(NASA-TM-81500) STATUS OF NASA FULL-SCALE ENGINE AEROELASTICITY RESEARCH (NASA) 21 p HC A02/MF A01 CSCL 20K

N80-23678

Unclas
G3/39 20114

NASA Technical Memorandum 81500

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Prepared for the
Twenty-first Structures, Structural Dynamics,
and Materials Conference
cosponsored by the AIAA, ASME, ASCE, and AHS
Seattle, Washington, May 12-14, 1980

E-437

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Abstract

Data relevant to several types of aeroelastic instabilities have been obtained using several types of turbojet and turbofan engines. In particular data relative to separated flow (stall) flutter, choke flutter, and system mode instabilities are presented. The unqiue characteristics of these instabilities are discussed, and a number of correlations are presented that help identify the nature of the phenomena.

Introduction

Requirements for high-performance aircraft engines with high thrust-to-weight ratios have resulted in the necessity to improve the state of the art of several disciplines associated with turbomachinery. One of these is aeroelasticity. The need for improvement in this discipline has led to government efforts in association with industry to improve the understanding of aeroelastic phenomena such as fan or compressor flutter. One such effort is the flutter research done on full-scale engines in the Joint NASA/USAF Engine System Research (ESR) program.

The ESR tests are conducted in the altitude chamber facilities at the NASA Lewis Research Center. These facilities provide for engine testing with a wide variety of simulated flight conditions, thus permitting various types of flutter to be studied. Data relative to separated-flow flutter, choke flutter, and system mode instabilities have been obtained. These data have been validated, reduced, and analyzed and are now part of a broad data bank, and additional programs are in progress to supplement and expand this data bank. Early findings from the data have been presented by the author.[1] The present paper reviews some of the early results and updates them with recent results.

Types of Aeroelastic Instabilities in Turbomachinery

Aeroelastic instabilities (flutter) in turbomachinery have five distinct types.[2] These are as follows, with their locations relative to a fan or compressor map being shown in figure 1:

I - Subsonic/transonic stall flutter
II - Choke flutter
III - Low-back-pressure supersonic flutter
IV - High-back-pressure supersonic flutter
V - Supersonic stall flutter

Subsonic/transonic stall flutter was the most commonly found aeroelastic instability in turbomachinery before the development of shrouded and high-tip-speed fans. It generally occurs near the stall line at large positive incidence angles in conjunction with considerable flow separation on the suction surface of the airfoil over part of the oscillatory cycle. The term "stall flutter" has been in use for a number of years. Its etymology is based on the fact that the phenomenon was first observed to occur near static stall on single airfoils and was associated with flow separation at large angles of attack. The use of this nomenclature has been carried over into turbomachinery aeroelasticity and has led to some misconceptions. At a "stall flutter" boundary in turbomachinery the rotor or stator row is not in cascade stall. Cascade stall would annihilate the instability. Although most commonly seen in the stall regime near the stall line relative to a fan or compressor map, this instability can also occur in the choke regime near the choke line. The latter is characterized by negative incidence angles and flow separation near the leading edge on the pressure surface of the cambered airfoil. To avoid any misconceptions this phenomenon is designated separated-flow flutter in this paper.

The frequency of separated-flow flutter has been found to be near but not necessarily equal to one of the first three natural frequencies of the blade (first bending, second bending, or first torsion). Both positive and negative incidence separated-flow flutter exhibit a hysteresis effect in recovery similar to that of rotating stall and cascade stall. A considerable amount of data has been obtained on this type of instability in the ESR program.

Choke flutter has been found to occur near the choke line at small positive or negative values of incidence with no evidence of flow separation but with evidence of partial choking in the cascade passage. The frequency again is near but not necessarily equal to a blade natural frequency. All the choke flutter data obtained in the ESR program have been restricted to the first fundamental mode, first bending.

No data relative to either high-backpressure or low-backpressure supersonic flutter have been obtained in the ESR program to date. Both of these instabilities are believed to be shock-induced or shock-associated instabilities and are discussed in detail by Adamczyk.[3]

Supersonic stall flutter is the terminology applied to an instability observed in the stall regime near the supersonic portion of the stall line of a fan or compressor. Until recently there was insufficient data to properly characterize this instability. However, recent data obtained in the ESR program and in other joint USAF/NASA programs have shown this flutter to be unlike separated-flow flutter in character. Rather, some characteristics of this instability are much the same as those observed in the coupled blade-shroud system mode instability.[4] This leads to the supposition that this phenomenon may be associated with system mode instabilities. For unshrouded blades it was observed that the frequency was near the blade-alone first bending frequency. For shrouded blades the instability occurs in a coupled mode, usually a coupling of first bending and first torsion.

Based on recent developments, the classification of aeroelastic instabilities set forth in figure 1 are being revised as shown in figure 2. The following definitions apply to any further discussions in this paper.

(1) Separated-flow flutter - Previously referred to as subsonic/transonic stall flutter. This type of instability can occur with isolated airfoils as well as with cascaded airfoils. The instability is assumed to be dependent on the location of the flow separation point. It can be on either the pressure or suction surface and thus can occur at either positive or negative incidence and not necessarily near the stall line.

(2) Choke flutter - An instability occurring in cascades operating with partial or full choking. The mechanism of this instability is not understood. A passage resonance phenmenon in conjunction with marginal aerodynamic damping is a possibility.

(3) System mode instabilities - A class of instabilities dependent on a unique coupling of an aeromechanical system to assume a structural system mode in an unsteady aerodynamic field whereby a net positive aerodynamic work (negative damping) is input to the system over the oscillatory cycle. In actual engines with inherent system asymmetry the aeromechanical system must be considered as a mistuned system. Interblade coupling, either aerodynamic or mechanical, is essential. The instability frequency can be, but need not be, near or associated with a blade-alone natural mode.

(4) High-backpressure supersonic flutter - As defined in reference 3.

(5) Low-backpressure supersonic flutter - As defined in reference 3.

Apparatus and Instrumentation

In the ESR flutter program, three different engines have been used to date, and the installation of these in the altitude chambers is shown in figures 3, 4, and 5. The types of engines used were

(1) A multistage, shrouded-fan, turbofan engine
(2) A straight turbojet engine
(3) A single-stage, unshrouded-fan, turbofan engine

The first two engines were tested exclusively to obtain aeromechanical data and were thoroughly instrumented for that purpose. The instrumenation used is discussed in detail in two references.[1,5]

The third engine tested was part of a propulsion technology program and was being aeromechanically monitored only for safety purposes. Some meaningful aeromechanical data were fortuitously obtained from this third engine test series. The principal aeroemechanical instrumentation on this engine was an adequate amount of strain gages on the fan stage and some stators and the Photoelectric Scanning (PES) System[6] on the fan stage alone. The latter apparatus is an electro-optical system that uses fiber optic bundles to capture reflected light from blade tips. By using once-per-revolution and once-per-blade speed signals as a time reference the time each blade passes a fixed sensor can be measured. If the time is not constant the blade is undergoing a nonintegral displacement, which is determined from engine speed and tip speed. Each and every blade is essentially being monitored simultaneously. This system was developed by the Instrumentation Research and Development Branch at the Lewis Research Center and has become an extremely useful monitoring and data system in aeromechanical research.

Results and Discussion

Instability data relative to three distinct types of aeroelastic phenomena have been obtained in the ESR program. These are

(1) Separated-flow flutter
(2) System mode instabilities
(3) Choke flutter

Each type has been found to possess unqiue characteristics that aid in its indentification and assist in improving understanding of the phenomena. These characteristics are discussed in detail.

Note that in order to obtain these data, it was necessary in every case to operate the engine either off-schedule or outside of the normal flight envelope. In no case was it possible to encounter any instability on a production engine within the normal flight envelope or on schedule.

"Flow Separation" Flutter

This instability is commonly referred to as subsonic stall flutter, which in turbomachinery is a misnomer that has led to some misconceptions concerning the nature of this instability. This instability was first observed ad studied in detail on isolated airfoils.[7,8] The results of these studies led to the conclusion that the basic cause for this instability was "aerodynamic hysteresis" associated with the behavior of the separated flow that occurs as airfoil dynamic stall is approached.

The principal characteristics unique to the flow-separation flutter observed in the ESR programs are

(1) Instability onset is preceded by a period of usually low-level flow separation vibrations observed on strain gages around the eventual flutter frequency.

(2) At flutter onset there is little coupling between blades as observed from light probe and strain gage data. There can be two or more flutter frequencies on a stage simultaneously, and blade-to-blade amplitudes vary.

(3) The observed flutter frequency was found to be a unique function of stage inlet pressure and temperature.

(4) The flutter frequency did not vary as the blade amplitude increased.

In every case of separated-flow flutter observed to date it has been possible to anticipate the onset of this instability by observing a flow separation vibration response in the flutter mode on blade-or vane-mounted strain gages. The level of this response was found to vary from stage to stage and also as stage inlet conditions varied on any particular engine. In some cases the flow separation response would be relatively low, ±10 MPa (±1.4 ksi), at instability development just before locking in on a singular blade flutter frequency. At other times it was possible to see flow separation vibrations as high as ±30 MPa (±4.3 ksi) before the instability locked into a singular flutter frequency. In one instance, at marginally stable stage inlet conditions of pressure and temperature, flow separation vibrations of ±70 MPa (±10 ksi) in torsion were observed around a frequency associated with a previous flutter mode. The instability never developed into a unique singular flutter frequency because rotating stall was encountered. This changed the rotor blade response to a first bending mode from a first torsion mode. Rotating stall, cascade stall, and probably any other strong and sustained extraneous impulse appears to be able to annihilate separated-flow flutter. Flow separation vibrartions that have been observed away from a known instability commonly excite the first bending mode. The fact that in this case the torsional mode was excited near a known torsional instability tends to support the hypothesis that this type of instability is affected by flow-separation effects.

Stage inlet condition effects were observed while monitoring a turbofan engine with a single-stage unshrouded fan and variable inlet guide vanes. At a cambered variable geometry setting, separated-flow flutter in first torsion was found at part speed near the stall line and at positive incidence. Pronounced low separation vibrations in first torsion were observed first. As the stall line was approached at constant corrected speed the magnitude of these vibrations increased up to ±35 MPa (±5 ksi) before the instability developed into a single unique frequency in first torsion. When the instability did develop, the number of blades seriously affected as observed from PES system data was small. There was very little aerodynamic coupling between blades over the whole rotor assembly. A few blades were in flutter at relatively large amplitudes, but the majority were barely oscillating. When the variable inlet guide vanes were changed from the cambered position to a setting that would increase blade incidence, about a 2° degree increase in positive incidence, and the instability was approached again at constant corrected speed, several different effects were observed. The period of observed flow separation vibrations was shortened, and the amplitude just before a single unique flutter frequency developed was much lower (±15 MPa (±2.1 ksi)). In addition, many more blades were seen to respond, indicating increased aerodynamic coupling. Both sets of data were obtained at essentially the same inlet conditions and speed.

As previously mentioned the lack of coupling at flutter onset has been found to be characteristic of separated-flow flutter. The development of the PES system has helped immeasurably in identifying this characteristic. A representative PES system display is shown in figures 6 and 7 for a torsional mode instability in the stable condition and in the flutter condition. In this display the arrangement of blips in the vertical direction at the center of the display denotes the blade tips. One blip for each blade. Figure 6 shows the stable condition. The reason for unevenness or variance of the array from the center of the display is that blade spacing in reality is never uniform. The horizontal axis in the display is time. This can be converted to displacement when tip speed and angular velocity are known. Figure 7 displays a flutter condition. If the blades are being displaced at a frequency not related to an engine order, the array of blips in the display will oscillate in the horizontal direction. The amplitude of the oscillation for each blade (blip) can be determined from the display.

In flutter it can be seen that there is a definite variation in amplitudes and that only a few blades in small groups are excessively active. Analysis of the strain-gage data[1] showed that several flutter frequencies were simultaneously present and that the interblade phase angles varied. For those data points with well-developed flutter (i.e., the existence of a single, unique blade flutter frequency) the coherence of the time-averaged phase angles was excellent. Nominally 32 averages are used in analyzing flutter data. Thus, although the interblade phase angle varied from blade to blade, it remained essentially constant temporally between any two blades. Fleetor[9] has reported similar results with respect to separated-flow flutter. These characteristics are the effect of aeromechanical mistuning, which in principal is similar to the effects of structural mistuning on rotor blade mechanical vibrations[10] only with the effect of aerodynamic variations included. Flutter and other aeroelastic phenomena encompass the interaction of aerodynamic, elastic, and inertia, forces. Mechanical vibrations encompass only the interaction of elastic and inertia forces. With respect to turbomachinery, note that the aerodynamic environment can have a profound effect on the dynamic response in several ways, most notably as a damping source and as an excitation source.

Fleeter also noted, with respect to separated-flow flutter, that with deep penetration into the instability zone several interesting observations occurred. A single flutter frequency became predominant on all the blades, and the interblade phase angle between blades tended to become uniform. In essence the rotor was coupling and an aeromechanical system mode was developing that was symmetrical. Several attempts were made in the ESR programs to drive deep into the flutter zone to achieve the same results, but these were always aborted because of a stress limit.

Szechenyi[11] has hypothesized that interblade coupling is not a necessary condition for the development of separated-flow flutter. The data and observations being obtained in the ESR program tend to support this hypothesis. Intuitively this hypothesis is reasonable. Separated-flow flutter occurs with isolated airfoils. Thus cascading is not a fundamental factor. However, there is sufficient evidence in the literature to support the fact that cascade effects to exercise a control on the instability. These effects have not been parametrically studied in the ESR programs, but there are efforts in the Joint USAF/NASA Aeroelasticity programs investigating these effects.[12] It appears that the fundamental mechanism of separated-flow flutter does not require the presence of adjacent airfoils, but their presence can have an effect on the unsteady aerodynamics. Since all cascades are in reality aeromechanically mistuned systems, only a few blades in a cascade assembly will be initially prone to flutter; and these few can couple, both aerodynamically and mechanically, with a few adjacent blades. Since more than one blade may be prone to flutter at its unique flutter frequency and the interblade phase angles around the cascade will be nonuniform, several flutter frequencies will be in the experimental data. Beyond flutter onset and into the instability regime the phenomena in a mistuned system become complex and dependent on nonlinear and cascade considerations.

Stage inlet conditions were found to have a strong influence on the behavior of separated-flow flutter. Increasing either inlet pressure or stage inlet temperature tended to increase the size of the instability region on a fan or compressor map.[13] Increasing stage inlet pressure was also found to have a strong influence on the stability boundary as a function of reduced velocity and incidence. This will be discussed later. Stage inlet pressure and inlet temperature were also found to have a unique effect on the flutter frequency.

Increasing either stage inlet pressure and inlet temperature tended to decrease the observed flutter frequency. This characteristic was found to be unique to the separated-flow flutter phenomenon. Two sets of data demonstrating this are shown in figures 8 and 9. One set of data is from a front fan stage that exhibited separated-flow flutter operating in the stall regime at large positive incidence. The other set of data is from a midstage stator cascade operating in the choke regime at negative incidence. Some question still exists as to the exact nature of the instability affecting the stator stage. This stage was operating near choke, at the tip, and it was first assumed that the instability was choke flutter. However, analysis of the strain gage data tended to indicate that this instability exhibited characteristics more like separated-flow flutter than choke flutter. Flow separation was observed on the strain gages near second bending before the development of the instability. As seen in figure 9 the flutter frequency responded to inlet pressure and temperature variations in the same manner as observed with separated-flow flutter in the stall regime. In addition, as seen later, the stability boundary as a function of reduced velocity and incidence responded to inlet pressure variations more like separated-flow flutter than choke flutter. Thus this instability is being treated as separated-flow flutter at negative incidence in the choke regime. Flow separation is occurring at or near the leading edge on the pressure surface of the airfoil in the tip region. It was not possible to determine if local choking may have precipitated the instability.

Another characteristic of the flutter frequency in separated-flow flutter is that the flutter frequency did not vary as the vibratory amplitude increased. As seen later, this is not characteristic of another type of instability in the stall regime. All the strain gage data obtained in the ESR program is analyzed by using state-of-the-art fast Fourier transform analysis techniques and apparatus to obtain a variety of flutter characteristics as a function of operating parameters.

The most frequently used parameter in correlating flutter data is the Strouhal number, usually referred to as either the reduced frequency or its inverse, reduced velocity. The standard form of the latter most commonly used is

$$\overline{V} = \frac{V_R}{\omega c}$$

where V_R is the relative velocity at the leading edge for a specified spanwise location and c is the semichord length at the same spanwise location. The most commonly used spanwise locations are 75 and 87-1/2 percent. The frequency is a circular frequency. Either the actual value of the circular flutter frequency can be used, or the natural circular frequency of the mode under consideration, corrected for centrifugal stiffening and blade temperature effects, can be used. The two are seldom the same and can vary as much as 5 percent or more. The designer will normally use the natural mode frequency because that is all that he knows beforehand. In correlating the data obtained in the ESR programs both frequency values have been used. On an expanded scale those correlations using the blade natural circular frequency yielded results that appeared more orderly and reflected known perturbations. The circular flutter frequency is used when working with experimental data since it relates the actual vibrational period to the passage flow period, provided the velocity gradient through the passage does not vary excessively.

The reduced velocity parameter and the incidence angle been used in correlating separated-flow flutter based on early successes with isolated-airfoil flutter data. Unlike isolated-airfoil flutter the phenomenon in cascades is somewhat more complex, and the simple correlation of reduced velocity versus incidence has not always been as orderly as desired. This indicates that other parameters must be considered. One of those is stage inlet pressure, as noted by Jeffers and Meece.[14] The first set of flutter data correlated in the ESR programs, with reduced velocity and incidence as parameters, were from the shrouded-fan program. It was found on an expanded scale that the data fell into groups, with the differentiating parameter being inlet pressure. Three data points from these data with only inlet pressure as a variable are delineated in figure 10.

Inlet temperature, speed, and nominal stress levels in these data were for practical purposes the same. As can be seen, the stability boundary moves to the left as inlet pressure is increased. The same behavior was observed with respect to a midstage stator instability at negative incidence in the choke regime, as seen in figure 11. In these data the shift of the instability boundary is more pronounced since this is a midstage with a much larger stage pressure differential than indicated by the inlet pressure differential. The instability zone on a plot of reduced velocity as a function of incidence is considered by some to be a closed, bounded region. This appears to be logical if one considers the center of the region to be a unique singular point surrounded by a bounded unstable region in which the governing parameters tend toward stability as the boundary is approached from within the region. In that case increasing stage inlet pressure on the governing parameters tends to cause the zone to expand.

To date only a limited amount of data has been examined in this respect. Additional data will be examined to better define the phenomena. The implication of this behavior is that an instability boundary defined at one stage inlet pressure may not be valid for another stage inlet pressure. There are other considerations to be investigated relative to the reduced velocity parameter - incidence correlation that have not been addressed yet. Examples are cascade geometry, relative Mach number, and blade material density.

Choke Flutter

Choke flutter occurs in cascades with localized passage choking in an aeromechanical environment, as yet not well understood, capable of sustaining blade oscillations in the absence of an external forcing function. Flow incidence angles relative to the blade leading edge are normally small and can be either positive or negative. Local Mach numbers will approach sonic values consistent with choking requirements. Localized choking alone is not sufficient cause for choke flutter. Many cascades have operated near or at choke conditions without exhibiting choke flutter, thus a unique set of aeromechanical conditions is necessary to sustain the oscillations.

The data obtained in the ESR programs relative to choke flutter exhibited the following characteristics:

(1) No evidence of flow separation was observed.

(2) Initiation of all cases observed was precipitated and sustained by extraneous blade perturbations in the flutter mode.

(3) The observed flutter frequency, as in separated-flow flutter, was found to be a unique function of stage inlet pressure and temperature.

(4) The aeromechanical (flutter) mode exhibited indications of system degeneracy, two different modes at slightly different frequencies, being affected by mistuning.

Unlike separated-flow flutter it was not possible to anticipate incipent choke flutter. Analysis of strain gage data in both the time domain and the frequency domain showed no evidence of flow separation. This does not indicate that there was no separation. It does indicate that, if there was separated flow, the unsteady forces generated were of insufficient strength relative to the elastic-inertia stiffness of the airfoil.

All cases of choke flutter responded at a frequency near the airfoil fundamental frequency of first bending. All choke instabilities were approached by doing an engine acceleration along an operating line. Two rotor stages were found that exhibited this instability, and in each case there were notable differences. In once case the instability was found to be poorly coupled. The PES system (light probes) was extremely useful in this case since the instability was localized on a small sector of the rotor assembly away from any functional strain gages. This is shown in figures 12 to 14. Figure 12 is a PES system display of the rotor in the stable condition. Figure 13 shows a nonintegral order response developing that affects only a few rotor blades; figure 14 shows the response deep into the instability. The displacements in figure 14 are large. The calculated stresses are of the order of ±85 MPa (±12.3 ksi). The largest observed strain gage response was about ±20 MPa (±2.9 ksi) on a gage near the bottom fringe area. Data were obtained relative to this instability at nominal inlet pressures of 138 and 103 kPa (20 and 15 psia) at inlet temperatures between -17.7° C (0° F) and -30° C (-20° F). Analysis of these data produced some anomalies. Increasing inlet pressure was found to be stabilizing, which was considered unusual. Interstage aerodynamic data indicated that the stage total pressure ratio was decreasing an engine speed increased; thus there was some partial choking occurring in the stage. Strain gage data were analyzed from a few strain gages located near the unstable sector. These data indicated a frequency response near first bending that was responding to variations in stage inlet pressures and temperatures consistent with a choke flutter response. Strain gage data also indicated a one-per-revolution impulse that could be interpreted as a blade rub. To clarify these anomalies, additional data points were acquired. While accelerating the engine along the nominal operating line at inlet conditions of 69 kPa (10 psia) and -17.7° C (0° F), a heavy rub was encountered and documented with the PES system. Approximately 70 percent of the blades on the affected rotor showed a large loss in reflectivity from midchord aft to the trailing edge. A similar response occurred when the data point was repeated, and for another data point at inlet conditions of 103 kPa (15 psia) and -17.7° C. At this point air at ambient temperature, normally used to cool the test cell for high-inlet-temperature testing, was introduced into the test cell to warm the cell. After increasing the test cell temperature by about 20° C the data points were repeated at the same inlet conditions used previously. No rubs nor instabilities were encountered. The ambient temperature near the compressor casing was observed to be about 18° C warmer than before. The results of this latter test series explained the anomalies observed in the original data. The instability occurring was choke flutter induced by a perturbation due to a local rub. Without the rub the stage is stable for the inlet conditions tested. The principal controlling parameter was blade tip clearance. For the lower inlet pressures both blade bending and casing expansion were smaller and the rub occurred sooner, explaining why increasing inlet pressure appeared to be stabilizing. Increasing cell temperature and thus casing temperature resulted in larger tip clearances due to casing expansion.

Noteworthy in these data was the fact that the instability could be induced and sustained in the presence of an external perturbation. This has, to date, not been observed in separated-flow flutter. A single external perturbation can induce separated-flow flutter, but ESR program experience has shown that a sustained perturbation will retard the instability - as an example, the experience with rotating stall noted before. Also in separated-flow flutter, frequency entrainment of a resonance response in close proximity to the flutter frequency has been observed. This apparently is not the case with choke flutter, as seen from another set of choke flutter data obtained from another rotor stage. On this stage all strain gages responded at the same frequency but with moderately varying blade-to-blade maximum amplitudes. There were no PES system data available from this stage because of interference problems with variable-geometry hardware. A typical spectrum of the strain gage response is shown in figure 15. Common to all the data analyzed was the coexistence of an engine-order blade response in close proximity to the flutter frequency. The flutter frequency varied as a function of inlet conditions and speed, but at no time did it vary more than ±5 percent from the engine order. For one set of conditions it was essentially the same as the engine-order response. The development of the engine-order response preceded the development of the flutter response. The engine-order response is now viewed as an important factor in establishing and sustaining the dynamic conditions necessary for choke flutter. It acts in much the same way as the blade rub previously discussed. Choke flutter is a cascade passage phenomenon (i.e., isolated airfoils are not prone to choke flutter). Thus any dynamic blade motion due to an external perturbation will influence the dynamic passage geometry and affect the unsteady aerodynamics sufficiently to precipitate and sustain the choke flutter instability. The sustained external perturbations observed in the ESR programs appear to be necessary at the inlet conditions tested to sustain the instability.

The flutter frequency in choke flutter, as in separated-flow flutter, appears to have a functional dependence with inlet pressure and temperature conditions, as shown in figure 16. In this data set the primary variables were inlet pressure and temperature. The flutter frequency was found to decrease as inlet pressure increased and inlet temperature decreased. The latter effect is the opposite of that seen with separated-flow flutter data. The general trend observed with choke flutter data was that increasing inlet pressure had a destabilizing effect except in the case where the blade rub induced the instability. For a given inlet temperature the instability would develop at a lower speed for a higher inlet pressure. In this respect speed is an implicit variable in the data shown in figure 16. The increase seen in the flutter frequency with decreasing inlet pressure is partly due to centrifugal stiffening and probably partly due to density effects.

Also apparent in the data shown in figure 16 is a change in aeromechanical mode where four of the data points appear to belong to a different set of eigenvalues. An analysis of the interblade phase angle data for all the points in the data set also indicated that two aeromechanical modes were present. The interblade phase angle data summarized in figure 17 indicates that there were two sets or groupings of interblade phase angles, designated as A and B, associated with this data set. One set or family (A) included the four data points noted and all the data points at 103-kPa (15-psia) inlet pressure conditions; the other set (B) included the remaining seven data points. The phase angle data at 103 kPa (15 psia) had poor coherence, indicating that at this condition the instability is not solidly developed. All other data had excellent coherence values, 0.98 or better, indicating that for the time span over which the data were averaged, 32 averages, the interblade phase angle remained essentially constant. These results indicate that there are two sets of eigenvalues and corresponding eigenvectors (aeromechanical modes) in the data set. Since the values of the eigenvalues for the two aeromechanical modes are only slightly different, these results are probably due again to mistuning effects that make the system aeromechanically asymmetrical. In a symmetrical (tuned) system, the condition where two eigenvalues have the same value for two distinct eigenvectors is called degeneracy. Degeneracy is removed by destroying symmetry (by making the system asymmetrical (mistuning)). Degeneracy is quite often seen in the study of mechanical vibrations of mistuned rotors. Implied in these results is the probability that the rotor is responding to the choke flutter stimulus as a system.

System Mode Instabilities

The concept of system mode instabilities is usually associated with shrouded blade assemblies.[4] This type of instability involves mechanical coupling of the rotor blades with part-span shrouds and/or the disk to form a structural system mode that in an aerodynamic field is partially negatively damped at some combination of unsteady aerodynamic conditions. Interblade coupling, which is enhanced by part-span shrouds, is essential to this instability. Some recent instability data have been obtained in the ESR program from unshrouded blade assemblies and indicate the existence of an instability in the stall regime quite unlike separated-flow flutter in character. The limited data obtained to date tend to suggest that the instability may be a type of system mode response being sustained aerodynamically.

Currently only a limited amount of data relative to system modes have been obtained in the ESR programs; thus it is not possible to fully characterize this instability. It has been possible, however, to use the limited data available to differentiate the instability from others and to determine a few unique features of the instability. From experimental observations and data reduction the following has been determined:

(1) No evidence of flow separation has been observed.

(2) Blade loading is high and may be a factor.

(3) The instability frequency decreases as the oscillating amplitude increases, thus structural nonlinear effects may be an equilibrating influence.

(4) The instability frequency is nonintegral in order.

(5) The PES system data indicate that a coupled standing-wave mistuned system mode is present.

As with choke flutter in the choke regime, this type of instability in the stall regime exhibited no indication of any flow separation on strain gages before and during the instability. The strain gage response is characteristic of a resonant response and would be assumed to be one were not the responding frequency nonintegral. Two sets of data, both limited in quantity, have been obtained in the ESR programs up to the present time. One set was obtained as part of an aeromechanical program with a full complement of aerodynamic instrumentation. Analysis of data from this instrumentation indicated that the diffusion factor and thus blade loading was high at the time of the instability. System mode instabilities are normally found in the stall regime near the stall line, where two possible contributory conditions exist: dynamic stall characterized by flow separation, and high blade loading. The absence of any indication of flow separation in all the data observed up to the present time makes it unlikely that this aspect is a necessary condition for unstable behavior. However, in all cases observed of this instability, it has been necessary to approach the stall regime and load the blades. The need to do so tends to support the hypothesis that the attendant effects of blade loading may be one of several necessary conditions to support the instability.

The other set of system mode instability data was obtained serendipitously while routinely monitoring strain gages and light probes during an engine research program. This program was not conducted to obtain aeromechanical data and thus was not thoroughly instrumented for that purpose. This engine was a single-stage, unshrouded-fan turbofan engine. The instability was encountered during stall line mapping of a research configuration. The fan was being backpressured and loaded to drive it up toward stall along a constant-speed line. The instability developed before stall. This same fan had encountered separated-flow flutter in first torsion at slightly lower corrected speeds in the stall regime preceded by strong indications of flow separation. However, the instability in first bending at the higher corrected speed was devoid of any indication of flow separation. This led to the supposition that the two instabilities were different in nature even though their locations on a fan map were in close proximity. At one point the two instabilities overlapped. At this point the separated-flow flutter in first torsion started to develop first but then was retarded by the other instability in first bending.

PES system data were obtained relative to the single-stage, unshrouded-fan instability. Typical displays of this data are shown in figures 18 and 19 for two different engine speeds. The responding frequency was nonintegral near first bending between 1 and 2 engine orders. The blade motion is assumed to be predominantly first bending. This type of response is similar to a mistuned rotor response undergoing a forced mechanical vibration. The instability developed softly and all blades responded simultaneously. As the instability was building, distinct standing waves of displacement were observed on the PES system that lasted for at most several seconds. These ranged from 2 nodal diameters to 6 nodal diameters. The fully developed instability displacement patterns as seen in the figures were not as distinctive, varied with speed, and appear to be combinations of several standing waves. These characteristics are typical of an asymmetrical or mistuned system.

A unique aspect of the system mode response is that the instability frequency was observed to decrease slightly as the oscillatory amplitude increased, as seen in figure 20. This has not been observed in either separated-flow flutter or choke flutter. The decrease in frequency is small and can only be resolved by using high-resolution digital signal analysis techniques now available because of advances in fast Fourier transform technology. The data in figure 20 were obtained from a shrouded fan stage while accelerating through the instability regime. The instability mode was a coupled system mode with a frequency about midway between above shrouded bending and above shroud torsion. The behavior of the frequency in these data is probably due to structural nonlinear effects with increasing amplitude.

Current plans call for additional experimental investigations of the system mode instability using full-scale engines in the ESR programs. These investigations will obtain data on the effects of stage inlet conditions, blade loading, and distortion. At the present time there is not a complete and comprehensive set of data available in this regard.

Concluding Remarks

Promient results obtained to date from the aeromechanical programs of the Engine Systems Research programs were discussed. Data-pertaining to several types of instabilities were obtained. These data indicate that each type of instability possesses unique characteristics that shed light on the nature of the instability as well as differentiate it from the others. These data are now part of a joint USAF/NASA data bank being used in government and industry to improve the understanding of aeroelastic phenomena in turbomachinery.

The ESR program data bank on separated-flow flutter and choke flutter is adequate to study these phenomena. The data in the ESR data bank relative to the system mode family of instabilities are limited; however, there are planned programs under way to remedy this. Also, there are considerable data available outside of the ESR programs: the majority of the cascade work done in the last decade using oscillating airfoils appears to be relevant to these phenomena. An uncertainty with respect to the system mode instability is that there may well be several different and distinct instability mechanisms that could result in this type of response. This uncertainty can only be resolved by thoroughly investigating and documenting this class of instability as the opportunity presents itself to differentiate intrinsic properties.

The study of aeroelasticity of turbomachinery is a continuing effort in the ESR programs. Judicious use is being made of opportunities to obtain meaningful aeromechanical data whenever possible. Areas of interest include obtaining additional comprehensive data on system mode responses, supplementing the available separated-flow flutter and choke flutter data, investigating the effects of inlet distortion on all classes of aeroelastic phenomena including forced responses, and obtaining quantitative damping data. Inherent in these efforts is the continuing effort to develop better and sophisticated measurement and data analysis techniques.

To support these efforts and make effective use of these data, basic research and technology must continue in computational fluid and structural mechanics, modal analysis, and the understanding of the aerodynamic and structural interfaces. Inherent in all the data obtained from full-scale engines, the real world so to speak, is the observation that flow and structural asymmetries are a fact of life and can be used, if understood, beneficially.

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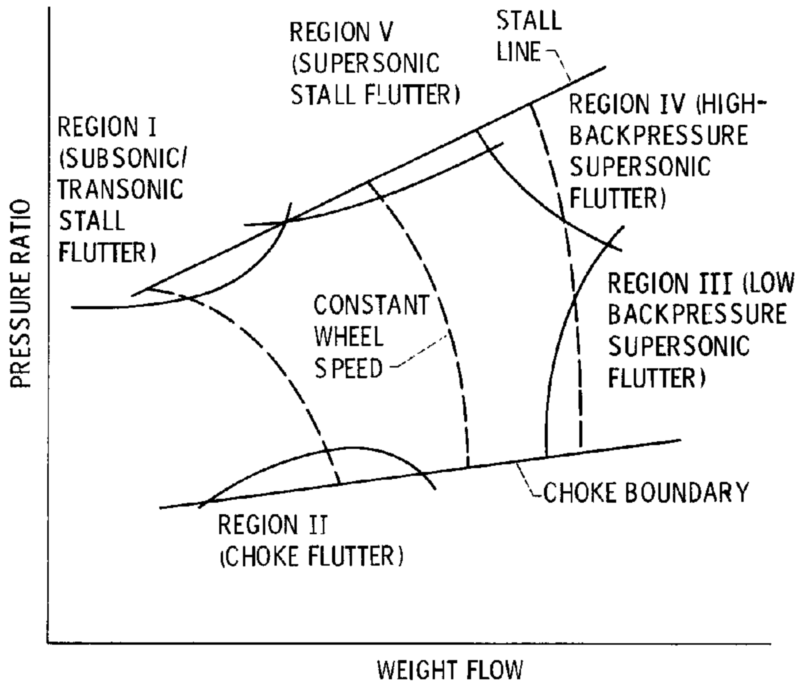

Figure 1. - Compressor performance and stability map.

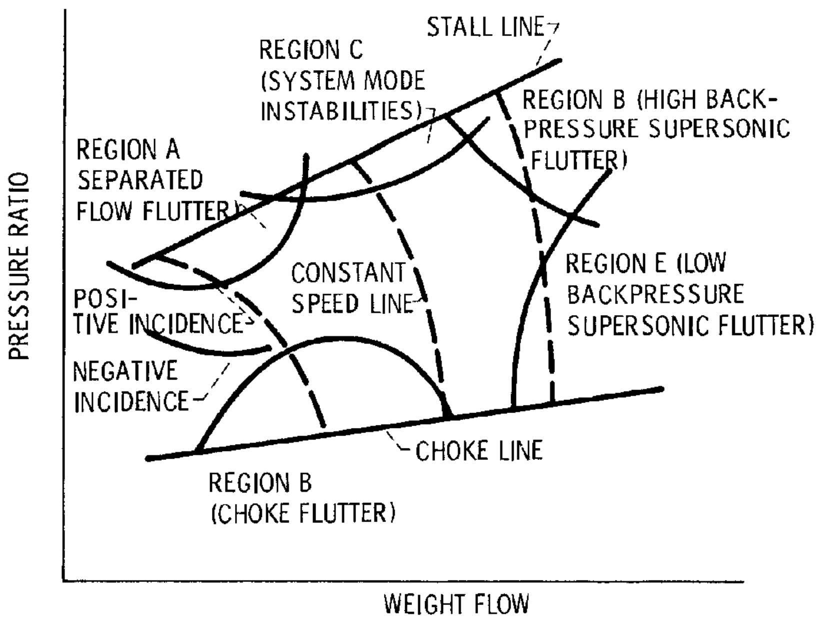

Figure 2. - Compressor performance and revised stability map.

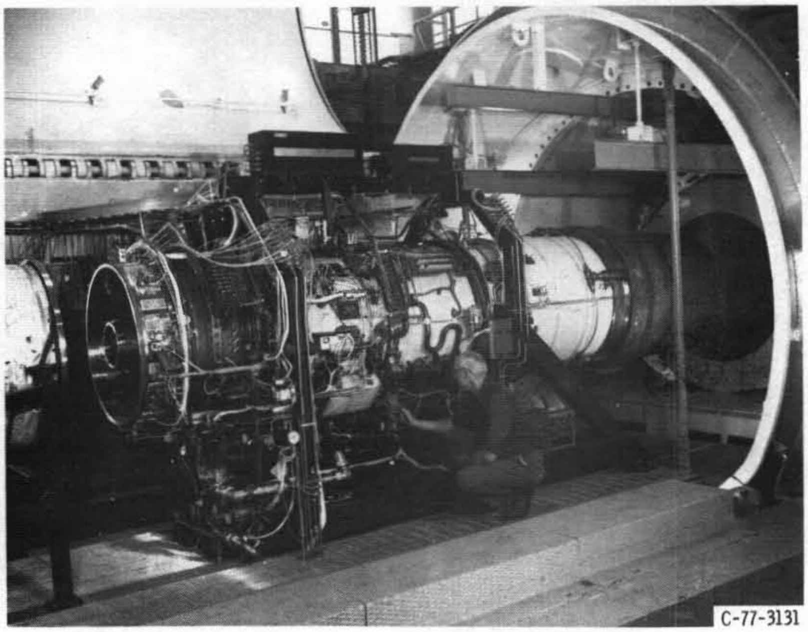

Figure 3. - Turbofan engine installation.

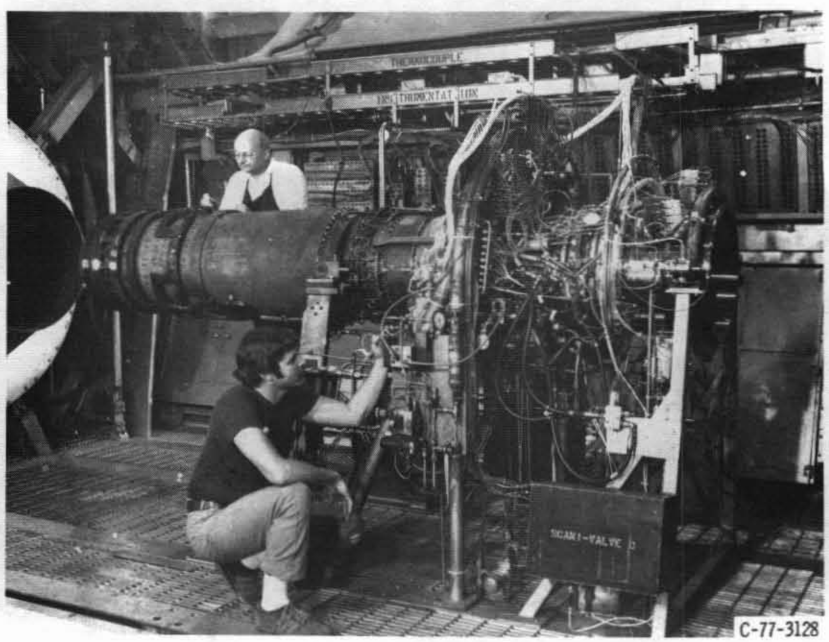

Figure 4. - Turbojet engine installation.

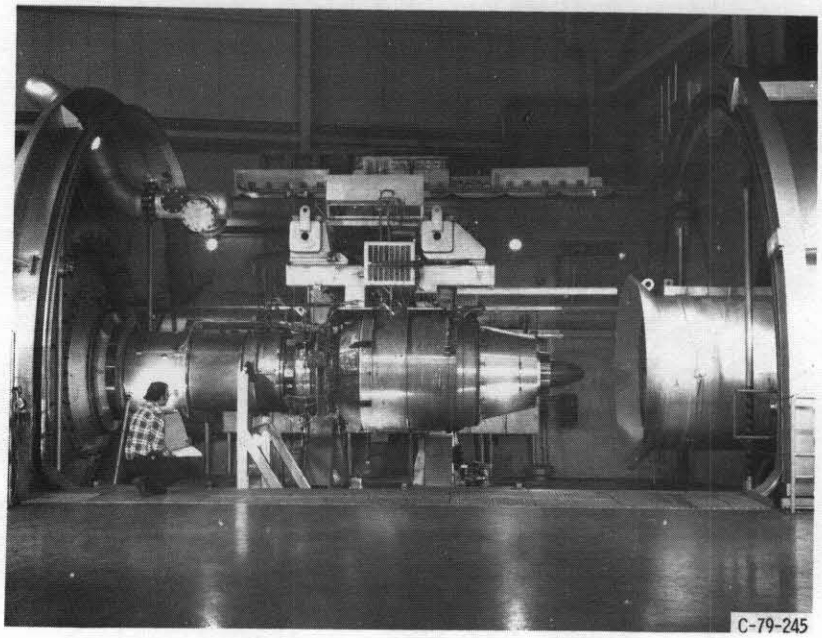

Figure 5. - Single stage fan, turbofan engine installation.

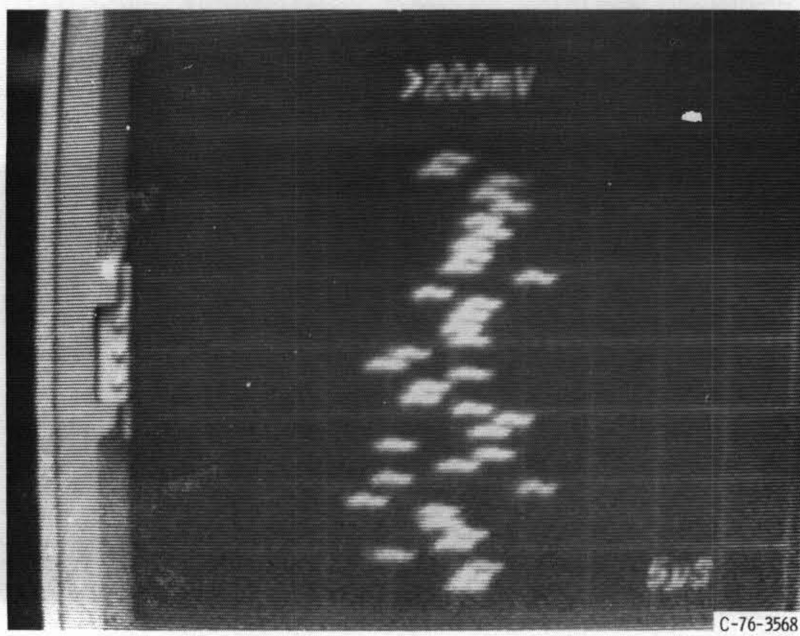

Figure 6. - PES display during quiet running condition.

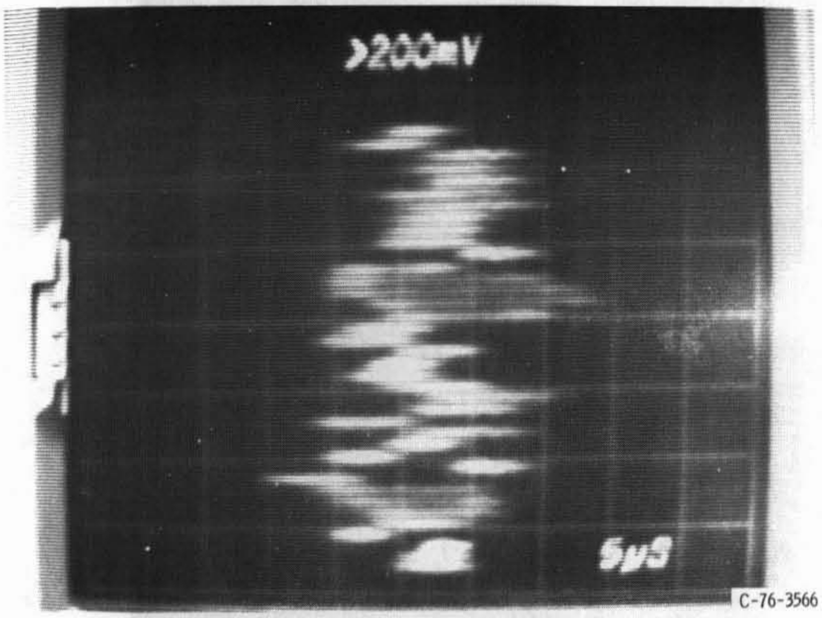

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Figure 7. - PES display during separated flow flutter.

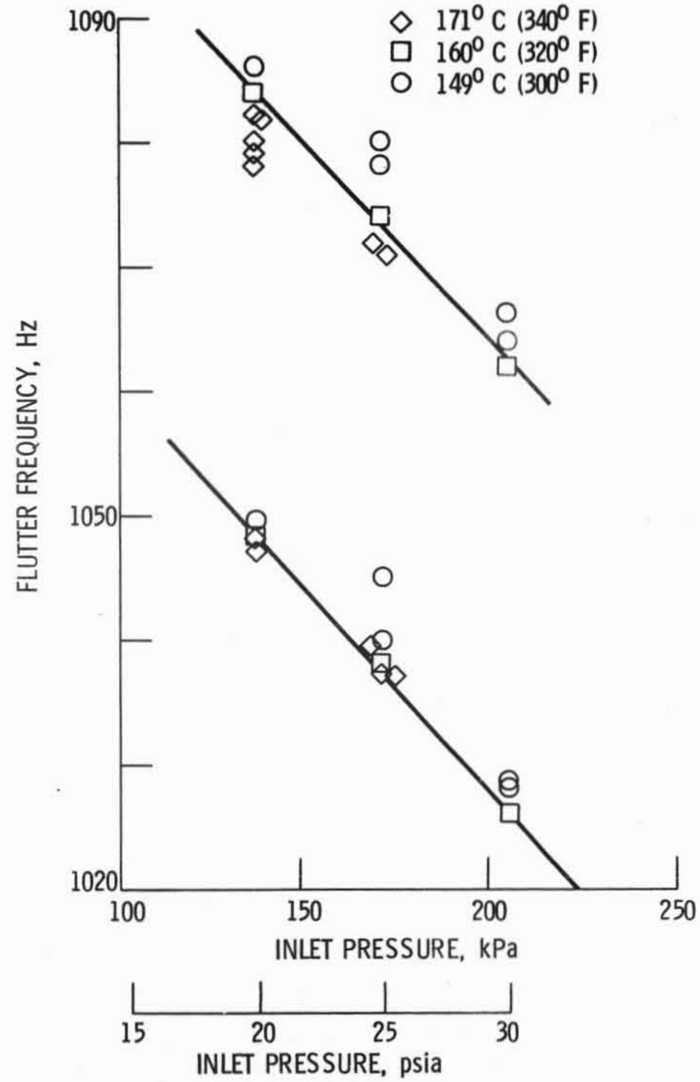

Figure 8. - Inlet pressure and temperature effect on fan flutter frequency.

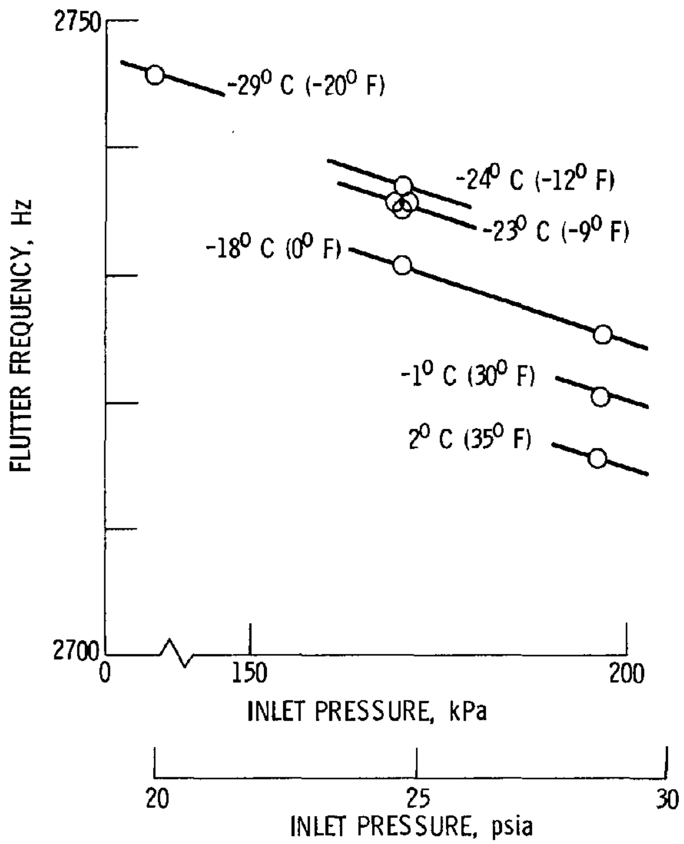

Figure 9. - Effect of inlet temperature and pressure on stator flutter frequency.

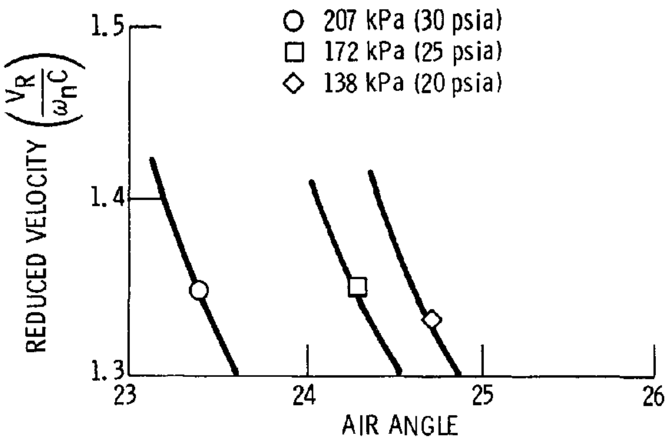

Figure 10. - Inlet pressure effect on reduced velocity-incidence correlation for fan separated flow flutter.

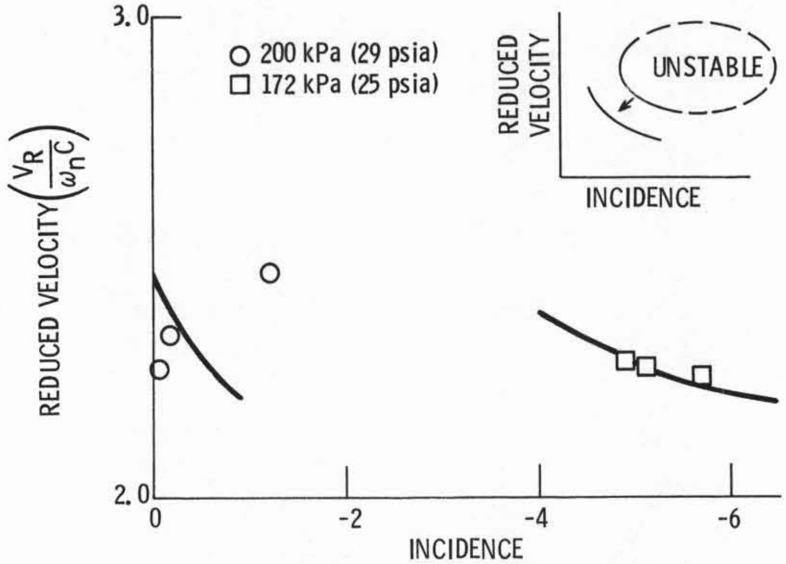

Figure 11. - Inlet pressure effect on reduced velocity-incidence correlation of stator separated flow flutter.

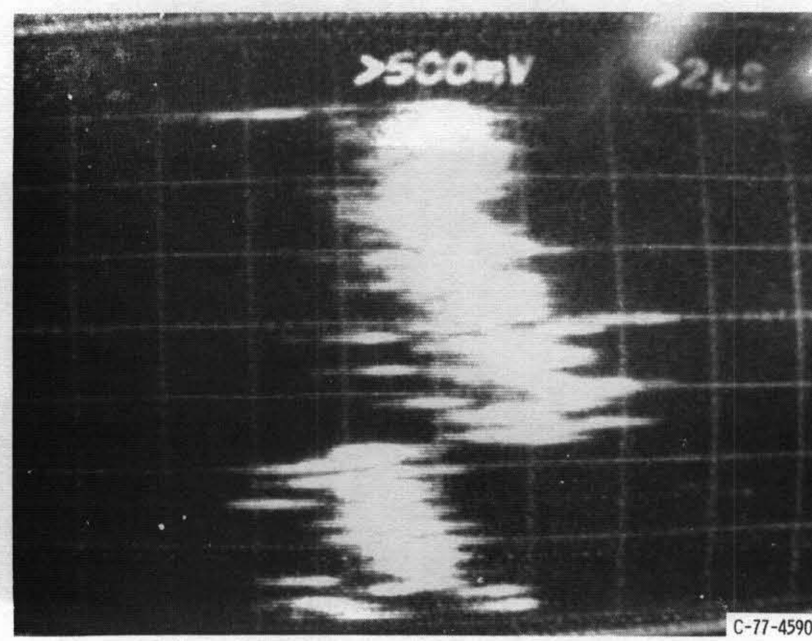

Figure 12. - Stable condition prior to localized choke flutter.

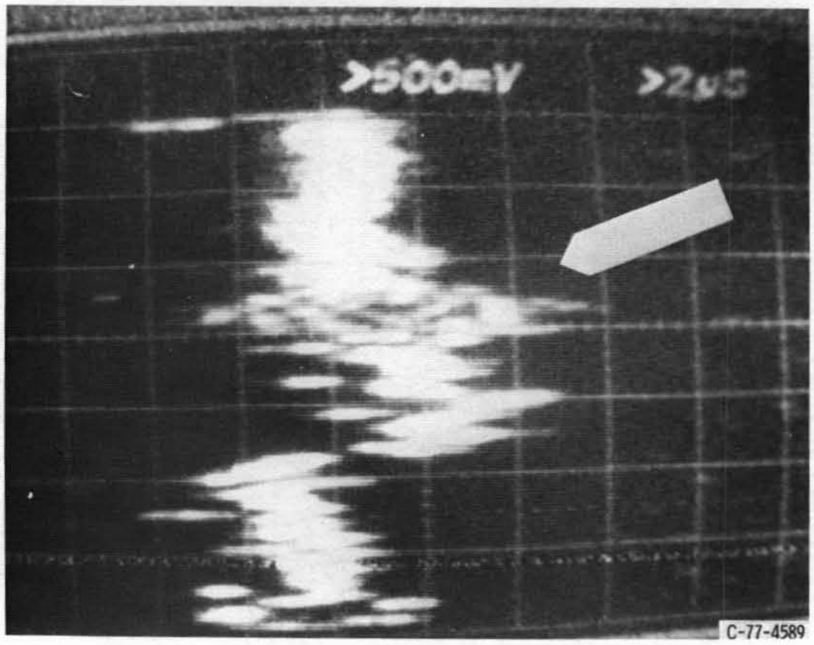

Figure 13. - Initial response of localized choke flutter.

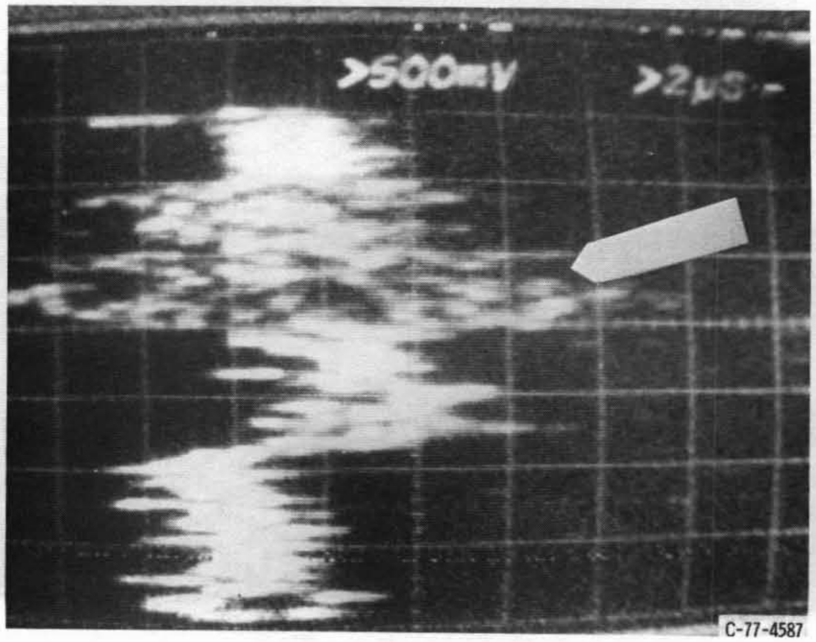

Figure 14. - Large amplitude localized choke flutter.

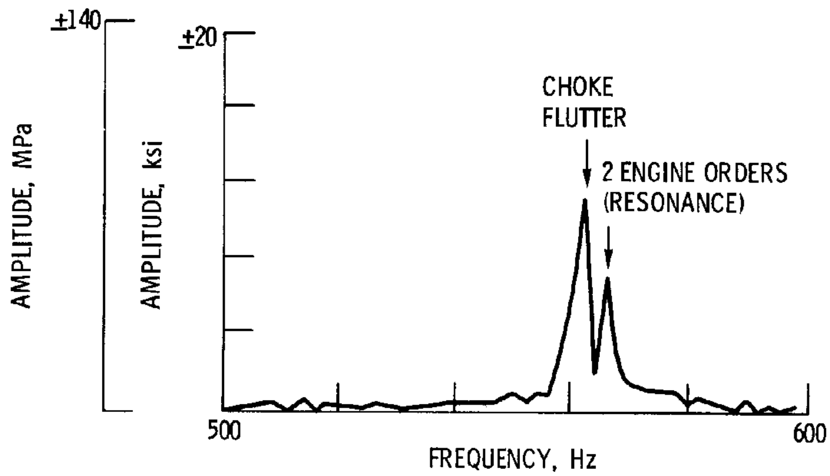

Figure 15. - Choke flutter strain gage spectrum.

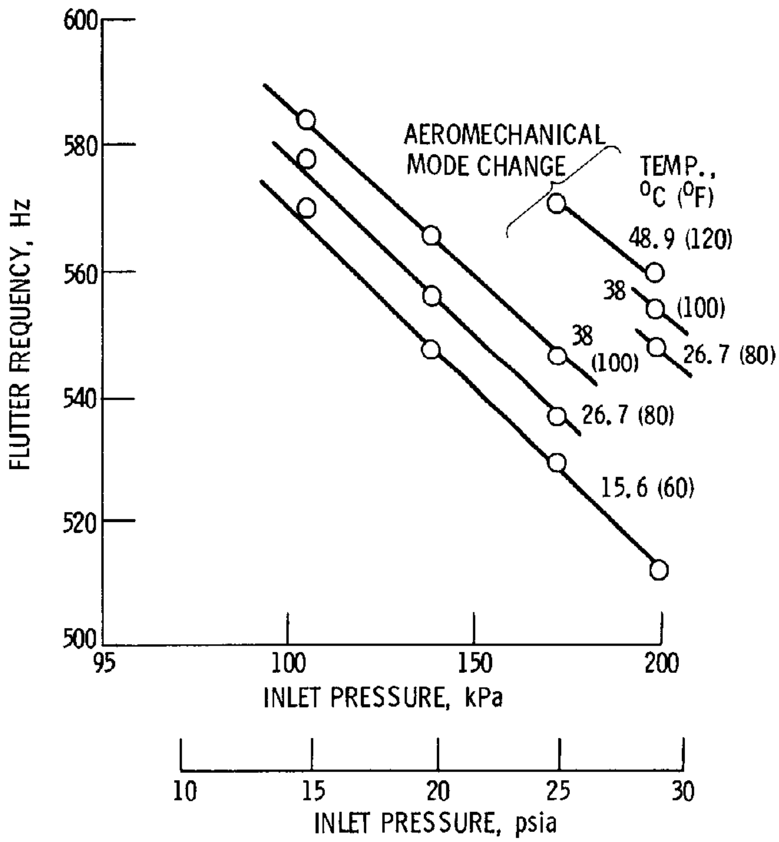

Figure 16. - Effect of inlet pressure and temperature on choke flutter.

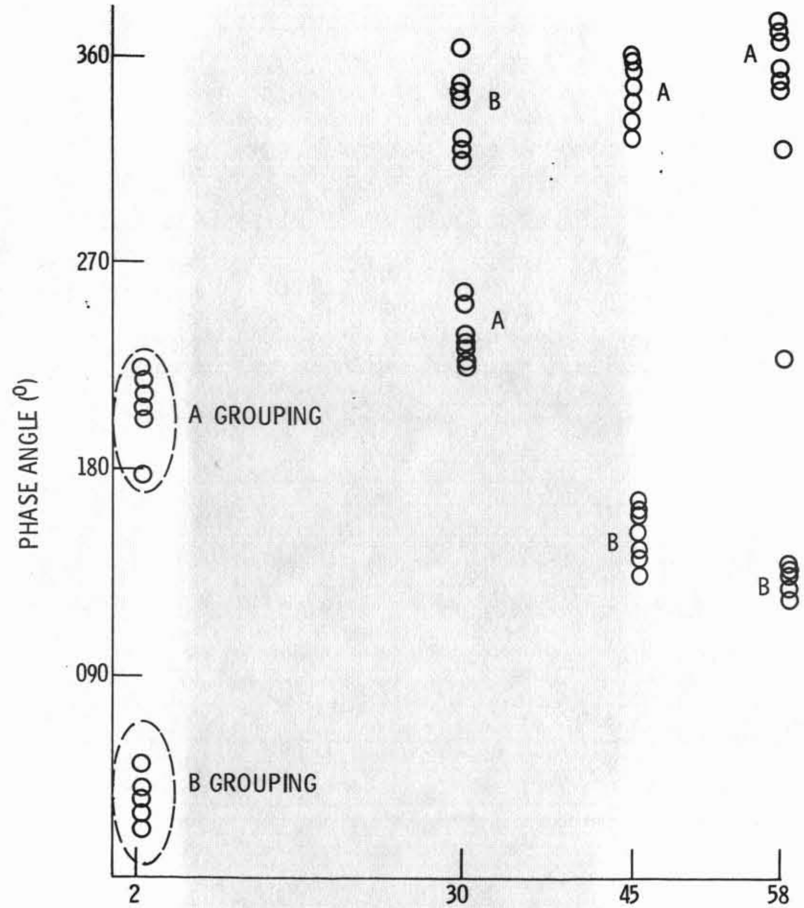

Figure 17. - Phase angle distribution for choke flutter.

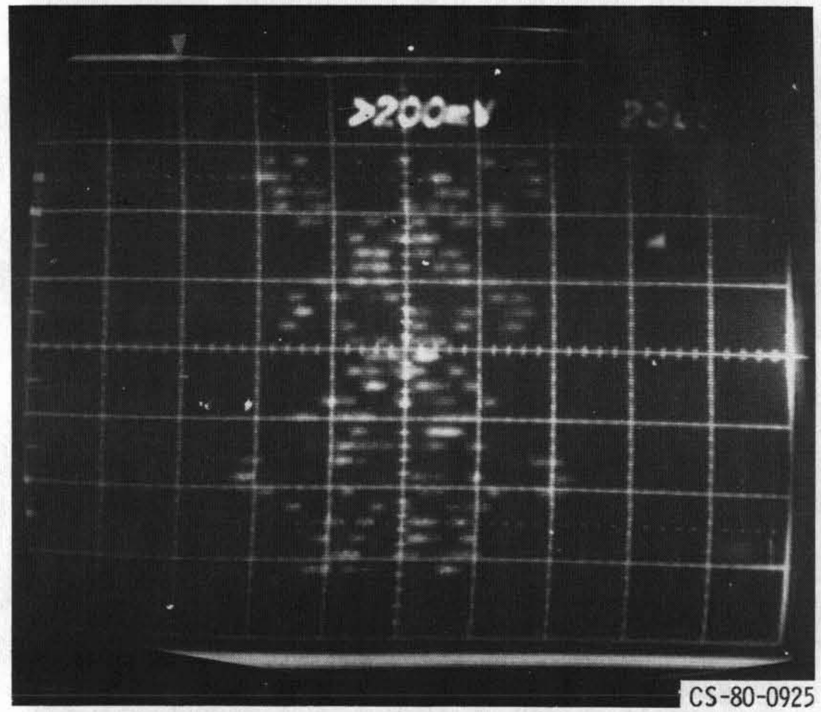

Figure 18. - System mode response in predominantly 1st bending at 100 percent speed.

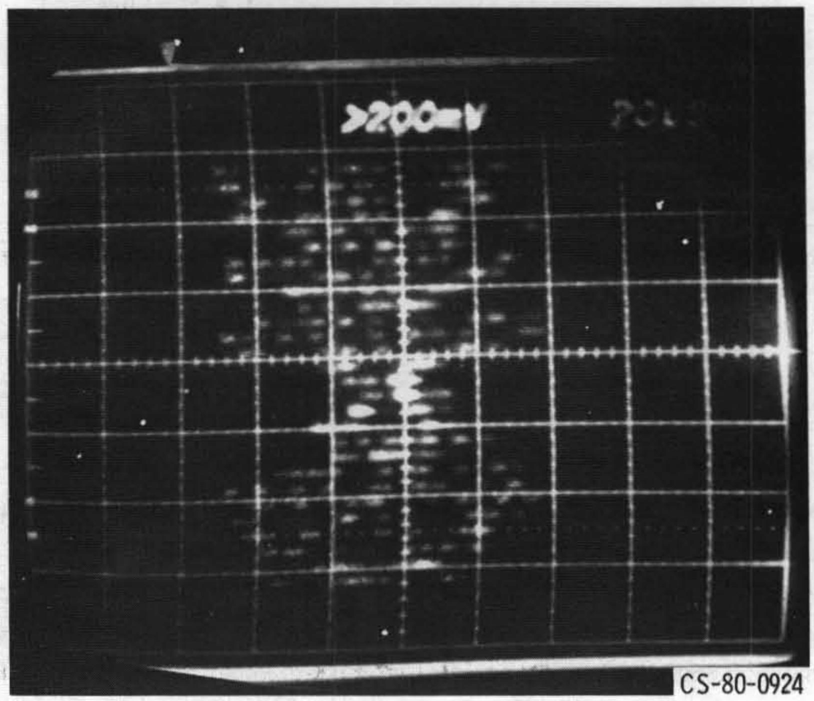

Figure 19. - System mode response in predominantly 1st bending at 105 percent speed.

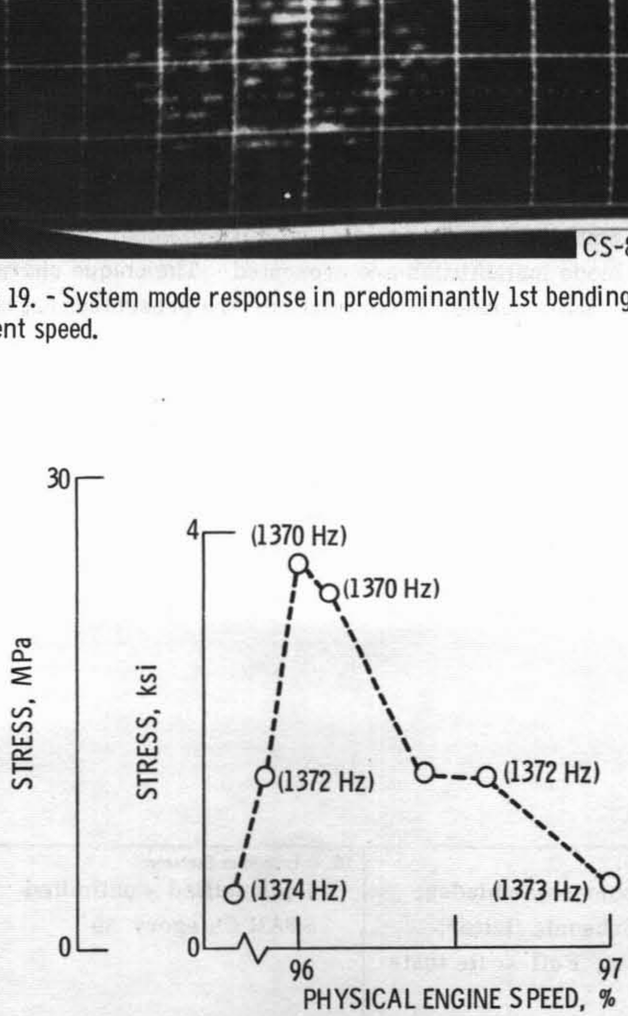

Figure 20. - System mode instability stress and frequency as a function of engine speed.

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