded and kept in storage. The data sampling rate is 125 samples/sec. For back-up data all these signals were recorded on-board by PCM tape recorder.

2.6 Aircraft Configurations & Test Points

2.6.a Mass Configurations

Flight flutter testing of N250-PA1 using flutter exciter has been done up to V_D at altitudes of 25000 ft., 10000 ft. and 17000 ft. Two mass configurations were performed namely: Max. Weight - most fwd CG and Light Weight - most aft CG.

Max. Weight - most fwd CG

- Max. Weight = 22 Ton
- Most fwd CG = 17 % MAC
- I/B tank was burnt first
- Test was stopped at approximately 1000 kg fuel used (tolerance consideration)

Light Weight-most aft CG

- Light Weight = 20 Ton
- Most aft CG = 41% MAC
- I/B tank was burnt first
- Test was stopped at approximately 600 kg fuel remain (safety consideration).

All altitude levels were tested with tolerance of 2000 ft.

All test points were tested with 'yaw damper-off' up to V_D and several test points with 'yaw damper- on' up to V_C. Also both 'autopilot -on' and 'yaw damper-on' were tested for several test points.

2.6.b Test Configurations Completed

According to the theoretical prediction, the 'autopilot-off' and 'yaw damper-on' condition is more critical than the 'autopilot-on' and 'yaw damper-off'. Since the rudder movement of 'yaw damper-on' can excite the fin torsion which is the flutter mode, it is clear that 'yaw damper-on' is more critical than 'autopilot-on'. Therefore, the flight flutter testing for the 'autopilot-on' and 'yaw damper-on' condition need not be performed.

3. ANALYSIS METHODS OF FLIGHT FLUTTER TEST DATA

3.1 Quick-Look Analysis

In conjunction with theoretical predictions, the sequence of resonance frequencies, the damping values and the transmissibility factors, as a function of the speed, provide a good estimation of the critical speed beyond which vibrational instability can occur. In deciding the safe continuation of a flutter test, the damping value of the least damped vibration mode at each test point must be immediately available. This requires quick-look analysis of a number of transmitted responses and excitation signals at each test point.

Two ways of quick-look analysis are used at PT. IPTN. The most important and direct way in making the decision to continue flutter testing to the next test point based on real time monitoring of the time traces of a limited number of response signals. The label of the vibration and the shape of the response due to sweep excitation contain important information about the vibrational damping, especially in relation to the previous test point. If a low damped mode is present, the comparison of the shape on the measured sweep response with pre-calculated sweep responses of a single- degree-of -freedom system for a series of damping values, gives a good indication of the amount of damping remaining in that low damped mode.

The second way of quick-look analysis is to analyze the least damped mode with a dedicated software package. The methods of analysis are based on curve-fitting one or a limited number of resonance peaks in either the power spectrum or the frequency response function (FRF) or its complex plane representation.

Post-flight analysis was performed by an accurate, multiple degrees of -freedom curve-fitting technique on all relevant power spectra or FRF's on all on-board registered signals.

3.2 Analysis of Measured Vibration Signals

To analyze the measured vibration signals, several methods are available. For all methods it is assumed that the flying aircraft can be represented by a linear system. The analysis of this linear system can be done in time domain, or more commonly, in the frequency domain.

The analysis is done in the time domain if the stick-rap excitation is used. It is possible to use the impulsive response of the aircraft structure to predict flutter on-set. In most cases the impulsive response is of short duration and, therefore, the accuracy of the measurement is reduced. However, a brief analysis directly from the stripchart recording can provide an initial guess of flutter on-set.

If the flutter exciter is used, the analysis is usually done in the frequency domain. In this case, the transfer function between excitation and response are calculated. From the averaged input and cross power spectrum, the transfer function is computed by using Fast Fourier Transform. This represents the complete system parameter description available.

The following two methods are used to analyze measured vibration signals:

- Levy Complex-Curve-Fitting Method
- Zimmerman Flutter Criterion

3.2.a Levy Complex-Curve-Fitting Method

For the system identification and parameter estimation, the Levy Complex-Curve Fitting method is used .

During the flight test the above methods are used to extract frequencies and damping from two accelerometer data that are located on the right wingtip and on the right horizontal tail plane (HTP). Therefore, the evaluation is done only for the critical modes. In addition to extraction of frequencies and damping data, these methods can also predict the flutter on-set (Ref. 9) based on the two critical modes. This prediction provides clearance information to proceed to the next test point.

After the flight flutter test a more detailed evaluation of all accelerometers data was also done by using Levy complex-curve fitting techniques.

3.2.b Zimmerman Flutter Criterion

One difficult aspect of flutter testing is that a flutter mode can suddenly become unstable with only a small increase in dynamic pressure. Furthermore, there may be little or no indication of approaching instability in a plot of modal damping against dynamic pressure.

The Zimmerman flutter criterion (Ref. 8) is based on considering the value of measured frequency and damping data for the characteristic equation of a two-degrees-of-freedom system as a flutter margin parameter with increasing speed. Using this information, it is possible to predict the behavior of the flutter margin at speeds not yet flown and to predict the speed of flutter on-set especially for on line analysis. It can be expressed in terms of the measured frequency and damping of the two modes which are input as parameters.

4. FLIGHT FLUTTER TEST RESULTS

In addition to on-line analysis of wingtip and HTP during the flight test with telemetry data, other accelerometer data were used for off-line analysis by playing back the telemetry data. The time histories of accelerometer and reference excitation signals were first plotted to determine the position of sweep and the parameters which contained the modes of interest.

All frequency response function (FRF) parameters and curve fits described previously were performed with 'Levy' Curve-Fitting' and an example of FRF result can be seen at Fig. 13.
After determining the frequencies and damping values, the V-g plots were supplemented with due consideration of the aircraft configurations. The fuel condition did not have a big influence on the frequencies and damping, since the critical mode is fin mode.

Table 1 and Fig. 14 show some V-g and V-f results of the anti-symmetric modes of flight flutter test results for max. weight-most fwd CG.
The damping results of the testing were presented as critical damping ratio. For small values of damping ratio, the structural damping (g) is equal to two times of critical damping ratio. Because of the limitation of altitude tolerance, only control surfaces impulses were done at dive speeds.

The plots of the measured frequency and damping trends versus speed at all altitudes show that the N250-PA1 is free from flutter up to V_D, and that damping values for all modes exceed $g=-0.03$ under test conditions. The damping trends also show that there is no large and rapid reduction in damping near V_D. In general, the theoretical predicted trends of suspected critical modes for frequency and damping versus airspeed and altitude showed moderate compliance with test results. The damping extrapolation based on the test data for higher speeds do not show trends for inadequate flutter stability within the 1.15 V_D range.

Several test points were performed using 'yaw damper-on'. It can be seen that the frequencies and damping with 'yaw damper-on' were in close agreement to the results of the 'yaw damper-off'. It is concluded that there is no feed back from 'yaw damper-on' (control system) to the flutter mode.

5. CONCLUSIONS

The following conclusions are reached on the basis of the flutter test results:

a. The fuel condition do not have a significant influence on the frequencies and damping, since the critical mode is fin mode.

b. The theoretically predicted trends of suspected critical modes for frequency and damping versus airspeed and altitude show moderate compliance with test results.
Extrapolating the above test data for higher speeds indicate no flutter instability within the 1.15 V_D range.

c. The tests show that the frequencies and damping with 'yaw damper-on' are in very close agreement to the results of the 'yaw damper-off'.
It is concluded that there is no feed back from 'yaw damper -on' (control system) to the flutter mode.

d. Based on comprehensive post-flight analysis after flight testing up to V_D, it is concluded that no flutter behavior is predicted within the V_D flight and CG envelopes of N250-PA1 including flaps speed placard.

e. The flutter test and analysis of the N250 Prototype 1 aircraft comply with all the certification requirements of FAR/JAR/CASR Part 25-269.

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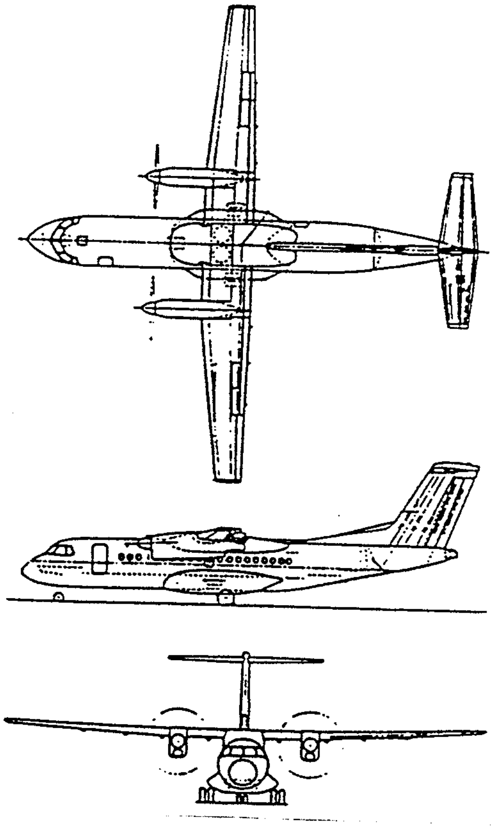

Figure 1. N250-PA1 Three View Drawing

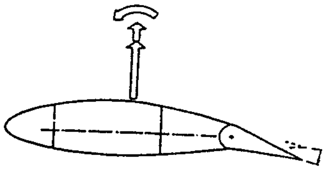

Figure 2. Stick Rap

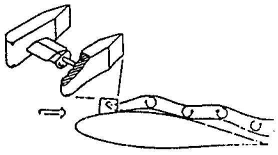

Figure 3. Rotating Vane

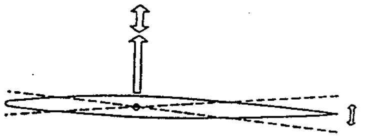

Figure 4. Pitching Vane

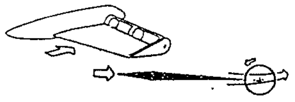

Figure 5. Fixed Vane (DEI)

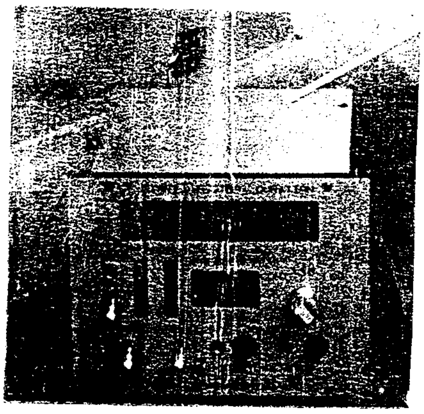

Figure 6. Cockpit Control Box

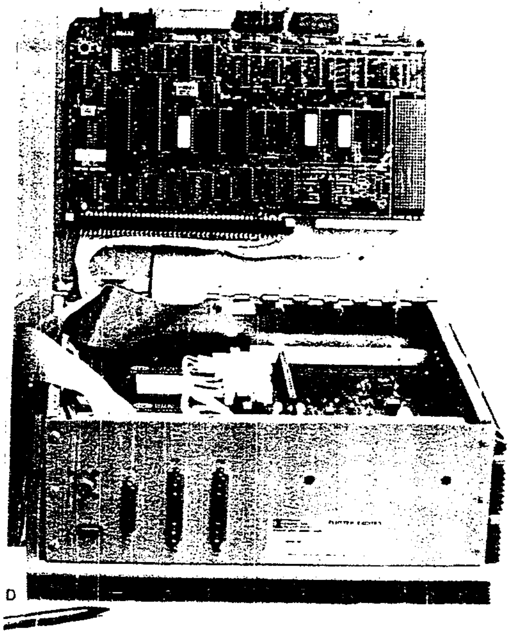

Figure 7. Avionic Box

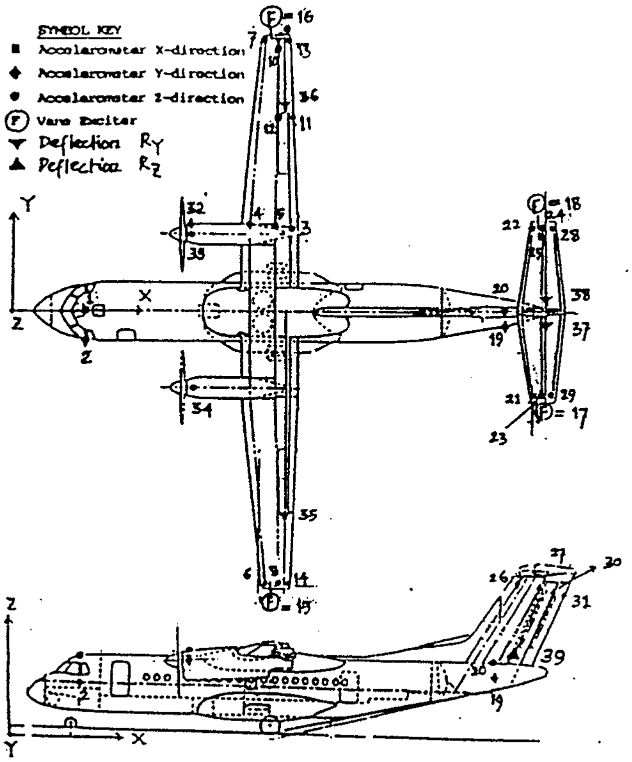

Figure 8. Accelerometer and Straingauge Location

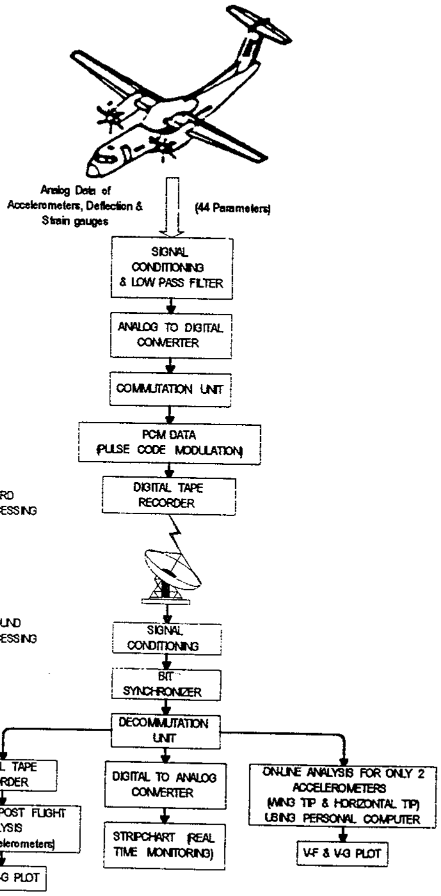

Figure 9. Telemetry Data Processing

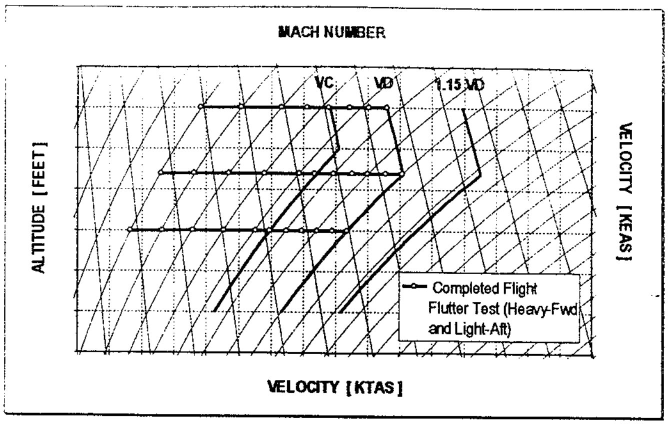

Figure 10. Flight Flutter Test Points

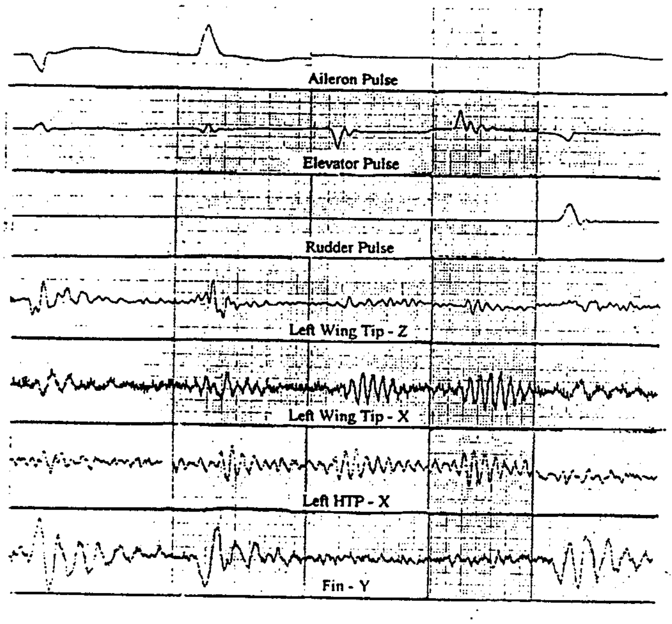

Figure 11. Stick Rap

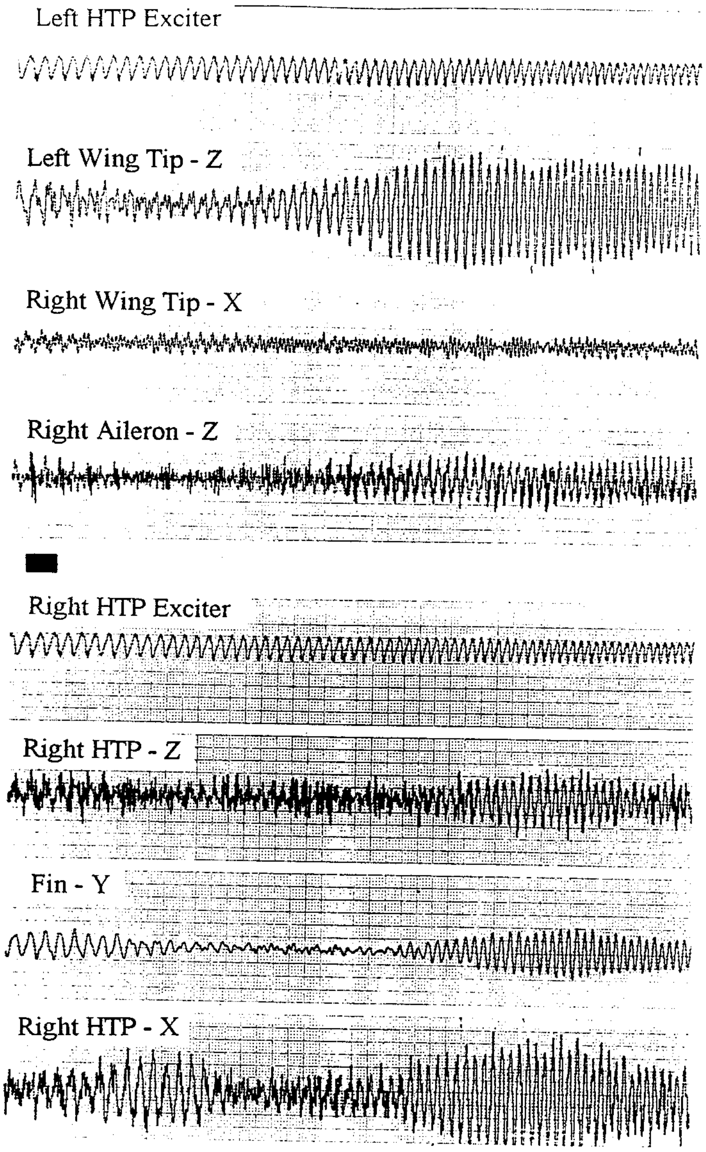

Figure 12. 8 Selected Parameter Strip Charts

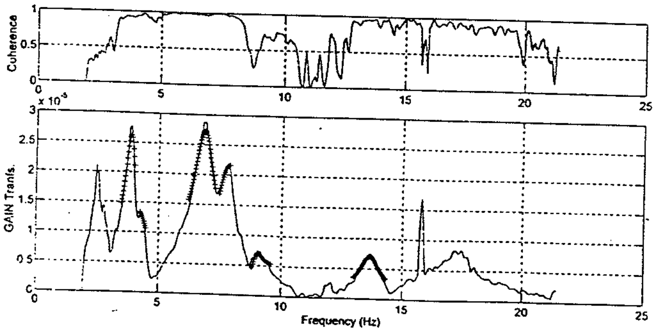

Figure 13. FRF Result

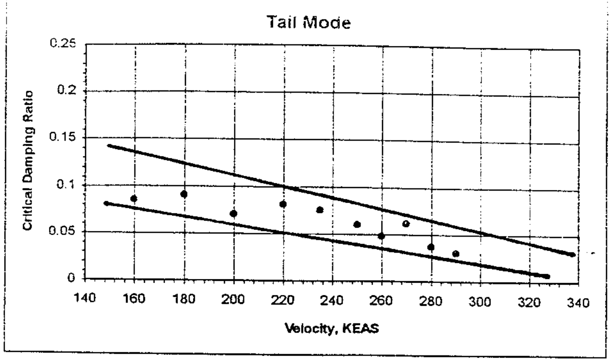

Figure 14. Critical Damping Ratio Evaluation

Frequency Interval		Natural Freq.	Crit. Damp. Ratio	Phase (deg)
3.469	4.011	3.893	0.05581	-71.46
4.228	4.471	4.200	0.08556	-102.40
6.233	7.317	6.906	0.05893	-74.50
7.479	7.913	7.828	0.06820	-126.90
8.807	9.593	8.977	0.02125	-151.20
12.950	14.310	13.640	0.02737	-94.75

Table 1. Frequency, Damping, and Phase from Test Result