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SURVEY OF AIRCRAFT SUBCRITICAL FLIGHT FLUTTER TESTING METHODS

by

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FOREWORD

A.R.A.P., under contract with Langley Research Center, NASA, has been studying the problem of subcritical flight flutter testing of aircraft. As part of this effort, a survey was made of aircraft industries to establish a summary of testing techniques and data analysis methods that are currently being used. The survey was made by Mr. Robert Rosenbaum, and is reported herein.

This report should be considered a companion to a second report, NASA CR-132480, entitled "Subcritical Flutter Testing and System Identification," by Dr. John C. Houbolt, principal investigator of the contract effort, who also performed some editing of this survey summary.

SURVEY OF AIRCRAFT SUBCRITICAL
FLIGHT FLUTTER TESTING METHODS

by Robert Rosenbaum*

SUMMARY

The results of a survey of U.S., British and French subcritical aircraft flight flutter testing methods are presented and evaluation of the applicability of these methods to the testing of the space shuttle are discussed. Ten U.S. aircraft programs covering the large civil transport aircraft and a variety of military aircraft are reviewed. In addition, three major French and British programs are covered by the survey. The significant differences between the U.S., French and British practices in the areas of methods of excitation, data acquisition, transmission and analysis are reviewed. The effect of integrating the digital computer into the flight flutter test program is discussed. Significant saving in analysis and flight test time are shown to result from the use of special digital computer routines and digital filters. Computer techniques have been developed which minimize the effect of extraneous noise (such as caused by turbulence) in the response signal.

INTRODUCTION

A survey of subcritical flight flutter testing methods employed by U.S. aircraft manufacturers was conducted during the latter half of 1972. The survey was conducted by visiting a number of companies and discussing with their representatives the methods currently used in the areas of: excitation; data acquisition, retrieval and analysis; and methods employed in extrapolating from subcritical conditions to the flutter boundaries. The survey did not include manufacturers of general aviation aircraft. In addition to direct discussions with representatives of U.S. industry, a limited survey of French and British practices was made through personal contact, correspondence and review of published material. For the U.S. as well as the Anglo-French surveys, emphasis was placed on recently completed programs and programs in progress, as well as those programs which, although the flight testing had not as yet started, were sufficiently far advanced in the planning

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stage to be considered current programs. Programs which were still in the research or preliminary development phase were not considered. The survey was intended to establish the current state of the art of subcritical flight flutter testing. The survey brought out the fact that a number of survey-type reports also exist, see references 1 through 8.

Having determined the state of the art, an evaluation of the applicability of current methods to testing the space shuttle was made.

SURVEY FINDINGS

U.S. Industry

The following material summarizes the information gathered during the survey of subcritical flight flutter testing methods. Not all the companies which are active in major flight flutter testing programs were contacted. However, those companies which were contacted were considered to provide a broad cross section of U.S. industry practices and were representative of the state of the art in regard to such tests. The companies which were contacted and the aircraft discussed covered the producers of the leading commercial transports (Boeing 747 and SST, McDonnell-Douglas-West DC-10 and Lockheed-California L-1011) as well as producers of a variety of types of military aircraft (Lockheed-Georgia C-5A, Lockheed-California S-3A, General Dynamics F-111, Grumman F-14, McDonnell-Douglas-East F-15, and LTV A-7A).

At the time of the survey of the listed aircraft, the 747, L-1011, DC-10, C-5A, F-111 and A-7A had completed their tests; the F-14 and S-3A were in the midst of their tests, and the F-15 was just ready to start its test program. The SST program, prior to its cancellation, had been scheduled to start in April of 1973.

<u>McDonnell-Douglas - Long Beach, California: DC-10.</u>- On the early flights for speeds up to 300Kts excitation was achieved by pilot pulses and by pilot-induced forced oscillations. Aerodynamic vanes were then used as exciters on all subsequent flight flutter tests. The vanes were located at the wing tips and tips of the horizontal stabilizers and fin. The vanes used on all of the surfaces were the same size (12" span, 16" chord). The frequency range covered was mainly 1 to 10Hz in 90 seconds, following the exponential sweep law. Some sweeps covered the range of 1 to 20Hz. In general, the frequency sweeps for wings, vertical tail, and horizontal tail were separate. Some tests were conducted with all vanes operating simultaneously. For each test condition, after sweeping through the frequency range, 4 to 6 resonant frequencies were

selected for dwell and quick stop of the exciters. Damping was then obtained from the decay records of each of the selected frequencies.

On the order of 300 to 400 channels of data (accelerometer, strain gage and position indicators) were recorded on tape recorders on board the aircraft. The data were transmitted by PCM to the ground station. The demodulated PCM signal was fed to a digital computer as well as strip charts providing twenty-four channels for direct monitoring. Broad band filters were used to eliminate high frequencies above 60Hz. In addition, tracking filters of 2Hz bandwidth were used during sweeps.

Force input from the vanes was obtained from strain gages on the vane shaft. Flutter indices used in evaluating stability over the required operating envelope were the variation in amplitude per unit input force and damping as function of dynamic pressure and Mach number.

Lockheed-California Division: L-1011.- Aerodynamic vanes installed outboard of the wing tips and stabilizer tips were used as the source of sinusoidal excitation. Both wing and stabilizer vanes had a chord of 18 inches; the wing vane span was 28 inches, while the stabilizer vane span was 20 inches. For the wing sweep, the frequency range varied from 1 to 18 Hz in approximately 90 seconds. Lockheed's procedure on the L-1011 involved sweeping up and down through the frequency range. During the sweep the period of the excitations force decreased linearly with time; i.e., linear period sweep law. The 90-second sweep time was the time to sweep in one direction. For the stabilizer, the frequency range covered was 3 to 25 Hz in approximately 30 seconds (time for sweep in either direction).

Response data were obtained from accelerometers, strain gages, and position indicators, with approximately 75% obtained from strain gages and 25% from accelerometers and position indicators. One hundred and twenty channels of data were recorded on tape on board the aircraft. The data channels were arranged in 6 banks of 20 channels each. Any set of 20 channels could be transmitted via FM telemetry at any one time. Damping was obtained from the bandwidth of the response curves; resonant frequencies were obtained from the shift of the frequency of peak response in sweeping up and down. This method is covered in the paper by E. Bartch (ref. 1) for the case of a linear variation of frequency with time. For the linear period sweep law used in these tests, a modification of the sweep parameter in the charts of reference 1 was employed. Most of the test runs involved sweeping up and down the frequency range. However, to a very limited extent, damping was also obtained from decay records after dwelling at a resonant frequency and quickly stopping the excitation.

Lockheed-California Division: S-3A.- Excitation of the S-3A was by aerodynamic vanes installed on each side of the fuselage in the vicinity of and below the stabilizer. Vane size was 18" chord and 22" span. The frequency range of interest was 1.5 to 18 Hz for the wing and 3 to 25 Hz for stabilizer. Time to sweep through the frequency range of interest was approximately 90 seconds in both cases. The sweep frequency variation followed the linear period law. In contrast with the L-1011 test, the S-3A sweep was up only (increasing frequency). Damping was obtained from response decay records after dwelling at a resonant frequency and quickly stopping the excitation. Pulse code modulation was used for transmitting the data from the airplane to the ground station.

Boeing: 747.- Early in the test program the 747 was cleared over the major portion of the flight envelope by pilot pulsing of the controls. On the basis of these tests, and on analytical studies and wind tunnel model testing, it was decided that wing tip excitation only was appropriate for subsequent subcritical flight flutter testing. An aerodynamic vane, 2 ft^2 in area, was located outboard of each wing tip. The vanes were electro-hydraulically driven. Although the excitation had the capability to operate over the range of .5 to 20 Hz, most sine sweeps covered the range of 1.5 to 7 Hz in 90 seconds. The sweep frequency varied exponentially with time.

Data from accelerometers, straingage pickups and control position indicators were transmitted by FM telemetry to a ground station for analysis. The test technique included frequency sweeps to determine resonant frequencies. Quick stops at the resonant frequencies provided the decay records for which the damping values were obtained. The variation of frequencies and damping with dynamic pressure and Mach number was established, especially to assure adequate damping over the required flight envelope. Figure 1 shows the location of the aerodynamic vanes at the wing tips of the 747 wing.

Boeing: Supersonic Transport.- At the time the SST program was cancelled in 1971, plans for the flight flutter program were well advanced. Flight flutter tests were scheduled to start on April 1, 1973. Based on analysis and flutter model testing, there were indications that in the transonic and low supersonic speed regime the required flutter margins could not be met. Because of the limited funding for the phase III government-industry cost sharing program, it was of particular importance to reduce the time for flutter testing. The technique of searching for resonant frequencies by relatively slow sweeps, tuning these frequencies by hand, and then quickly stopping the excitation to determine damping (as in the 747 tests) was therefore discarded.

Wing tip aerodynamic vanes similar to those used on the 747 were planned for the SST. In addition, aft body inertia shakers were planned to provide lateral and vertical body excitation. Plans were to use a fast sine sweep covering the range of 1 to 20 Hz for the wing vanes and sweeps from 5 to 10 Hz for the inertia exciters. Variation of frequency with time was to follow the exponential sweep law.

Response data were to be obtained from accelerometers and control position indicators. Vane input data were to be obtained from strain gages on the torque shaft of the vanes. The data were to be recorded on tape on the airplane and telemetered to a ground station. After demodulation, the force input and response data were to be recorded on a magnetic tape recorder and a step chart recorder for direct observation of the analog signals, and was also to be digitized and fed to the digital computer for fast Fourier transform analysis. From the ratio of the Fourier transforms of response to input, the frequency response information was to be obtained in the form of Kennedy-Pancu vector plots (ref. 9). The frequencies and damping for each mode would then be deduced; the variation of damping with Mach number was considered of prime interest. Figure 2 shows the flow diagram for data acquisition, transmission and reduction that was envisioned for the SST. These proposed flight flutter test techniques were evaluated in low speed wind tunnel studies and are reported in reference 10.

Lockheed-Georgia Division: C-5A.- The vane system for excitation of the C-5A aircraft differed significantly from the external aerodynamic vane system used by Boeing, Douglas and the Lockheed-California Division. The system consisted of one rotating vane on the top of each wing near the wing tip and one rotating vane on the top of each horizontal stabilizer tip. The vanes rotated through 360° with two cycles of excitation provided for each revolution. Each vane was supported between two pylons which were structurally fastened to the aircraft at the closing rib of the surface. The vane chord was 14 inches. The span of the wing exciter could be varied from 13 to 26 inches by telescoping two 13-inch sections. For the stabilizer, a fixed 13-inch span exciter was used since layer vane spans were found to lead to high structural loads. Figure 3 shows the vane and pylon assembly and Figure 4 is a photograph of the assembly on the C-5A airplane. Wind tunnel tests of the installation indicated that the best measure of oscillating input force could be obtained from the drag measured on the vane supporting structure. The vanes could be tuned manually to any desired frequency with a quick stop capability, or they could be programmed to sweep over the range of .25 to 12.5 revolutions per second, which resulted in excitation varying from .5 to 25 Hz. Frequency of excitation varied exponentially with time. The time to sweep through the frequency range was 60 seconds for most flights. However, for those flights involving sustained dive attitude, the time to sweep was reduced to 30 seconds to minimize altitude variation at the test point. Both sets of vanes were synchronized to permit either symmetric or antisymmetric excitation. When not in operation the vanes automatically returned to a zero lift streamlined position.

On-board instrumentation included accelerometers, strain gages and control position indicators. Eighty channels of data were recorded on an airborne tape recorder. Thirty channels of preselected data were telemetered to the ground. Any of the other channels could be selected in flight for transmission to the ground station.

The telemetered data were recorded on tape at the ground receiving station and simultaneously monitored on pen recorders for visual real time qualitative evaluation. Twenty of the thirty telemetered signals were then transmitted from the receiving station to the hybrid computers. Nine of the signals in analog form were then passed through 2 Hz bandwidth tracking filters continuously tuned to pass only the excitation frequency. The time of zero crossings and peak amplitudes were then used by the digital computer to generate response envelopes from which frequences and amplitudes were obtained. Amplitudes were normalized through use of the concurrent amplitude of the drag force signal of the vane. Significant frequencies and amplitude were displayed approximately 3 seconds after the end of each sweep.

During the sweep tests two basic structural modes were excited to amplitudes approaching 80% of limit load. The damping for these modes was obtained by tuning to the critical frequencies, dwelling at the frequency and then using the quick stop technique to obtain the decay records.

Some difficulties were encountered with the tracking filters which resulted in phase drift during the sweep tests. This prevented accurate determination of damping values. The flutter index used in the subcritical tests and for extrapolation beyond the operating envelope was in the form of a plot of normalized amplitude versus velocity or Mach number.

General Dynamics-Ft. Worth: F-111.- Wing excitation was provided through aerodynamic vanes located outboard of the almost full span flaps. The vanes were within the normal contour of the wing and were similar to small span ailerons. The area of each vane was approximately 1.5 ft^2. The hydraulic power supply used to drive the vanes was completely independent of the normal airplane hydraulic system. System frequency capability extended from very nearly zero to 50 Hz. Sweep variation followed the exponential sweep law, starting from 35 Hz and ending at 2 Hz for each run. Time to sweep through this range was approximately 45 seconds.

Horizontal and vertical tail excitation was provided by inertia shakers. These units were hydraulically driven with the mass in each unit moving in pure translation. A 150# peak force shaker was installed on the vertical tail; a 300# peak force shaker was installed at each side of the rear fuselage for horizontal tail excitation.

Response data from accelerometers, position indicators and flight parameters were recorded on tape in the airplane. Twenty-four channels of data were transmitted by FM telemetry to a ground station for recording in raw form (no filtering). Band pass and tracking filters were then used to provide analog records on an x-y plotter at the ground station. Most of the flutter data were obtained from the selected telemetered transmissions. On board tape recording was used in post flight analysis of random channels other than those telemetered to the ground.

Frequency sweeps were used to identify resonant frequencies. Damping of modes of interest was obtained from decay records resulting from dwelling at the resonant frequencies and quickly stopping the exciter.

Good results were claimed for the wing vanes and vertical tail inertia shaker. However, for the horizontal tail, insufficient excitation was obtained from the inertia shakers at the side of the fuselage. Adequate horizontal tail excitation was obtained from the wing aerodynamic vane when the wing was in the 72° sweep position. However, for the 50° sweep position, wing tip excitation was not effective in exciting the horizontal tail. An explosive shaped charge was tried on the horizontal tail for the 50° sweep position but was not successful. Finally, reliance was placed on pilot pulsing as the source of excitation for the 50° sweep position.

Figure 5 shows the location of the wing exciter, as well as a flow chart for data transmission.

McDonnell Douglas-St. Louis, Missouri: F-15.- The F-15 program was planned so that it would follow the pattern of the most recent F-4 flight flutter test with the major significant modification being the utilization of digital computing equipment in conjunction with the analog equipment previously used.

Aerodynamic excitation is provided by introducing sinusoidally varying electrical signals to the servos of the aileron and stabilator control systems. Linear frequency sweeps over the frequency range of 2-16 Hz were planned in 100-200 seconds. Some sweeps in the range of 5-10 Hz in approximately 45 seconds were also planned.

Strain gages, accelerometers and position indicators will be used to obtain response data. Input force will be obtained from the control surface actuator force links. All of the response and input force data will be recorded on tape by on-board recorders and 18 channels of selected data will be transmitted by FM telemetry to the ground station.

Data received at the ground station will pass through band pass and tracking filters and recorded on pen-type strip charts for immediate visual on-line monitoring, and, in addition, will be recorded on tape. The tape will be sent to a hybrid computer where the analog data from the tape will be digitized. The fast Fourier transform technique will be used to compute the Fourier transform of the response and input force. A plot of the transfer function will be obtained from the ratio of response and input transforms. Damping and resonant frequencies will be obtained from Kennedy-Pancu vector representation of the transfer function. The computer has also been programmed to compute the Zimmerman flutter margin (ref. 11) and to extrapolate to the predicted flutter speed for each combination of two frequencies that might couple at the flutter speed or Mach number. Figure 6 shows a schematic drawing of the flight flutter system.

Although the basic program to be followed is the one outlined above, the exciter system can be controlled so that the pilot can select any frequency and dwell at that frequency. In addition to the completely automatic linear frequency sweep, quick stops of the excitation are planned at selected frequencies in order to obtain the damping from the resulting decay curves.

Grumman: F-14.- Excitation of the wing is by aerodynamic vanes located outboard of the wing flaps and within the normal contour of the wings. The vane area is approximately 1 ft^2. Each fin is fitted with an auxiliary aerodynamic vane. The fin vane is located at the tip of each fin, external to fin surface, and has an area of 30.7 in.^{2}. An inertia shaker is used on the horizontal tail (right side only). Most tests have been conducted by sweeping through the frequency range of 5-50 Hz in 50 seconds following the exponential sweep variation. The system has the capability of sweeping through the range of 2-70 Hz in 15 seconds and in the latter part of the program, the upper end of the frequency range is to be extended from 50-70 Hz. In addition to the rapid sweep, the capability exists for manually setting the frequency, dwelling and stopping the excitation rapidly. Approximately 98% of the data have been obtained from rapid sweep tests.

Response data are obtained from accelerometers, velocity pickups and control position indicators and the data transmitted to the ground by a hybrid PCM/FM transmitter. Demodulated FM and PCM data are recorded on magnetic tape on the ground. The analog data are digitized for use in data reduction by the high speed digital computer. In parallel with the digital flow, 16 channels of the analog data are fed to two banks of 8 channel Brush recorders. The resulting strip charts are monitored for the evaluation of data quality which might influence the digital computer program (e.g., telemetry malfunction during sweep, etc.), as well as for monitoring flight safety. At each test point frequencies and damping are obtained from the digital computer by a technique described by Grumman as "model matching" (ref. 6).

An analytical model of the motion of a multimode representation of the aircraft response to an externally applied force is programmed in the form of difference equations in the digital computer. Constants are derived which cause the model response to be identical, within some prescribed degree of accuracy, to the airplane response to an input force. The constants are then used to determine frequencies and damping. Matching is done over a limited frequency range by use of digital filters. Each significant frequency band is analyzed separately and a different model match is obtained for each band. The system used by Grumman has the capability of computing all the resonant frequencies and associated dampings in less than 30 seconds after a 15-second shaker sweep from 5-50 Hz. A high storage capacity is required. The procedure actually followed is one in which five separate shakers sweeps may be made during a single flight run (typically involving wing symmetric and antisymmetric excitation, and excitations of the horizontal tail and fins). The response data from the five sweeps are digitized and stored on a disk. The airplane is then slowed while all the frequencies and dampings are computed; this computation takes less than five minutes.

Vought Aeronautics Division of LTV: A-7A.- The A-7A is a close derivative of the F-8 airplane which was a supersonic fighter. The F-8 has had a successful history of approximately 15 years. It was felt that on the basis of analysis and wind tunnel flutter model testing that the wing stores problem was the only potentially critical flutter problem. On the basis of the analytical and wind tunnel evaluation, it was determined that the critical frequencies were in the range of 3 to 9 Hz.

Based on the engineering evaluation of the relationship between the F-8 and the A-7A, as well as wind tunnel tests and analytical work, the decision was reached that the complexity involved in the installation and operation of harmonic excitation was unwarranted. Excitation was provided by pilot pulsing on the controls. Strain gage and accelerometer and position indicator response data were recorded on board the airplane and telemetered down to the ground station for recording and analysis of the decay records. The decay records were used to obtain damping at each subcritical flutter point.

Anglo-French Programs

Concorde SST.- Information on the Concorde flight flutter program was obtained during a visit to Societe National Industrel Aerospatiale (SNIAS) at Toulouse, France early in March 1970. Additional supplementary information was obtained from Piazzoli's paper "Aeroelastic Test Equipment for the Concorde SST" (ref. 12) and by correspondence with the British Aircraft Corp., Bristol, England.

Excitation for the Concorde tests has varied, covering both sinusoidal sweeps and transient excitation. For the French prototype (airplane 001), harmonic excitation was provided by electrodynamic shakers in the early flights. Each shaker consists of a coil which is rigidly attached to the structure and a permanent magnet which produces a magnetic field perpendicular to the coil. An artificial seismic platform is created by suspending the permanent magnet from the structure by a "soft" suspension system. The suspension system frequency for this type of seismic exciter is chosen so that its natural frequency is at most 1/3 the value of the lowest natural frequency of the structure it is attached to. Ground vibration tests of the Concorde indicated that the lowest frequencies of the wing were of the order of 2.5-3 Hz. The spring suspension for the shakers was therefore taken as approximately .75 Hz.

As in the case of electrodynamic shakers used for ground vibration tests, simultaneous operation of numerous exciters in flight was employed. Input force which is proportional to the current in the shaker coil was found to be easily controllable for each shaker independently and was kept constant during a frequency sweep. Ten shakers were used on the wings (5 on each wing), four on the fin and five on the fuselage (3 for vertical excitation and 2 for lateral excitation). The flight test was programmed to insure proper scheduling of force for each mode under study. Prior to each flight a tabular form was provided to the flight engineer listing 24 cent al frequencies to be explored. Sweeps were then made [illegible] 15% below each central frequency to 15% above it. The a[illegible].de and phase distribution of forces appropriate to ea[illegible]de was preprogrammed for each shaker. Ground vibration [illegible]s were used as the starting point and analysis was used to predict the change in structural mode shape due to aerodynamic effects. For each subsequent step up in air speed or Mach number, the distributions of force input were suitably modified. The frequency range covered by the harmonic excitation tests was from 2 to 50 Hz. The time allowed for exploration of each central frequency of interest was adjustable to insure that negligible distortion of the response would result; i.e., slow sweeps were used approximating steady state conditions.

For the most part the electrodynamic shakers worked well. However, difficulties were encountered under turbulent flight conditions and for flight in the transonic speed regime. Because of the very soft suspension, turbulence caused the permanent magnet to bottom out and shut off the shaker. In the transonic range, vortices shed from the leading edge of the wing were at a frequency close to the natural frequency of the suspended permanent magnet and resulted in intolerable response of the mass.

Harmonic excitation of the fin and rudder was provided on the 002 airplane (the British prototype) by feeding electrical signals to the power controls. The frequency range was from

4 to 36 Hz following either the linear frequency or the linear period sweep law. The time to sweep the entire range varied up to 4 minutes.

In addition to sinusoidal excitation, transient excitation of several types were used. For control surface excitation, impulsive, explosive charges were employed. The combustion time chosen was .030 seconds to match the medium frequency of the relevant frequency band of 10-20 Hz for the control surfaces. Pilot excitation of the controls was also used. However, because of inability to adequately control the pilot pulse (in order to excite higher frequencies), shaped electrical inputs were ed to the power controls which provided repeatable results. The electrical inputs provided triangular shaped impulses of 50 milliseconds duration and control surface amplitude of up to 2 degrees of rotation.

Accelerometers and position indicators were used to obtain response data. The data were recorded on airborne tape recorders. Selected channels of data were available in the form of strip charts for on-board monitoring of the records. Data obtained in flight were transposed on the ground to digital tape for analysis after each flight.

For harmonic excitation admittance curves were obtained and Kennedy-Pancu plots were used to obtain frequencies and damping. In the case of analysis of the response records from transient excitation, early techniques employed analog applications of the Mazet method. The original record played in reverse is passed through a tracking filter to isolate each mode and determine frequencies and damping (ref. 12). More recently, a digital application of the Mazet approach has been used with a significant reduction in analysis time.

A-300B Airbus. - The A-300B used excitation techniques essentially similar to those used on the Concorde 001 airplane. Fifteen electrodynamic shakers were distributed as follows: on each wing - 2 at the wing tip, 2 at midspan and 1 on the nacelle; on the stabilizer - 1 at each tip; on the fin - 2 at the tip and 1 at midspan. In addition, electromagnetic control of the actuating rod permitted symmetric and antisymmetric excitation of the aircraft through the control systems. Symmetric excitation was provided through the elevators and low speed ailerons, whereas antisymmetric excitation was provided through the rudder and low speed ailerons.

Impulsive excitation was provided by 19 exciters similar to those used on the Concorde 001. Combustion time for the exciters was in the range of 25-30 milliseconds. The impulsive exciters were distributed as follows: 3 on each rudder, 3 on each elevator, 3 on rear span of each wing, 2 on each engine nacelle.

Accelerations of various points of the structure were recorded on magnetic tape. At least 48 accelerometer records from accelerometers located on fixed and movable surfaces were recorded for each flight (13 lateral, 34 vertical and 1 longitudinal).

Data analysis techniques were identical to those used on the Concorde 001. In regard to flutter indices, Aerospatiale (SNIAS) carefully follows the variation of damping as a function of speed (or Mach number) as the sole criterion for the authorization of each following flight. Comparisons between calculations and test results are continually made to provide additional assurance for the safe continuation of the tests.

Jaguar.- Sine sweep, random noise and impulsive excitation was employed on this military aircraft. Sweep excitation was provided through the control surfaces by injecting electrical signals into the servo system. Sweeps through a factor of 7 from either 3, 6 or 8 Hz were used in 100 seconds. The linear period sweep law was used. The random noise was a pseudorandom binary sequence with bandwidth of either 50 or 12.5 Hz with a sequence period of about 10 seconds. The binary sequence in the form of an electrical signal drove the control system through the servos. Impulsive excitation was either by pilot input (used for qualitative indication of damping but not for quantitative analysis) or by firing explosive charges mounted on the main surfaces to excite important bending and torsion modes of the surfaces and fuselage.

Current data reduction techniques are based on the use of the fast Fourier transform method. Noise is removed from the sweep excitation records by correlation techniques.

DISCUSSION

A comprehensive survey of the methods and techniques of flight testing practiced in the U.S.A. and Great Britain during the 1950's was presented at a conference sponsored jointly by the Aircraft Industries Association and the Office of Scientific Research, held in Washington, D.C. on May 15-16, 1958. The proceedings of that conference were published in OSR-9-0269 (ref. 1). Of particular interest at that time was the development of aerodynamic vane exciters for large aircraft and shaped explosive charges to provide controlled pulse excitation, particularly for application to smaller aircraft. In addition, the development of hydraulically driven inertia shakers and the introduction of variable frequency electrical signals into the servos of the autopilot system were advances in excitation techniques described by industry representatives. In regard to methods of obtaining resonant frequencies and associated damping from the response data, of particular interest were the application of the Kennedy-Pancu vector plotting method as reported by Broadbent of the RAE in Great Britain and the technique developed by E. Bartch of Lockheed in which the shift of frequency and amplitude of peak response for a linearly varying frequency sweep up and down the frequency range is used to determine the resonant frequencies and damping of lightly damped modes.

In the interim period from 1958 to the present time, a number of papers on flight flutter testing have been presented at meetings of AGARD Technical Panels and published either as AGARD reports or incorporated in AGARD manuals (refs. 2-6).

It is of interest to note that for the most part excitation techniques developed during the 1950's and early 1960 period are still used today. Pilot pulsing of the controls is still used although generally the technique is reserved for checkout of instrumentation and qualitative evaluation of the response of lower structural frequencies. Most companies tend to use pilot pulsing of the controls just before the start of a sinusoidal sweep of the frequency range. United States industry relies almost exclusively on sinusoidal excitation provided by auxiliary aerodynamic vanes, inertia shakers or the power control system. Of the ten aircraft covered by the U.S. survey, eight used sinusoidally driven aerodynamic vanes and one used the power control system for wing excitation. Several of the aircraft which used aerodynamic excitation for the wings used inertia shakers to excite the empennage. In the case of the 10th aircraft, pilot pulsing of the controls was the only source of excitation. This aircraft was a low speed derivative of an earlier higher speed vehicle and the test was aimed at an evaluation of possibly critical store configurations in the frequency range of 3-9 Hz.

For the harmonic excitation test programs, a fairly rapid sweep of the frequency range of interest was used in almost all cases. The effect of sweep rate, although sufficient to shift the steady state resonant frequency and decrease the amplitude, was slow enough to permit identification of the region of critical frequencies so that pilots could tune to the resonant frequencies of interest so that associated damping values could be established. Most companies used the exponential variation of frequency with time in the sweeps; one used the linear variation of frequency, and one used the linear period sweep variation. Table 1 summarizes the excitation methods, frequency ranges, time to sweep and sweep laws followed for the aircraft covered in the survey of U.S. practices. It may be noted that single source excitation on any one surface has been the practice in the U.S. (one exciter on each wing tip, one on each stabilizer, one on the fin).

The use of explosive charges for pulse excitation has for all practical purposes been abandoned by U.S. manufacturers. Where they have been used in recent years the results have been unsatisfactory. Random excitation techniques have not been used for flutter testing nor has programmed pulsed excitation been used to drive the power control systems.

French and British practice in regard to excitation, Table II, although similar to U.S. practice in some respects, differs quite significantly in others. Thus, for Anglo-French Concorde, sinusoidal excitation was provided by electromagnetic seismic exciters in the wing, fin and fuselage. In addition, sinusoidal excitation of the fin and rudder was provided through the control system. Transient excitation was also used in the Concorde tests in the form of explosive charges (used mainly on control surfaces) and shaped electrical inputs to the power controls were used to provide repeatable triangular shaped pulses. Neither the British nor the French have used aerodynamic vanes in flutter testing. In contrast with U.S. practice, the Concorde used multiple shakers (5 on each wing, 4 on the fin, 2 along the fuselage for lateral excitation and 3 along the fuselage for vertical excitation). For the smaller military aircraft such as the Anglo-French Jaguar program, power control system excitation has been used involving either harmonic sweeps or pseudorandom binary input. In addition, groups of explosive charges have been used on main surfaces to provide pulse excitation of wing and fuselage modes. In the case of the Dassault Mercure, pseudorandom excitation was used to drive the normal power control system as well as to drive hydraulically powered inertia shakers.

In regard to data acquisition and transmission, it is the general practice by U.S. industry to record the response data (obtained from accelerometers, strain gages and control position indicators) on magnetic tape on board the airplane. A fairly large number of channels of data are telemetered to a ground station in the form of frequency modulated or pulse code modulated signals. After demodulation on the ground, the signals are recorded on tape. Approximately 20 channels of data (varies with the companies) are recorded on pen-type strip charts for on-line visual montoring. In addition, all of the ground-recorded tape data are available for computer analysis. In contrast with U.S. practice, the French and British transmit little if any flight test data by telemetry. Data are recorded and monitored by flight personnel on board the airplane during the test. The majority of the response data are then analyzed after each flight.

The greatest advance in the field of flight flutter testing within the last few years has occurred in the field of data reduction and analysis. This is attributable to the use of high speed digital computers. The more sophisticated analysis methods associated with the use of the digital computers (fast Fourier transform, auto-and cross-correlation routines) permit the use of transient excitation in the form of very rapid frequency sweeps or programmed pseudorandom excitation. The effect of extraneous noise such as atmospheric turbulence can be minimized. Loss of test time due to the presence of atmospheric turbulence can thus be significantly reduced.

The correlation techniques are based on the fact that if a system with a single degree of freedom is subjected to excitation which has a flat energy spectral density over a bandwidth wider than the resonant frequency, the response autocorrelation function is an exponentially decaying oscillation whose decay rate and frequency are identical to those of the impulsive response of the system. If more than one resonant response is present in the system then the response autocorrelation function (for flat energy spectral input) is a superposition of the exponentially decaying cosines. Since fast frequency sweeps, pseudorandom binary sequences and shaped charge inputs provide wide spectrum excitation, the autocorrelation function of the response to such excitation will be a decaying oscillation containing the frequencies and damping of each of the resonant modes of the system (refs. 13, 14, 15). The decaying oscillation can be analyzed by the digital Mazet (ref. 12) technique by passing the autocorrelation signal backwards through a narrow band pass recursive filter. In addition to the Mazet technique, the damping and frequencies of the resonant modes can be obtained by taking the Fourier transform of one side of the autocorrelation function and using the Kennedy-Pancu vector plots. In order to reduce the noise in the signal due to turbulence, Turner and Elkins (ref. 14) suggest the use of an exponential weighting function before Fourier transforming. The introduction of the weighting function does not affect the frequencies in the transfer function and increases the damping in a manner than can easily be corrected.

CURRENT STATE OF THE ART OF SUBCRITICAL FLIGHT FLUTTER TESTING

A review of the most recent U.S., English and French subcritical flight flutter test programs (F-14, F-15, SST, Concorde and Jaguar) indicates that great strides have been made in advancing the state of the art of subcritical flight flutter testing through the use of large, high speed digital computers. In the last few years there has been a steady trend from analog processing to digital processing of response records. During this same time, because of the greater and faster analysis capability of the digital computer, the trend has been away from the use of slow frequency sweep which resulted in essentially steady state response conditions for the plotting of admittance curves, as well as away from the use of the technique of tuning of resonant frequencies, dwelling and quickly stopping of the excitation to obtain decay curves. The development of special digital computer routines and digital filters have, in addition to reducing response analysis time, opened the door to transient excitation programs (such as fast frequency sweeps, programmed pulsed excitation or random excitation) with an associated reduction in test time.

Grumman's model matching technique, McDonnell-Douglas' use of the fast Fourier transform, vector plotting and flutter margin determination by a fully automated digital computer routine, and the Anglo-French use of fast Fourier transform routines in conjunction with autocorrelation and cross correlation techniques, are examples of applications of the latest techniques of subcritical flight flutter data reduction and analysis techniques. A fairly new process (randomdec), involving the analysis of a random output system, has also created much interest, reference 16.

SPACE SHUTTLE FLIGHT FLUTTER TESTING

Flight flutter tests of aircraft are conducted under conditions that can essentially be described as steady state. In these tests the aircraft is flown at constant speed and altitude, and the resonant modes are excited by one or more methods of excitation. The response is recorded from transducers and analyzed on the ground for each steady state condition. The decision of whether to increase speed at a given altitude is based on the variation of the damping and frequency (for each of the modes) with airspeed and Mach number that has been established. If adequate stability appears to exist at the highest speed tested, the test speed at the same altitude is increased. In this manner the speed-altitude or Mach-altitude range over which the aircraft is designed to be operated is shown to be safe or an incipient flutter condition is identified. Thus, the clearance of the aircraft over its required operating range, or the approach to a possible critical flutter condition, is achieved through a flight-by-flight cautious extension of the flight envelope.

Based on preliminary analyses, the critical flutter region for the shuttle will be in the transonic, high dynamic pressure range during the launch phase of the operation. Figure 7 shows nominal space shuttle trajectory during launch for the first two minutes of flight. From this figure it can be seen that a maximum dynamic pressure of 650 psf at a Mach number of 1.45 will be reached in approximately 80 seconds after launch. The time to cover the Mach range from $M = .95$ to 1.45 will be approximately 15 seconds. Off-nominal trajectories will lead to more severe dynamic pressures or more critical rates of change in the parameters.

Although consideration has been given to the use of auxiliary airbreathing engines on the shuttle to evaluate low-speed handling characteristics, such a vehicle would not have the capability of achieving the critical Mach number and dynamic pressure simultaneously.

It is fairly clear that a cautious flight-by-flight extension of the flight envelope at stabilized flight conditions of speed and altitude, in a manner similar to aircraft testing, is not feasible for the shuttle. Techniques of the type described in reference 17 are therefore of interest. Greater emphasis will be required on analytical work and wind tunnel testing of flutter models of the launch vehicle and shuttle. Flight conditions least likely to lead to flutter, as based on model testing and the best analysis available, should be carefully considered in selecting the first launch trajectory. As much response data as possible should be acquired during the launch for verification of the methods that have been developed for evaluating flutter in a transient environment.

Preliminary analysis of the frequency range of interest in regard to possible flutter indicates that wing frequencies up to 10 Hz and empennage frequencies from 10 to 30 Hz might be involved. For the evaluation of flutter, transient excitation in the form of square waves of approximately 16 milliseconds duration or pseudorandom (white noise) excitation of adequate bandwidth could be imposed through the fly-by-wire control system during the critical phase of the launch trajectory. The techniques employed in data reduction and analysis of aircraft subcritical flight flutter test records could then be used to obtain damping and frequencies of modes that appear significant with respect to flutter.

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APPENDIX

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TABLE I

SUMMARY OF SUBCRITICAL FLUTTER TESTING TECHNIQUES USED IN THE U.S.

(a) Aerodynamic Excitation

COMPANY	AIRPLANE	SURFACE	LOCATION	FREQUENCY RANGE	TIME TO SWEEP SECONDS	SWEEP LAW
Boeing	747	Wings	External vanes at wing tips	1.5-7.0 Hz	90	Exponential
	SST	Wings	External vanes at wing tips	1-20 Hz	90	Exponential
McDonnell-Douglas-Long Beach	DC-10	Wings horizontal Vertical tail	External vanes at tips of main surfaces	1-20 Hz and 1-10 Hz	90 90	Exponential
Lockheed-California	L-1011	Wing stabilizer	External vanes	1-18 Hz 3-25 Hz	90 30	Linear Period
	S-3A	Side of fuselage under stabilizer	External vanes	1.5-18 Hz 3-25 Hz	90	Linear Period
Lockheed-Georgia	C-5A	Wing stabilizer	External vanes on top of surfaces near tips	.5-25 Hz	60 Normal 30 Dive only	Exponential
Grumman	F-14	Wing fin	Aero-tab External vane	5-50 Hz	15	Exponential
McDonnell-Douglas-St. Louis	F-15	Normal control Ailerons Stabilator		2-16 Hz 5-10 Hz	100-200 45	Linear Frequency
General Dynamics-Ft. Worth	F-111	Wing	Aero-tab	35-2 Hz	45	Exponential
(b) Inertial Excitation						
Boeing	SST		Aft Body Vertical and Lateral	5-10 Hz	90	Exponential
Grumman	F-14	Horizontal tail	Right side stab. only	5-50 Hz	15	Exponential
General Dynamics-Ft. Worth	F-111	Horizontal vertical tail surface	Inboard on stab. near side of fuselage Top of fin	35-2 Hz	45	Exponential

SWEEP LAWS*

Linear Frequency $\omega(t) = \omega_o\left(1 + \frac{\lambda\omega_o t}{2}\right)$

Exponential $\omega(t) = \omega_o e^{\frac{\lambda\omega_o t}{2}}$

Linear Period $\omega(t) = \dfrac{\omega_o}{1 - \frac{\lambda\omega_o t}{2}}$

ω_o is Frequency at Start of Sweep

λ is Proportional to the Change in Frequency per Cycle

*See reference 7.

TABLE II

SUMMARY OF ANGLO-FRENCH SUBCRITICAL FLUTTER TESTING TECHNIQUES

(a) Aerodynamic Excitation

COMPANY	AIRPLANE	SURFACE	LOCATION	FREQUENCY RANGE	TIME TO SWEEP SECONDS	SWEEP LAW
SNIAS-BAC	Concorde 001 and 002	Rudders	Power control system actuation	4-36 Hz	Varied up to 4 minutes	Linear Freq. and Linear Period
		Rudders	Power control system actuation	Triangular-shaped electrical pulses fed through normal power control system	Base of triangular pulse 50 miliseconds	
		3 Elevons 2 Rudders	Explosive impulse charges located in control surfaces	Freq. range of interest 10-20 Hz	Impulse time 30 miliseconds to match med. frequency ~ 15 Hz	
Anglo-French Military	Jaguar	Major control surfaces	Power control system actuation	Factor of 7 starting from 3, 6 or 8 Hz	100 seconds	Linear Period
		Major control surfaces	Pseudorandom binary sequence fed electrically to power control system	Band width 25 Hz or 50 Hz	Sequence period approx. 10 sec.	

(b) Electrodynamic Excitation

COMPANY	AIRPLANE	SURFACE	LOCATION	FREQUENCY RANGE	TIME TO SWEEP SECONDS	SWEEP LAW
SNIAS	Concorde 001	Wing Fin Fuselage	10 on Wing 4 on Fin 3 Fuselage Vert. 2 Fuselage lat.	2-50 Hz	Slow sweep No fixed time	Prior to each flight 24 central frequencies to be explored was established. Slow linear frequency sweeps made from 15% below to 15% above each central frequency.

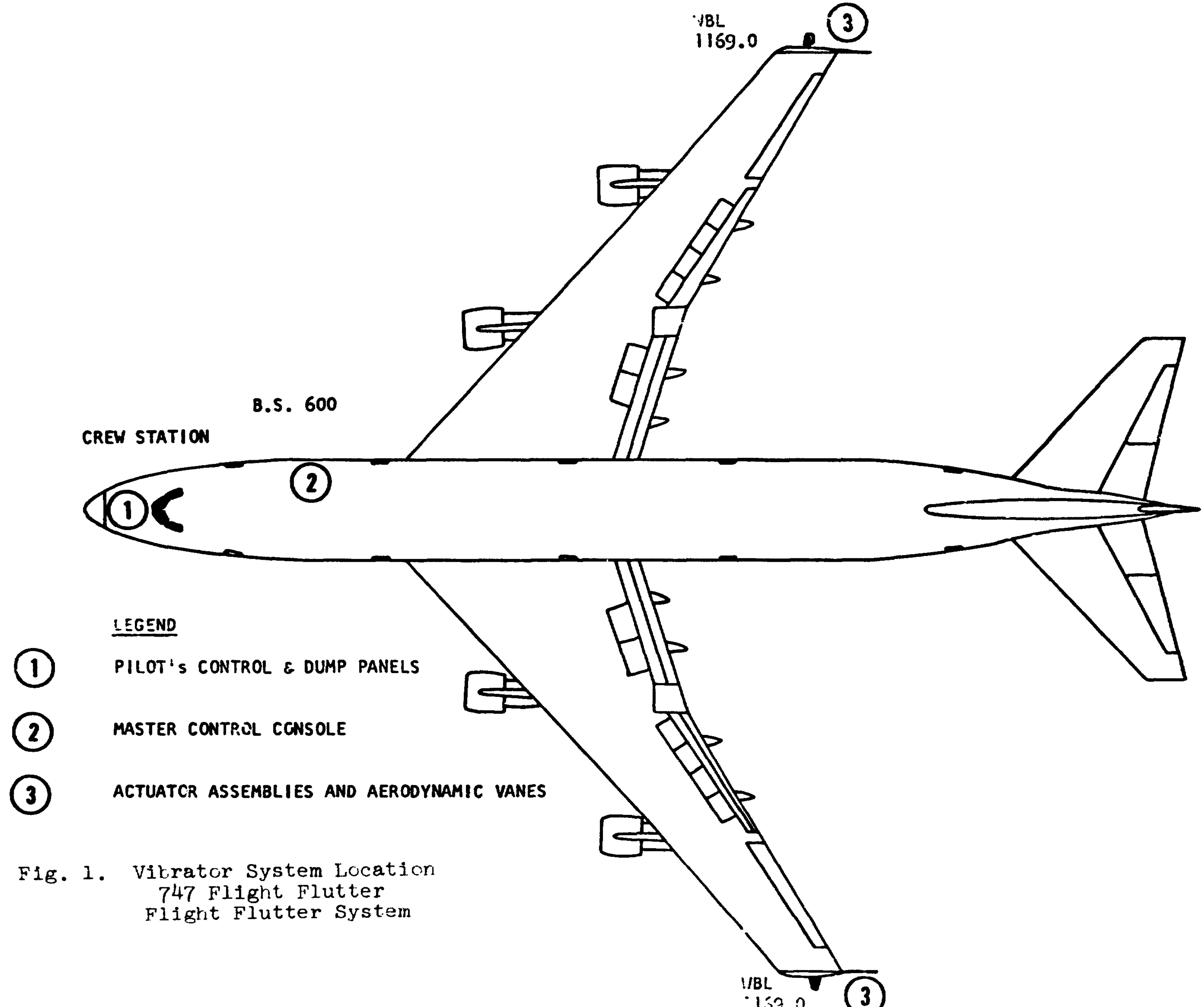


Fig. 1. Vibrator System Location
747 Flight Flutter
Flight Flutter System

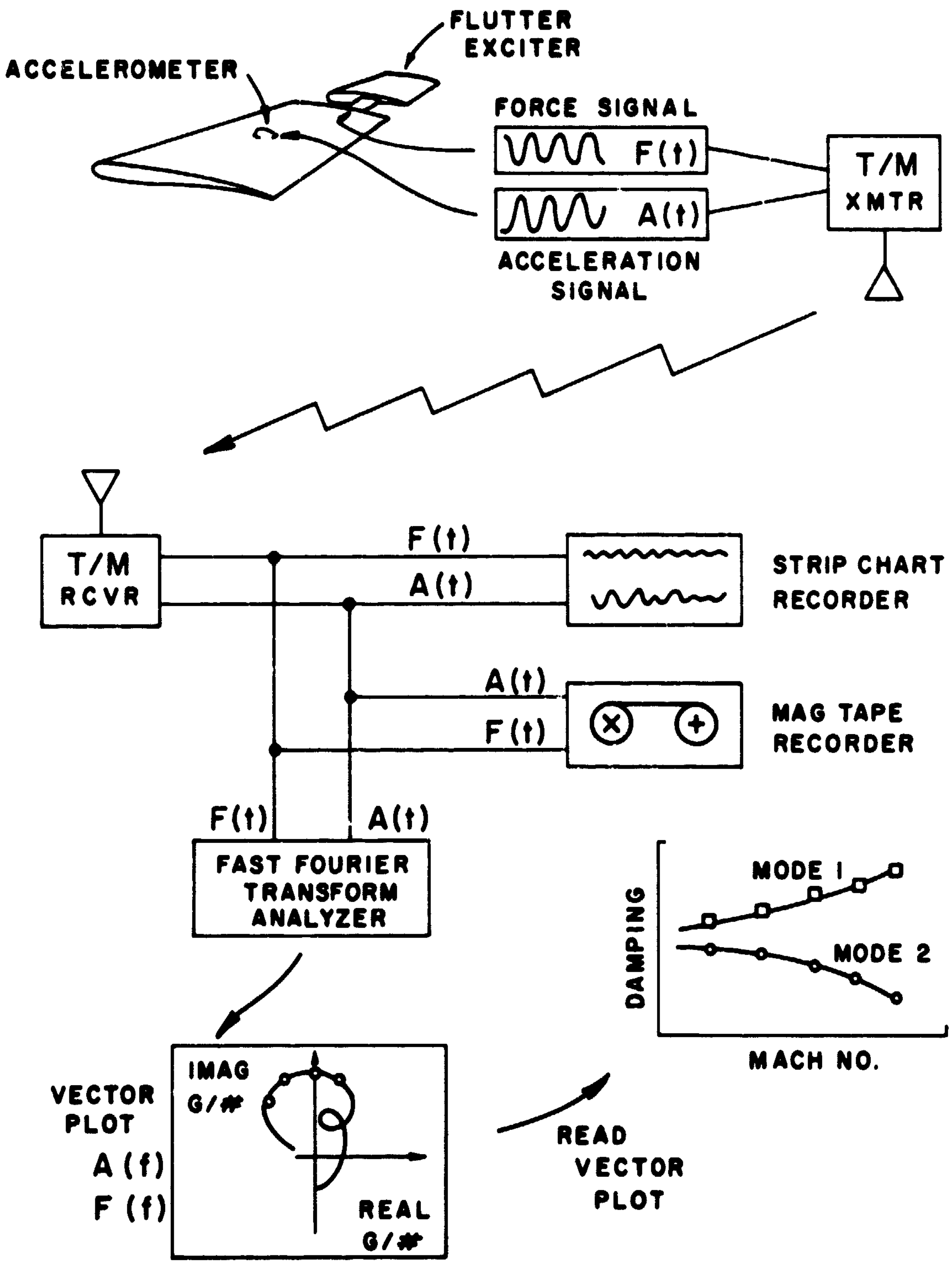
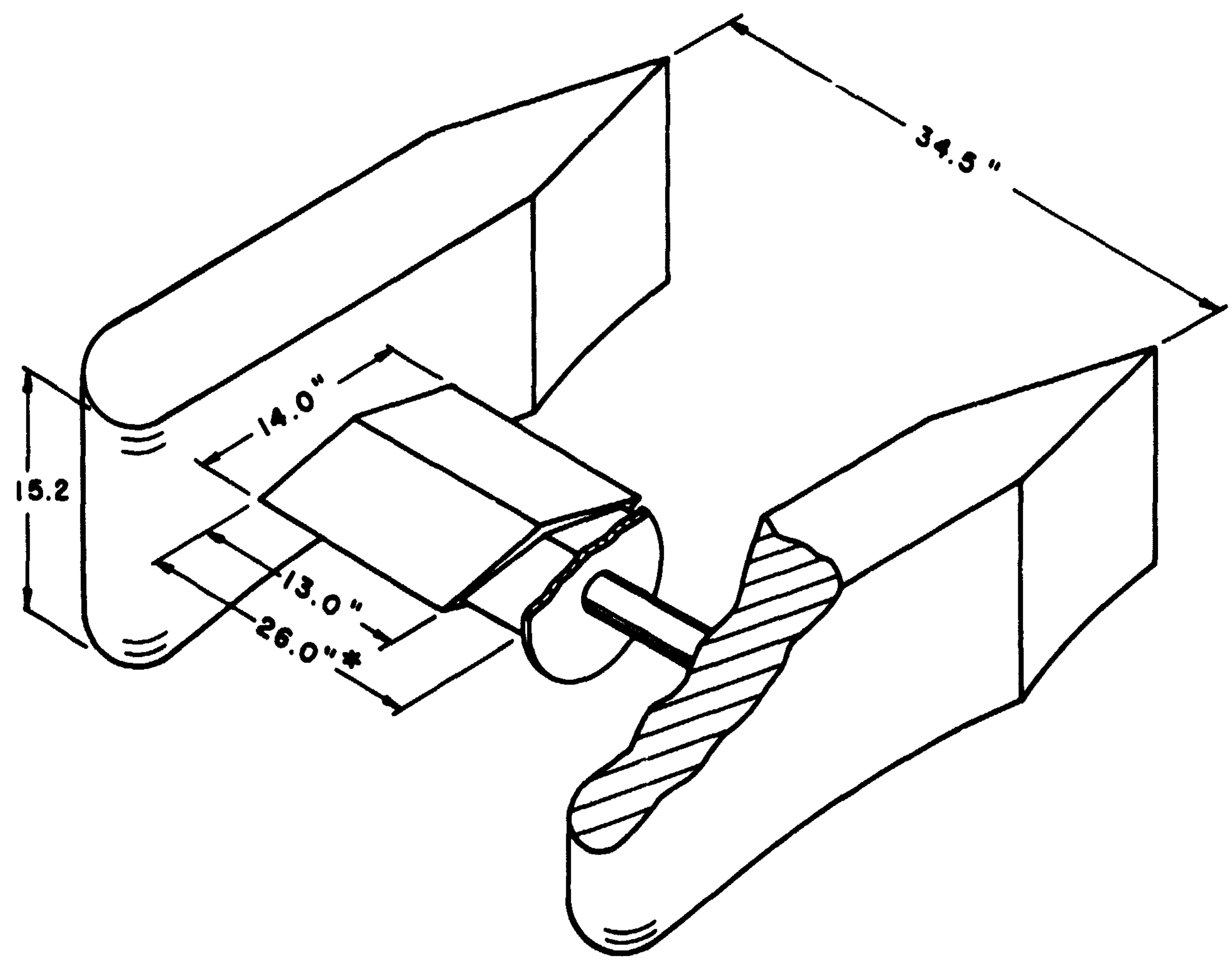
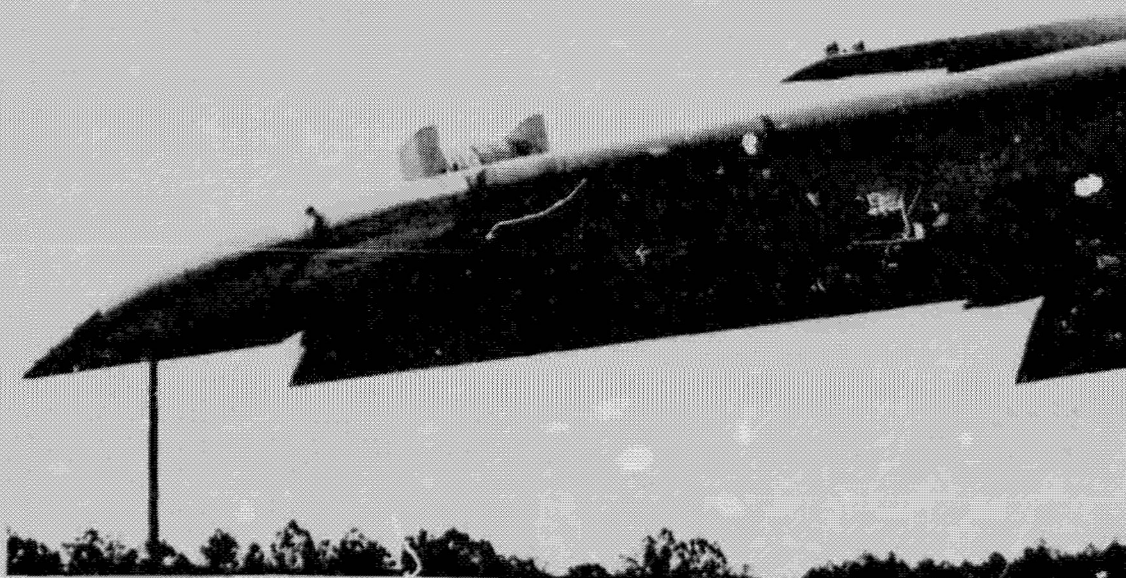


Fig. 2. SST Flight Flutter Data Reduction



*VARIABLE - MAX DIMENSION = 26.0"

Fig. 3. C-5A Flight Flutter Tests - Vane and Pylon Assembly



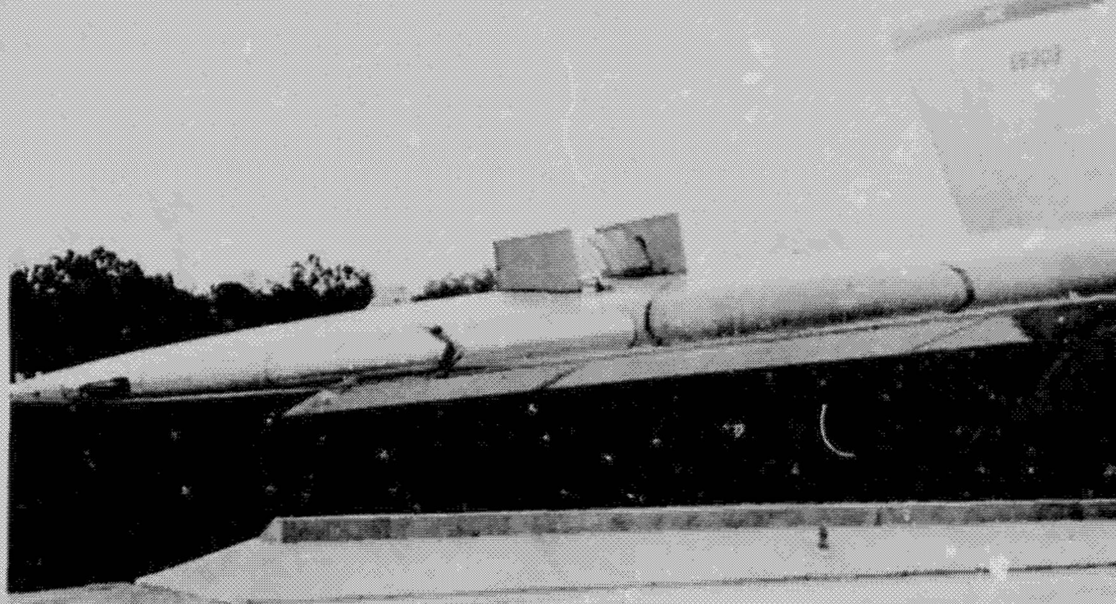


Fig. 4. C-5A Flight Flutter Tests - Aerodynamic Vane Installation

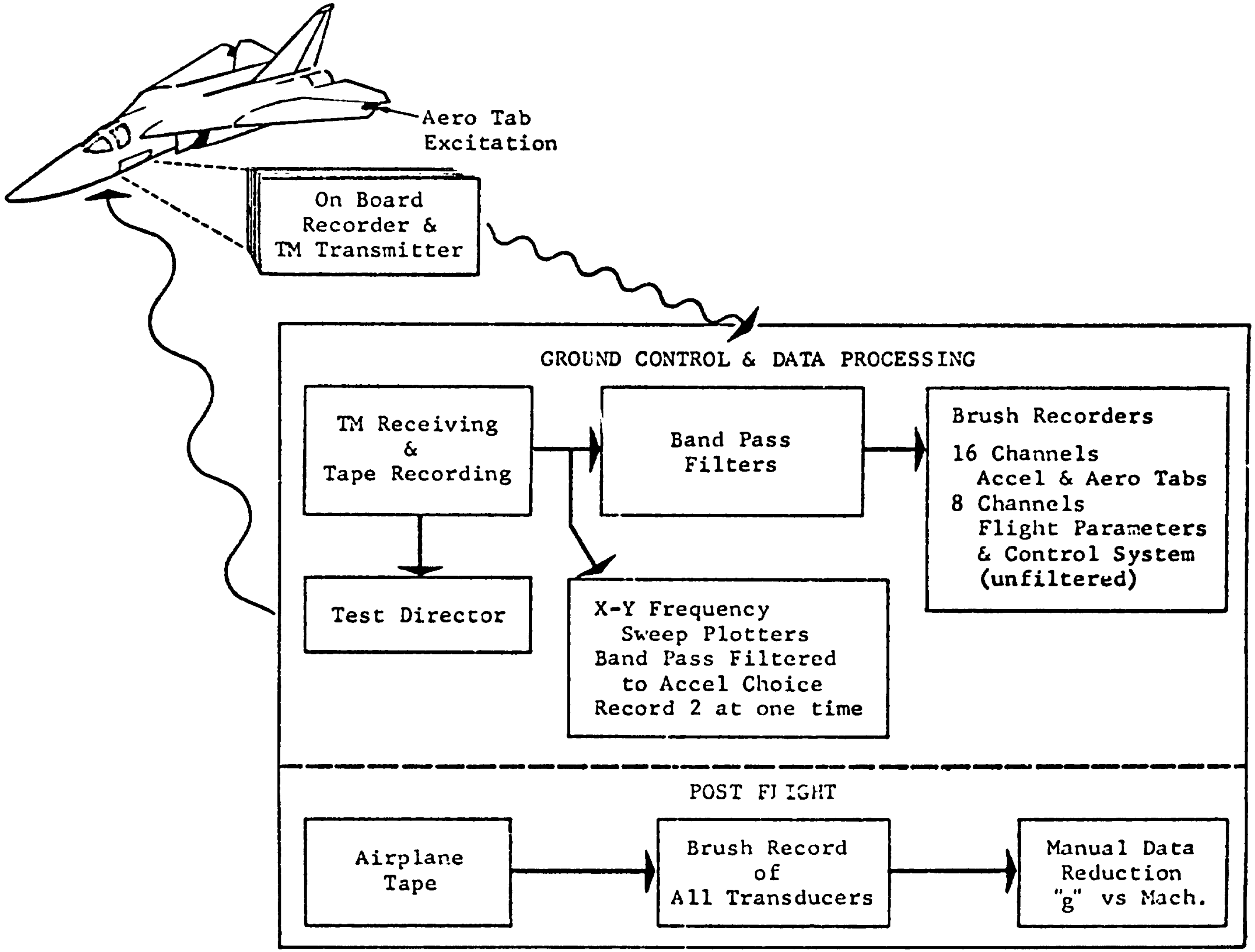


Fig. 5. F-111 Flight Flutter Test Procedure

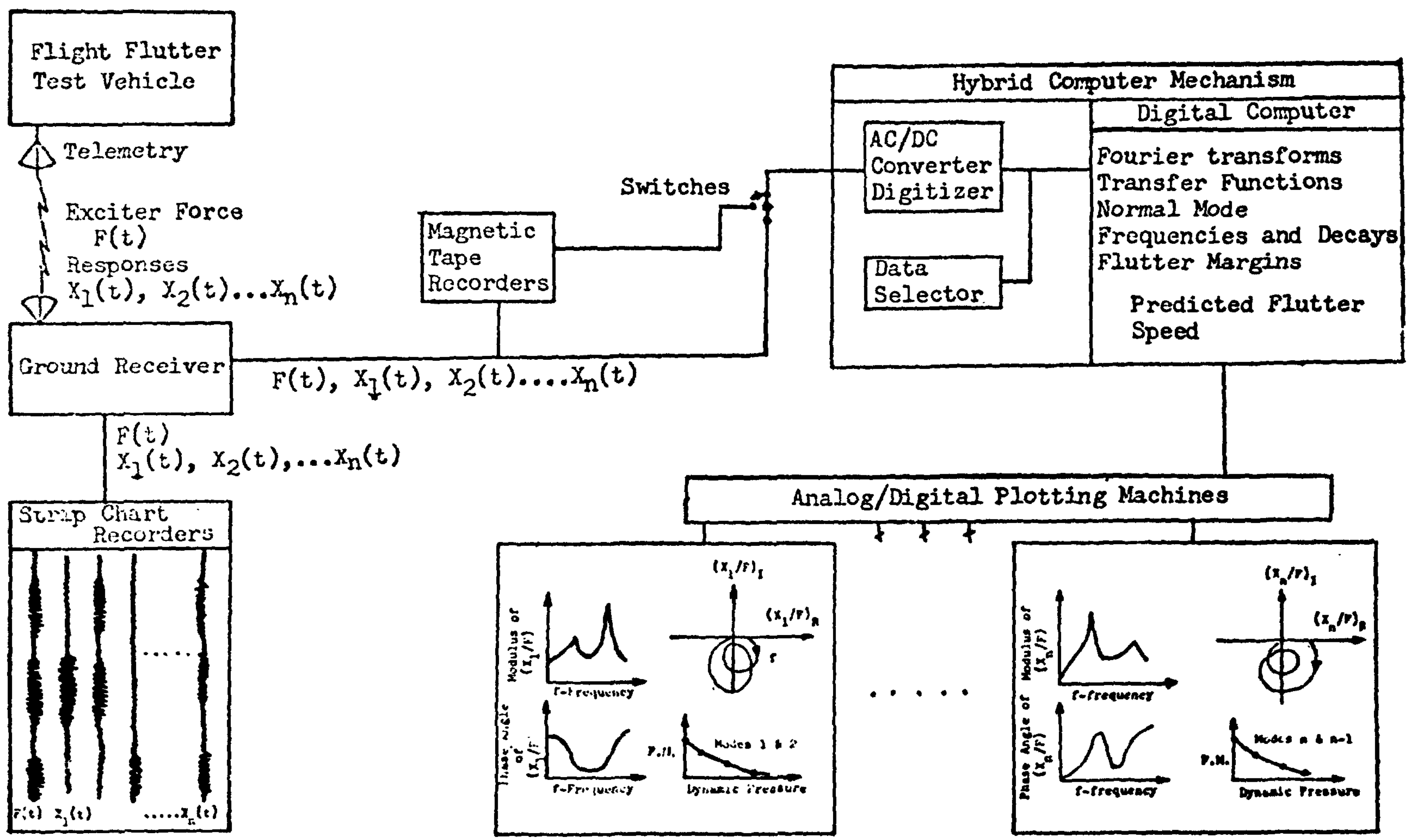


Fig. 6. F-15 Schematic of Final Flight Flutter System

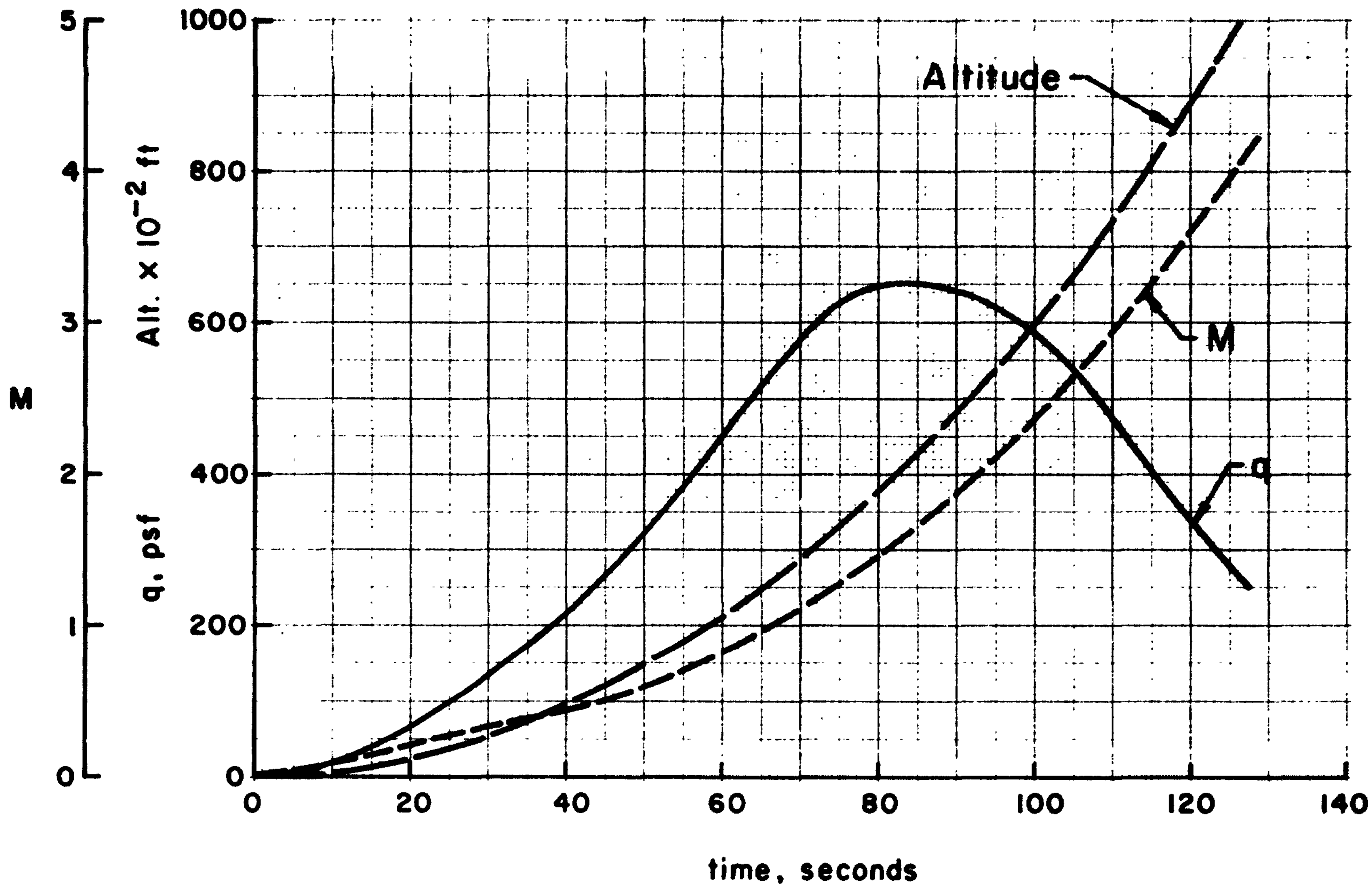


Fig. 7. Nominal Space Shuttle Launch Trajectory (Preliminary)