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IN-FLIGHT INVESTIGATION OF A ROTATING CYLINDER-BASED STRUCTURAL EXCITATION SYSTEM FOR FLUTTER TESTING

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Abstract

A research excitation system was test flown at the NASA Dryden Flight Research Facility on the two-seat F-16XL aircraft. The excitation system is a wingtip-mounted vane with a rotating slotted cylinder at the trailing edge. As the cylinder rotates during flight, the flow is alternately deflected upward and downward through the slot, resulting in a periodic lift force at twice the cylinder's rotational frequency. Flight testing was conducted to determine the excitation system's effectiveness in the subsonic, transonic, and supersonic flight regimes. Primary research objectives were to determine the system's ability to develop adequate force levels to excite the aircraft's structure and to determine the frequency range over which the system could excite structural modes of the aircraft. In addition, studies were conducted to determine optimal excitation parameters, such as sweep duration, sweep type, and energy levels. The results from the exciter were compared with results from atmospheric turbulence excitation at the same flight conditions. The comparison indicated that the vane with a rotating slotted cylinder provides superior results. The results from the forced excitation were of higher quality and had less variation than the results from atmospheric turbulence. The forced excitation data also invariably yielded higher structural damping values than those from the atmospheric turbulence data.

Introduction

During flutter testing, it is important that sufficient excitation is provided to the aircraft's structure. The frequency and damping values of the aircraft's structural modes need to be accurately estimated to determine adverse damping trends or levels that would indicate the onset of flutter. Sufficient in-flight excitation provides high-quality data, which improves data analysis accuracy and reduces the time required to obtain results. Overall, this makes flutter testing safer and more efficient.

At the NASA Dryden Flight Research Facility, flight flutter testing has been performed on many research aircraft using a variety of excitation systems.[1] Most testing has used natural atmospheric turbulence. Natural atmospheric turbulence, however, is often difficult to find and seldom excites all of the aircraft's structural modes.[2] Control surface pulses, or stick raps, are also frequently used with atmospheric turbulence. Stick raps typically do not excite structural modes above 5 Hz. The dangers in not obtaining adequate excitation using these methods were shown in Ref. 3. This reference describes an aircraft whose flight envelope was cleared for flutter using natural atmospheric turbulence and stick raps. The aircraft later fluttered within the cleared flight envelope when it encountered severe turbulence that provided higher levels of excitation than were obtained during the flutter test.

Other means of excitation include sinusoidal control surface excitation, oscillating aerodynamic vanes, rotary inertia exciters, and pyrotechnic bonkers. While each means of excitation has been successfully used for flight flutter testing, each also has some disadvantage that prevents it from being used consistently on a variety of aircraft. In sinusoidal control surface excitation, the control surfaces are programmed to oscillate through a predetermined frequency range.[4] The frequency range, however, is limited by the actuator frequency response, and implementing this method requires modifications to the control system software, which can be very costly and time consuming.

Oscillating aerodynamic vanes tend to be very effective. The vane is mounted externally at a specific location on an aircraft and oscillated in pitch at the desired frequency. Because of the large loads on the vane, however, this system requires a relatively large amount

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of power and must be run from the aircraft's hydraulic system, resulting in costly and time-consuming installation procedures.[4]

A rotary inertia exciter consists of a rotating unbalanced weight attached to a shaft. As the unbalanced weight rotates, a sinusoidally varying force is applied to the surface to which it is attached.[5] Because the acceleration depends on the rotational frequency and the force produced is proportional to the moving mass and its acceleration, at high frequencies the force level of the excitation is high. This also works as a disadvantage, however, since at low frequencies the force level is low; it may be difficult at the low frequencies to produce enough force to sufficiently excite the aircraft. One way to overcome this would be to add mass to the exciter, which would increase the amount of force on the surface. Unfortunately, adding mass would also increase the weight of the exciter, and a risk is taken in that additional weight might affect the vibrational characteristics of the aircraft.

Pyrotechnic bonkers are small, single-shot, solid propellant rockets with burn times of about 18 to 26 msec and maximum thrust levels ranging from 400 to 4000 lb.[6] The bonkers are attached to the aircraft at various points; upon ignition they impart a short-duration impulse to the aircraft structure, exciting a number of aircraft structural modes. This method's disadvantages include questionable reliability under arduous environmental conditions such as extreme cold and vibration, the difficulty of synchronizing several distributed percussions at different points on the structure to excite the different modes of interest, and the fact that the number of impulses per flight is limited.

The disadvantages of current flutter excitation methods demonstrate a need to develop a low-cost, effective in-flight structural excitation system. A unique excitation system that addresses these needs was designed and built by Dynamic Engineering, Incorporated (DEI) of Hampton, Virginia. This system was flight-tested at NASA Dryden on the two-seat F-16XL aircraft to determine the exciter's effectiveness as a structural excitation system. The concept incorporates a wingtip-mounted vane with a rotating slotted cylinder behind the trailing edge. This system is intended to be a lightweight, self-contained exciter that could be installed on a variety of aircraft with minimal interface with the aircraft's systems.[7]

This paper presents the flight test results on the exciter system. Primary research objectives for the test flights were to determine the system's ability to develop adequate force levels to excite the aircraft's structure and to determine the frequency range over which the system could excite structural modes on the aircraft. In addition, studies were conducted to determine optimal excitation parameters, such as sweep duration, sweep type, and energy levels.

Aircraft Description

The exciter was tested on an F-16XL aircraft (Fig. 1). This aircraft is powered by a General Electric F110-GE-129 engine (General Electric, Inc., Lynn, Massachusetts) and has a highly swept wing. The inboard region of the leading edge has 70° of sweep and the outboard wing leading edge has 50° of sweep. The aircraft is capable of speeds exceeding Mach 2.

The aircraft was instrumented with nine accelerometers located on the wingtips, in the aileron actuator housing, in the fuselage, and on the vertical tail (Fig. 2). The exciter vane was located on the F-16XL's left wingtip.

A conventional flutter clearance was conducted on the airplane at the time it was built.[8] The current tests served only to evaluate the new exciter system.

Exciter System Description

The excitation system hardware consists of three main components: a cockpit control panel, an electronics box, and a fixed-vane exciter (Fig. 3). System installation required mounting the control box in the cockpit, mounting the electronics box in the instrumentation bay, and routing electrical wire through the leading edge flap to the fixed-vane exciter at the wingtip. Eighty workhours were required to install this system on the left wing of the F-16XL.

The cockpit control panel, which is mounted in the aft cockpit of the aircraft, controls the excitation system. The system incorporates several operating modes: constant frequency, linear or logarithmic sine sweeps, sweep frequency range and duration, a quick-stop feature for free-decay response measurements, and high- or low-force amplitude options. The exciter system is capable of excitation frequencies up to 50 Hz, and the force level is measured by a bending moment strain-gauge bridge mounted near the root of the exciter vane. The electronics box is a self-contained package that contains the closed-loop motion controller card and other signal conditioning.

The fixed-vane exciter consists of a diamond-shaped, symmetric airfoil section and a rotating slotted cylinder at the trailing edge (Figs. 4 and 5). The vane was attached to the left wingtip of the F-16XL using an adapter plate designed to slide into the missile launcher rail. The vane has a span of 1.0 ft with a total area of 0.85 ft^2. The weight of the vane is 10 lb. A ground vibration test showed that the vane's weight did not change any of the modal characteristics of the F-16XL.

The two slots cut in the cylinder generate periodic lifting forces that excite the aircraft. As the cylinder rotates during flight, the flow is alternately deflected upward and downward through the slots, resulting in a periodic lift force at twice the cylinder's rotational frequency. Figure 6 illustrates this. Point A shows the zero force position, point B is the maximum positive force position, point C is zero force again, and point D is the maximum negative force position. Note that the cylinder has only rotated 180° for one full sinusoidal forcing period. The amplitude of the excitation force depends upon the dynamic pressure and the amount of the slot opening.

The amount of slot opening is controlled by the direction of rotation of the slotted cylinder. Reversing the rotational direction of the cylinder drive motor causes half of the spanwise slot opening to be blocked by an inner cylinder in the inboard slot. Closing the inboard slot attenuates the excitation force by half in flight. In addition, a plug was added to the outboard slot by the manufacturer after wind-tunnel tests indicated that the vane may produce more force than is desirable at high dynamic pressures. This plug spans 25 percent of the slot opening and reduces the amount of force that the excitation system can provide. With this plug, when the exciter is in the high-force mode, the slotted cylinder is 75 percent open (Fig. 7(a)). When the exciter is in the low-force mode, the slotted cylinder is 25 percent open (Fig. 7(b)).

The lift force produced by the vane-rotating cylinder concept is analogous to that of an oscillating vane. The rotating cylinder's main advantage is that it requires only the relatively small amount of power needed to overcome the aerodynamic and frictional forces opposing its rotation. Therefore, a low-wattage electric servo motor is used to run the system. Requiring only 28 V, the system can be readily integrated with an aircraft's normal power supply.

The design condition for the vane is Mach 1.2 at 10,000 ft (1467 lb/ft^2 dynamic pressure) at an angle of attack of 4°. The vane stalls at an angle of attack of about 12°.

Test Procedures

Flight testing was conducted to determine the excitation system's effectiveness in the subsonic, transonic, and supersonic flight regimes. The vane was flight-tested at an altitude of 30,000 ft from a Mach number range of 0.6 to 1.7. Frequency sweeps were performed from 5 to 35 Hz. This frequency range covers the primary modes of interest on the F-16XL, which are shown in Table 1 (taken from Voracek, David F., Ground Vibration and Flight Flutter Test of the F-16XL Aircraft With a Modified Wing, NASA TM-104264 to be published). Random atmospheric data were also acquired at each test point to compare with the forced excitation data. Table 2 gives a test matrix of the points flown.

Linear sweeps were conducted for durations of 60, 30, 15, and 7 sec to assess the effect of test duration on modal excitation. Logarithmic sweeps were conducted at 30 and 60 sec for comparison with linear sweeps of the same duration. Response data were also acquired for continuous frequency dwells of 8 and 10.8 Hz. These frequencies correspond to the first symmetric wing bending and antisymmetric wing bending modes, respectively.

The accelerometer response data and strain-gauge load data were telemetered to a ground station for real-time data collection and monitoring. The data were displayed on strip charts and a four-channel frequency spectrum analyzer. The accelerometer responses were monitored during each frequency sweep and dwell to observe structural response levels. The data were sampled at a rate of 200 samples/sec. For analysis, power spectral density plots were generated using a block size of 2048, which gave a frequency resolution of approximately 0.1 Hz.

Results and Discussion

The flight test evaluation of the exciter showed that it adequately excited most of the aircraft's structural modes between 5 and 35 Hz. Figure 8 shows the power spectral density plots from the left-wing accelerometers for the Mach 0.9 at 30,000 ft flight condition with a linear sweep. Responses from the forward and aft accelerometers on the left wing indicate that, for all flight conditions, all modes identified from ground vibration test results were excited, with the exception of the 12.5-Hz vertical fin mode and the 13.7-Hz symmetric launcher pitch mode (Table 1). The vertical fin mode was not excited because the excitation energy was not transmitted to the vertical fin from the wingtip for this airplane. The vane was placed on the node line for the symmetric launcher pitch mode, so this mode was not expected to be excited.

Exciter Sweep Compared With Random Atmospheric Turbulence Excitation

At each stabilized test point, 60 sec of aircraft random response data generated by natural atmospheric turbulence excitation was collected before the exciter sweep response data were collected. Frequency and damping estimates were obtained at each flight condition for each type of excitation. The power spectral density plots shown in Fig. 9 are a comparison of the left-wing response caused by random atmospheric turbulence and forced excitation from the exciter vane.

At this flight condition, Mach 0.9 at 30,000 ft, the pilot reported encountering light to moderate turbulence. From the atmospheric turbulence excitation only the 8 Hz mode is well excited. Natural atmospheric turbulence did not excite any structural modes above 14 Hz. All expected structural modes were excited by the exciter vane. This data clearly indicate that the excitation provided by the exciter vane was superior to natural atmospheric turbulence.

The most critical flutter frequencies for this airplane configuration are predicted to be in the range of 20 to 30 Hz. It is especially important that such modes be excited during flight flutter testing to ensure detection, subcritically, of impending aeroelastic instabilities. In this example, the exciter vane provided excitation at these frequencies while atmospheric turbulence did not.

For every flight condition, the forced excitation data yielded higher structural damping values than those from the atmospheric turbulence data. Figure 10 shows a graph of the structural damping values for the symmetric and antisymmetric wing bending modes. The structural damping estimates for the forced excitation data are often as much as twice the value of the data for the atmospheric turbulence. Figure 9 also reflects this phenomena. The width of the peaks, which is proportional to structural damping, is clearly smaller for the atmospheric turbulence data than for the forced excitation data. This is attributed to the fact that the amplitudes for the modes excited by atmospheric turbulence have a very low signal-to-noise ratio. The modes are not well excited and are contaminated by noise; therefore, the damping levels are difficult to calculate accurately.

Static Forces

The exciter vane was mounted at 0° with respect to the launcher rail. When it was installed, no attempt was made to determine a mounting angle that would minimize static loads at the planned flight conditions. Figure 11 shows the static loads generated at each Mach number. At Mach 0.8, the aircraft was at an angle of attack of 6.5°, and the vane generated 160 lb of upward force. The magnitude of the static loads decreased until the aircraft reached Mach 1.7, with an aircraft angle of attack of 2°, when 30 lb of downward force was measured. The local angle of attack of the exciter vane was not measured.

Dynamic Forces

The dynamic forces generated by the exciter vane at each Mach number are shown in Figure 12. The forces shown are given in pounds, peak to peak, and are all for the high force setting (cylinder slot 75 percent open). Overall, the average dynamic force increased with increasing Mach number, which was expected because dynamic pressure was also increasing. The dynamic forces ranged from about 50 lb at Mach 0.8 to almost 90 lb at Mach 1.7 (all at 30,000-ft altitude). These loads were less than expected. For the design condition of Mach 1.2 at 10,000 ft (1467 lb/ft^2), DEI wind-tunnel and flight test data estimated 409 lb peak to peak for an exciter configuration with no plug in the slotted cylinder.[9] The flight condition of Mach 1.7, 30,000 ft (1271 lb/ft^2) was therefore expected to be close to that. The difference may be due in part to the addition of the plug, which cut the slot opening by 25 percent, and due to local flow conditions at the launcher rail of the F-16XL, which may have decreased the exciter's effectiveness. While less than predicted, the dynamic force levels were more than sufficient to excite the aircraft's structural modes of interest.

Force Roll-Off

The dynamic forces generated at Mach 0.9 and 1.1 are shown in Fig. 13 as a function of frequency. This figure shows that the exciter vane generated adequate force across the entire frequency range of interest (5 to 35 Hz). The force is not flat across the frequency bandwidth, however. The dynamic force peaks at two frequencies that correspond to antisymmetric structural modes. The increase in force at these frequencies is most likely caused by an inertial reaction of the exciter as these structural modes are excited. An increase in amplitude is also seen at the sweep cut-off frequency at 35 Hz. This is a result of the excitation frequency approaching the exciter vane first bending mode, which is at 43 Hz.

Logarithmic and Linear Sweeps Compared

Figure 14 shows a comparison of the 60-sec logarithmic and linear sweeps at several Mach numbers for a frequency sweep of 5 to 35 Hz. At Mach 0.9, the logarithmic and linear sweeps are nearly identical. As Mach number increased, however, the logarithmic sweep did not excite the control surface modes, from 20 to 30 Hz, as well as the linear sweep. This trend was even more pronounced for the 30-sec sweeps. Overall, the linear sweep was more consistent in exciting the structural modes over the range of Mach numbers tested.

Linear Sweep Durations

To determine the effect of different sweep durations, linear sweeps from 5 to 35 Hz were performed for 60, 30, 15, and 7 sec. Figure 15 shows a comparison of the different sweep durations at Mach 0.8. The 30- and 60-sec sweeps are nearly identical. As the sweep duration decreased, however, less excitation energy is transmitted to the structure, and at the 7-sec sweep, some modes are not excited. Overall, the 30-

and 60-sec sweeps produce about the same level of response, regardless of Mach number, and these levels were considered adequate.

High- and Low-Force Levels

Figure 16 shows a comparison of the high- and low-force levels for the vane at Mach 0.9 at 30,000 ft. Both force levels were sufficient to excite the modes of interest; however, the high-force level provided considerably more energy. A slight frequency shift, as much as 3 percent for some frequencies, in the data comparison can be seen in Fig. 16. As the force was increased, the frequency of the modes decreased. This trend is a result of structural nonlinearities and is commonly measured during ground vibration tests.[10]

Harmonic Excitation

The exciter produced harmonics which excited modes higher than the primary sweep frequency. An example of the harmonic excitation is seen in Fig. 17, which shows an 8.0-Hz frequency dwell and the harmonics produced by the vane at Mach numbers of 0.8, 0.9, and 1.05. The harmonics appear to have the highest amplitude in the transonic Mach number range.

Another example of the harmonic excitation is seen in Fig. 8, in which a mode at 43 Hz was observed. The 43-Hz mode is the exciter's first vane bending mode, measured from a ground vibration test done on the vane, and it was excited while the sweep passed through 21.5 Hz. This effect can be seen more clearly in Fig. 18. Here, the exciter has swept through a frequency range of 5 to 15 Hz, and the data indicate that the modes in the 15- to 30-Hz frequency range have also been excited. This effect may not be desirable, as in the case of exciting the vane's first bending mode, or if a single frequency dwell is required.

Excitation Energy Distribution

During the evaluation flights, the vane assembly was mounted on the left wingtip of the aircraft. Accelerometers were mounted both on the left and right wingtips. The response from these accelerometers was used to measure the energy transferred from the left wing to the right wing during exciter operation.

Figure 19 compares the power spectral density of the left-wing response with that of the right wing. The symmetric and antisymmetric wing bending modes (8 and 10.8 Hz) were excited well on both wingtips; however, the 13.2-Hz launcher pitch mode was not excited on the right wing. The exciter, as well as the aft accelerometer, was placed near the node line for this mode. There was sufficient energy to excite this mode on the left side of the airplane, which is seen in the left-wing forward accelerometer response. There was insufficient energy, however, to excite this mode on the right side of the airplane. In addition, the higher frequency control surface modes were not excited as well on the right wing when compared to the left wing. Overall, the modes above 20 Hz were not excited well on the side opposite the exciter. This deficiency could be overcome by adding an exciter to the right wingtip.

Conclusions

A vane and rotating slotted cylinder excitation system was flight-tested to investigate the exciter's effectiveness in the subsonic and transonic flight regimes. The objectives for the flight tests, to determine the system's ability to develop adequate force levels to excite the aircraft's structure and to determine the frequency range over which the system could excite structural modes on the aircraft, were met. In addition, studies were conducted to determine optimal excitation parameters, such as sweep duration, type, and energy levels.

The structural response data quality obtained with the exciter was superior to that obtained with random atmospheric turbulence. The vane and rotating cylinder assembly excited all expected modes of the aircraft in a frequency bandwidth of 5 to 35 Hz, while the atmospheric turbulence only excited the wing's first bending mode. By using atmospheric turbulence excitation, a critical flutter mode may not be excited during flutter testing. A structural excitation system that adequately excites all modes of interest is required to verify the absence of flutter within an airplane flight envelope.

In general, the best results were obtained with 30- and 60-sec linear frequency sweeps. Shorter duration sweeps and logarithmic sweeps did not always sufficiently excite the structural modes above 20 Hz.

The vane and rotating cylinder system produced harmonics that excited modes above the primary sweep frequency and outside of the selected excitation frequency bandwidth. This had an undesirable effect in that the exciter first vane bending mode at 43 Hz was excited. The excitation of this mode could lead to high dynamic loads on the exciter vane.

Because the exciter system was mounted on the left wingtip of the aircraft, the energy distribution to the right side of the aircraft was evaluated. The symmetric and antisymmetric wing bending modes were excited well on both wingtips; however the launcher pitch mode was not excited on the right wing. In addition, modes above 20 Hz were not excited well on the side opposite the exciter. This deficiency could be overcome by adding an exciter to the right wingtip.

Overall, the relatively simple installation requirements, precise excitation control, low-power requirements, and effectiveness over a large frequency range are all aspects that qualify the vane and rotating cylinder concept as a viable solution for safer, more effective flutter testing.

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Table 1. Structural modes for the F-16XL as measured from a ground vibration test.

Mode identification	Frequency, Hz
Symmetric modes	
First wing bending	7.98
Symmetric launcher rail pitch	13.70
Control surface mode	21.74
Control surface mode	26.42
Antisymmetric modes	
Antisymmetric wing bending	10.79
Vertical fin bending	12.48
Antisymmetric launcher rail pitch	13.24
Control surface mode	20.40
Control surface mode	22.19
Control surface mode	27.05
Control surface mode	28.78

Table 2. Exciter system test matrix at an altitude of 30,000 ft.

	Linear sweeps, 5–35 Hz				Logarithmic sweeps, 5–35 Hz		Continuous dwells	
Mach	60 sec	30 sec	15 sec	7 sec	60 sec	30 sec	8 Hz	10.8 Hz
0.6	L	L	L	L	H	H	H	H
0.7	H	H	H	H	H	H	H	H
0.8	H	H	H	H	H	H	H	H
0.9	H,L	H	H	H	H	H	H	H
1.05	H,L	H,L	L	L	L	L	L	L
1.10	H,L	L	L	L	L	L	L	L
1.20	H,L	L	L	L	L	L	L	L
1.30	H	–	–	H	–	–	–	–
1.50	H	–	–	H	–	–	–	–
1.70	H	–	–	H,L	–	–	–	–

L = low-force setting (cylinder 25 percent open)
H = high-force setting (cylinder 75 percent open)

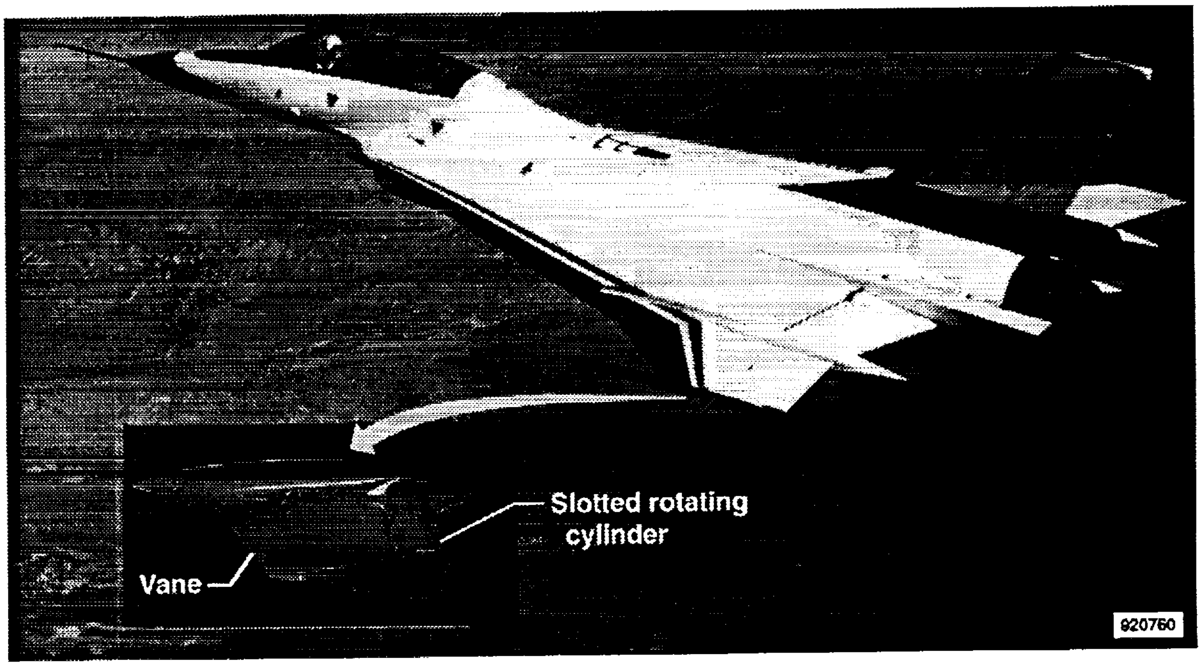

Fig. 1. F-16XL with vane and rotating slotted cylinder excitation system.

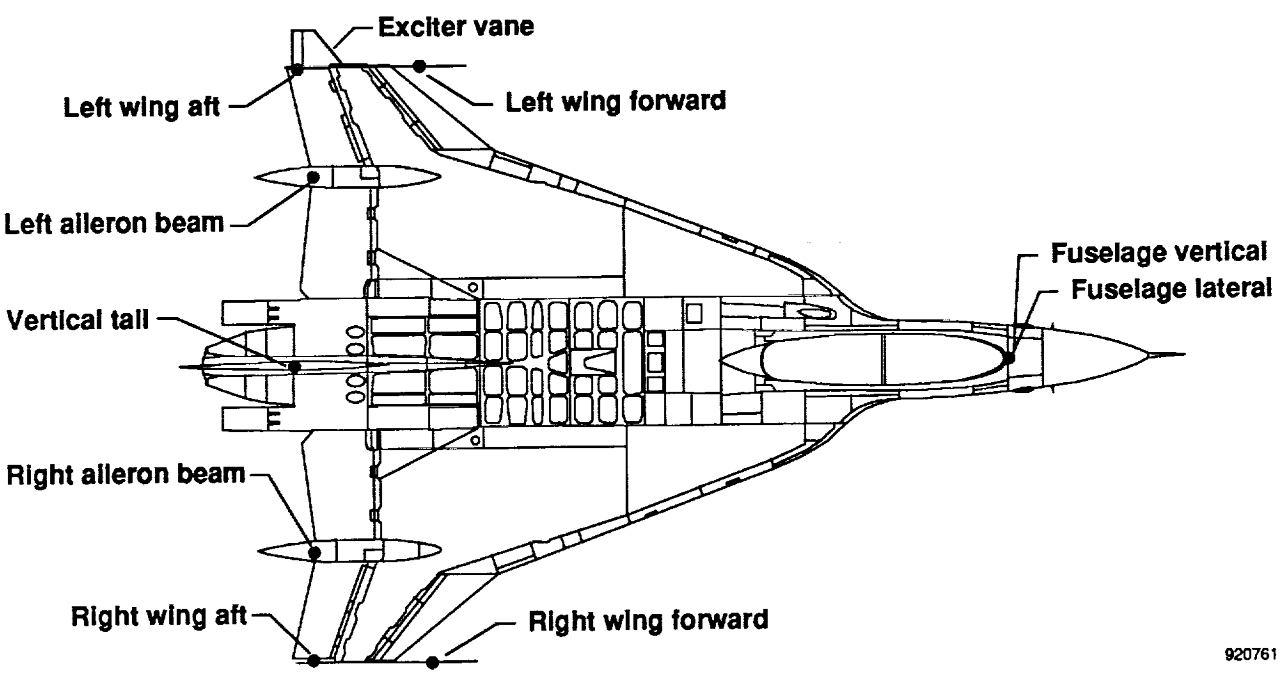

Fig. 2. Accelerometer locations on the F-16XL aircraft.

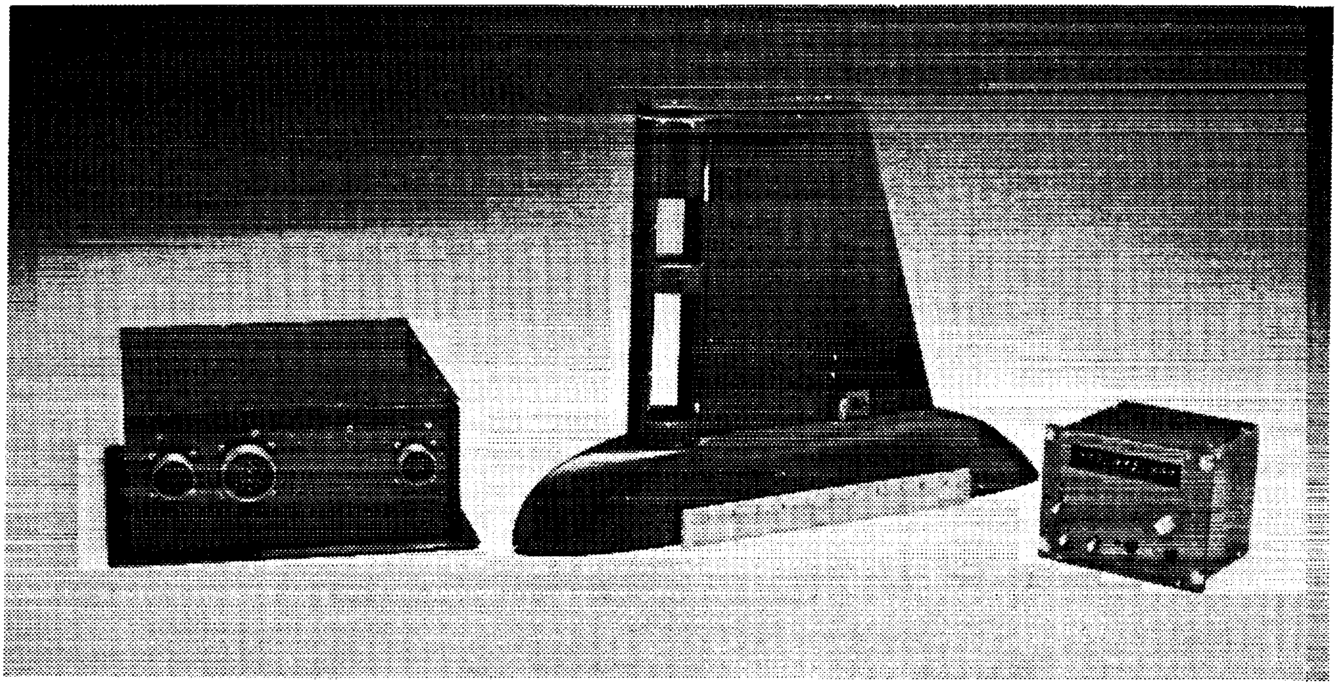

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Fig. 3. The excitation system's three components: electronics box, vane and rotating cylinder assembly, and cockpit control box.

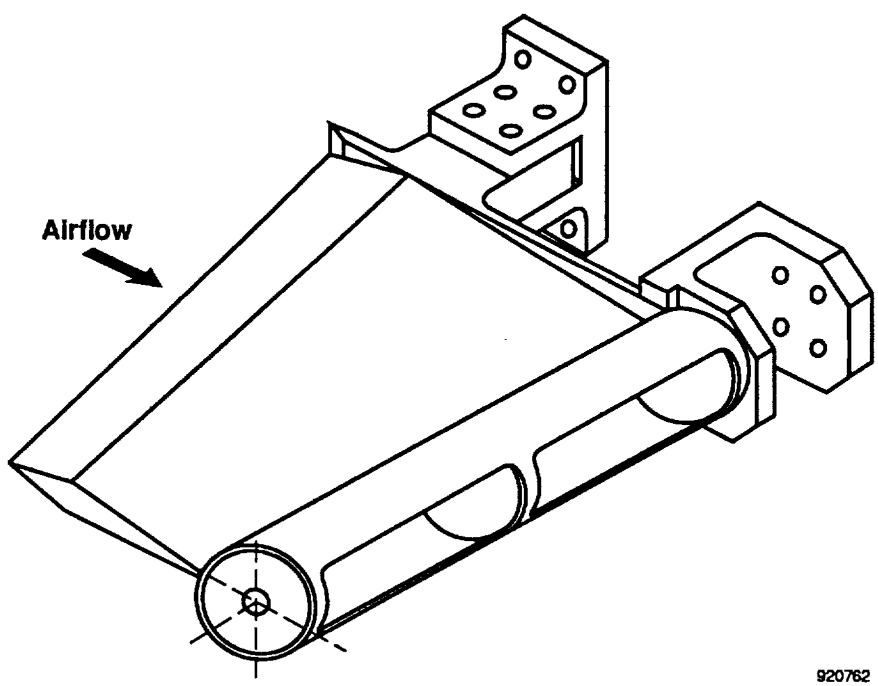


Fig. 4. Exciter vane and rotating slotted cylinder.

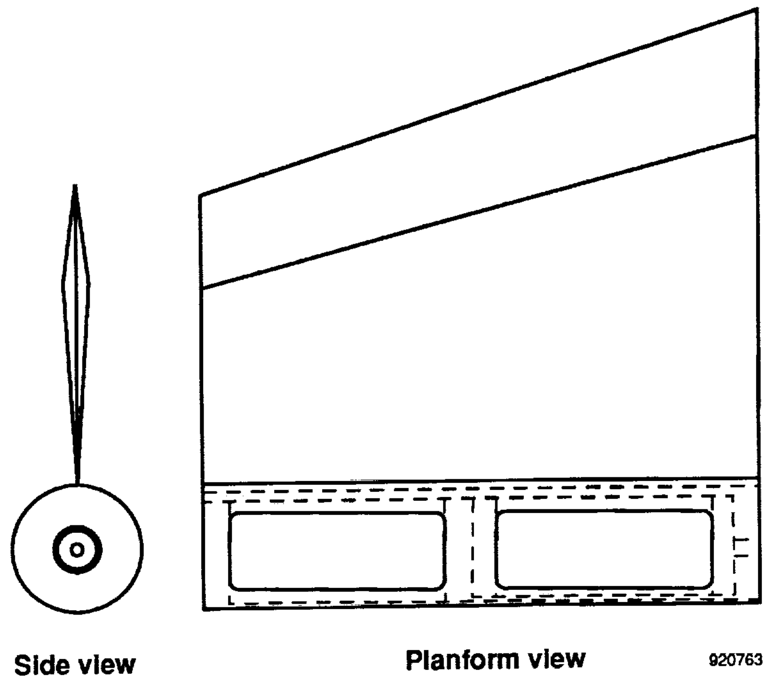


Fig. 5. Planform and side views of exciter.

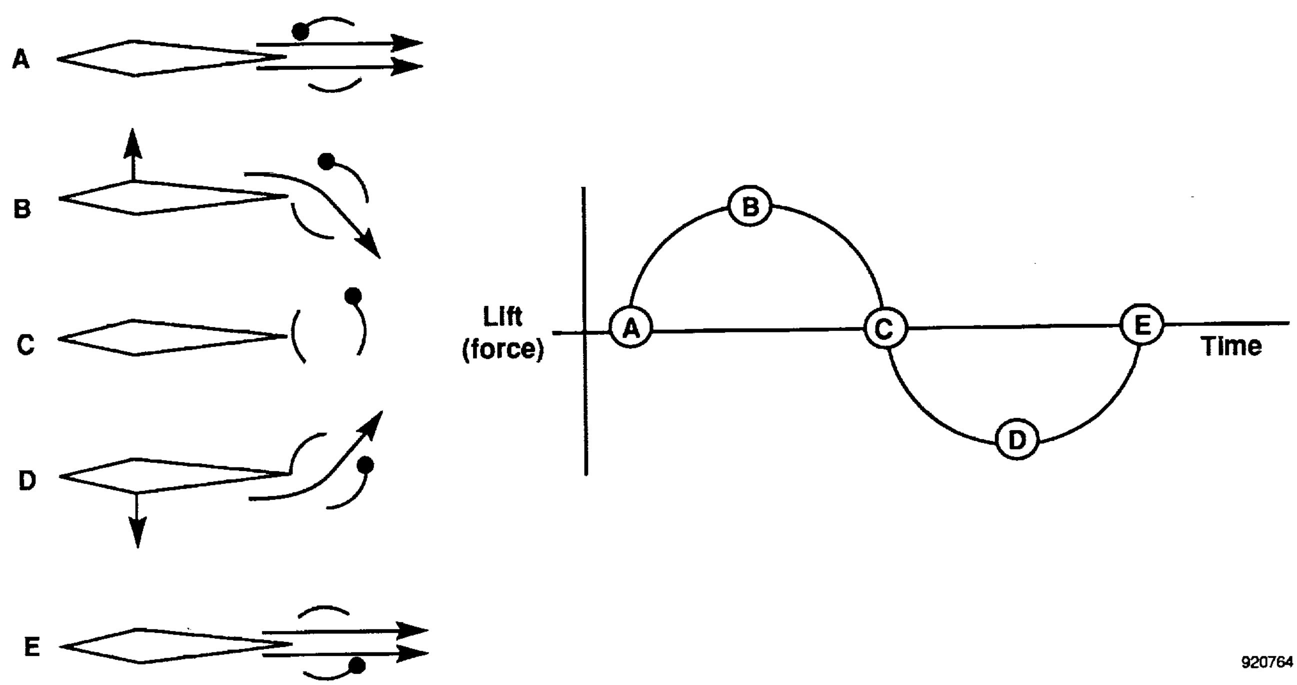
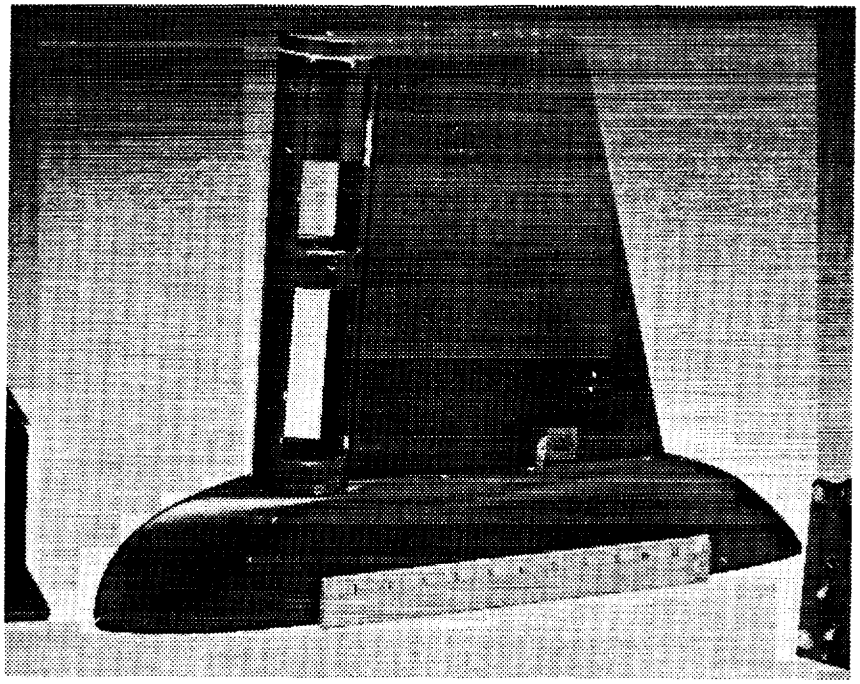


Fig. 6. Periodic lift force generated by exciter.



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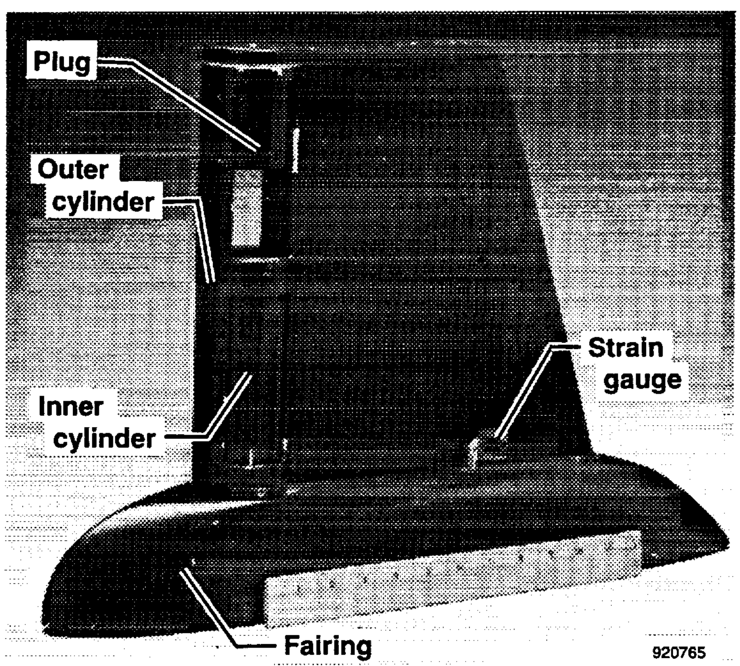
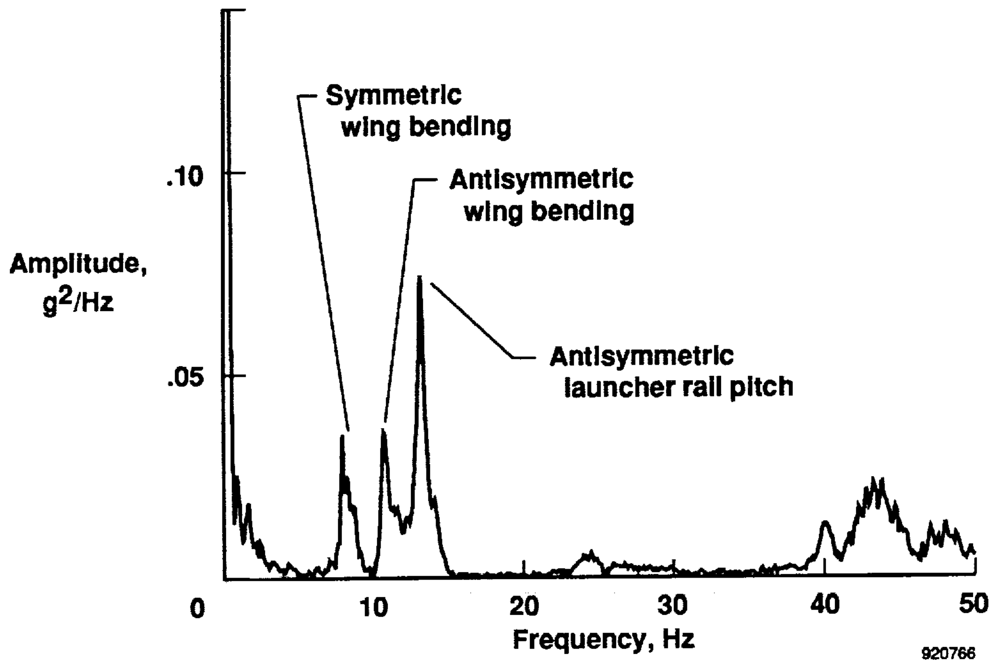
(a) High-force position.

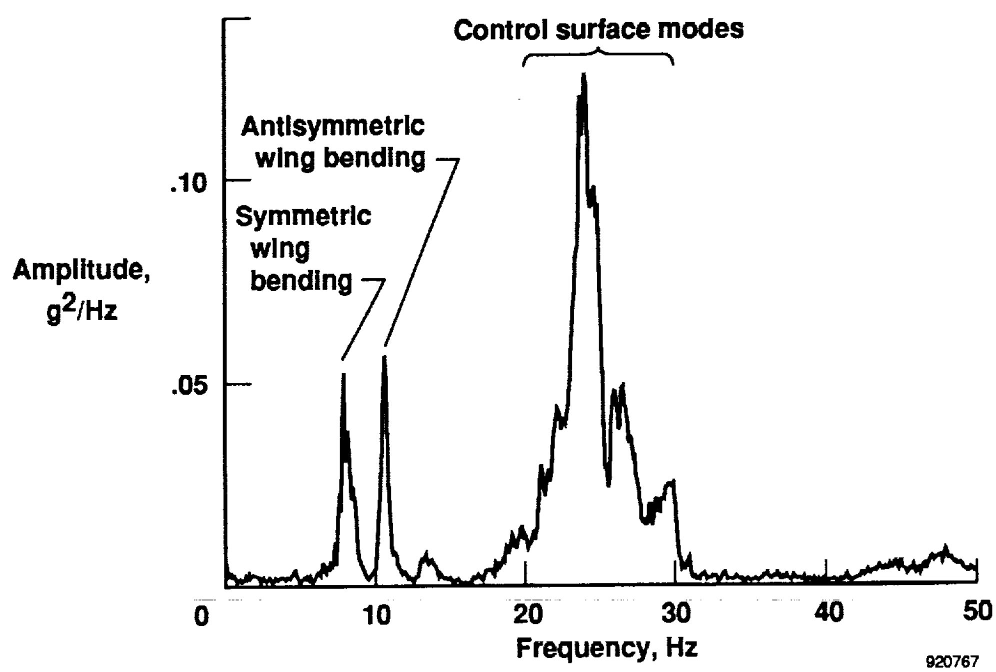


(b) Low-force position.

Fig. 7. The exciter vane with cylinders in different positions.

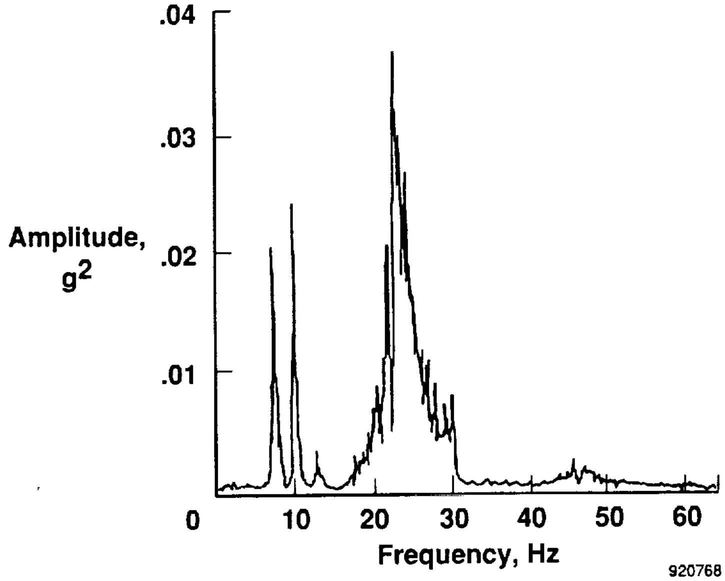


(a) Forward accelerometer.

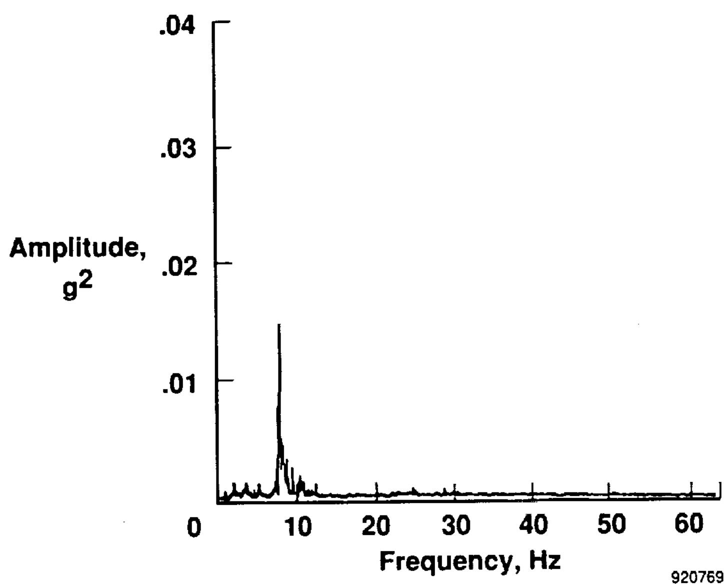


(b) Aft accelerometer.

Fig. 8. Left-wing accelerometer responses caused by linear exciter sweep, Mach 0.9 at 30,000 ft, high-force level.

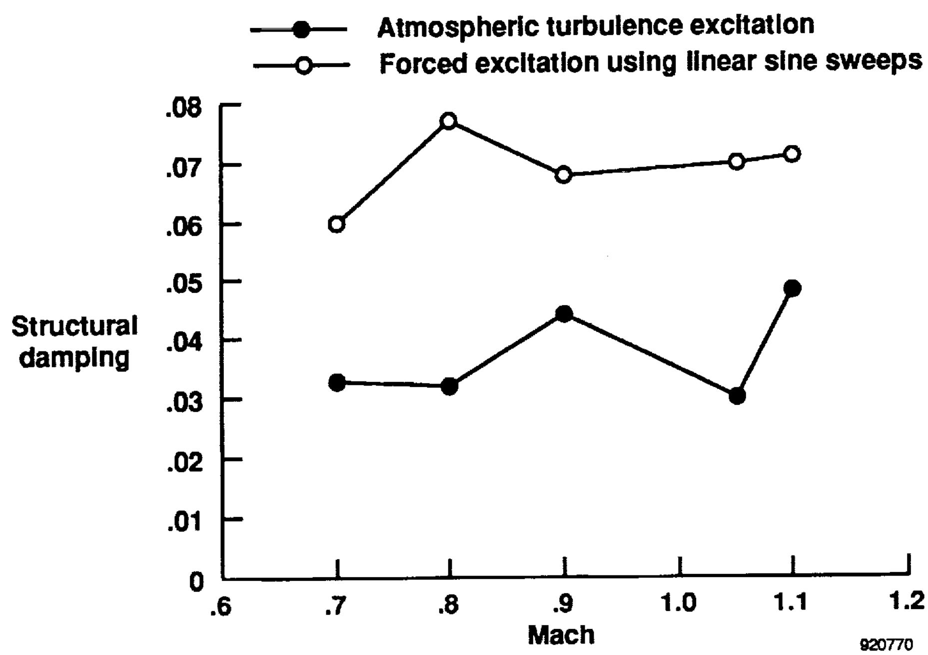


(a) Exciter sweep.

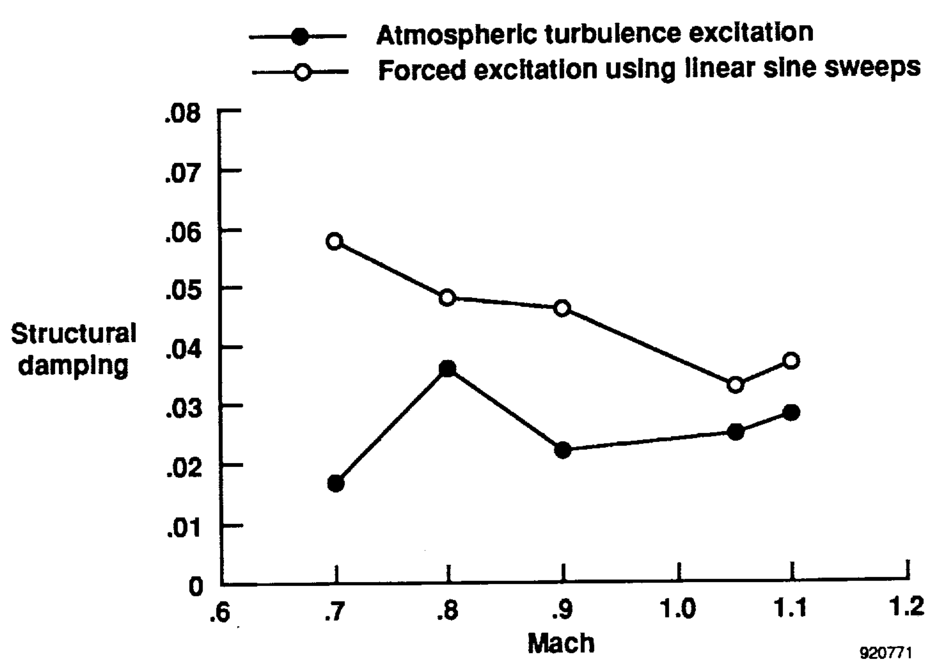


(b) Random turbulence.

Fig. 9. Comparison of excitation of the left-wing aft accelerometer at Mach 0.9 and 30,000 ft.



(a) Symmetric.



(b) Antisymmetric.

Fig. 10. Structural damping values for wing bending modes.

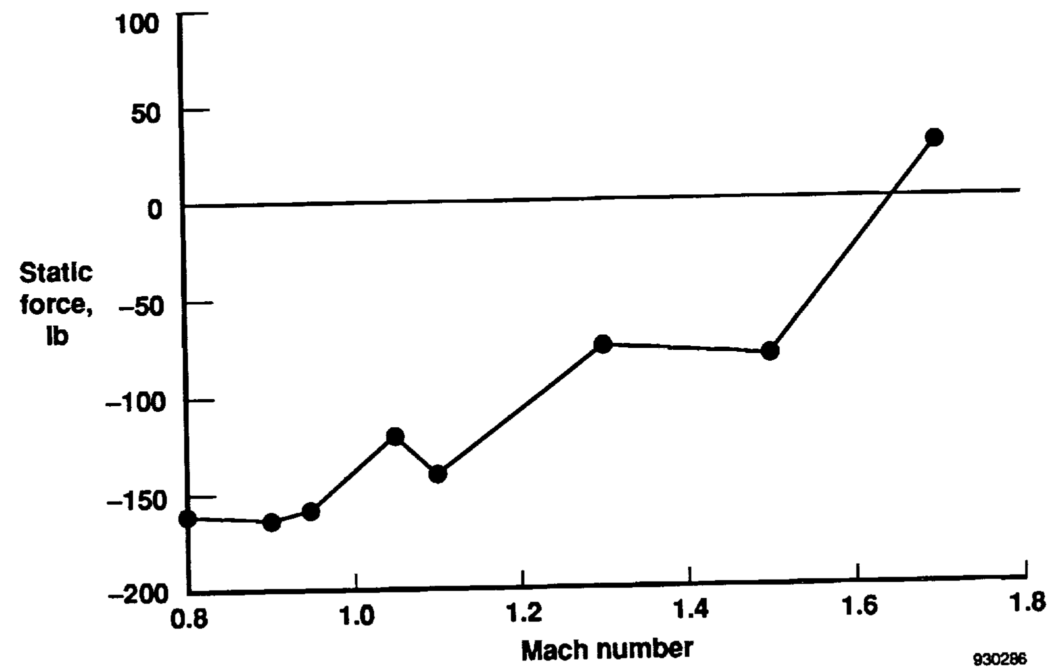


Fig. 11. Exciter static force levels at each test Mach number.

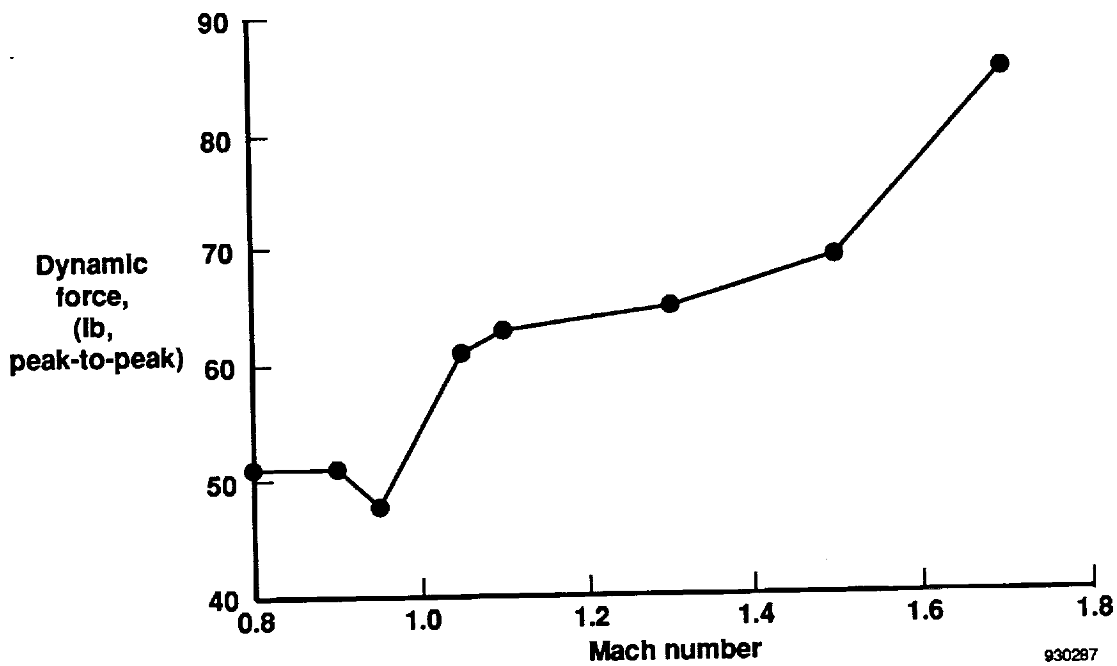


Fig. 12. Exciter dynamic force levels at each test Mach number.

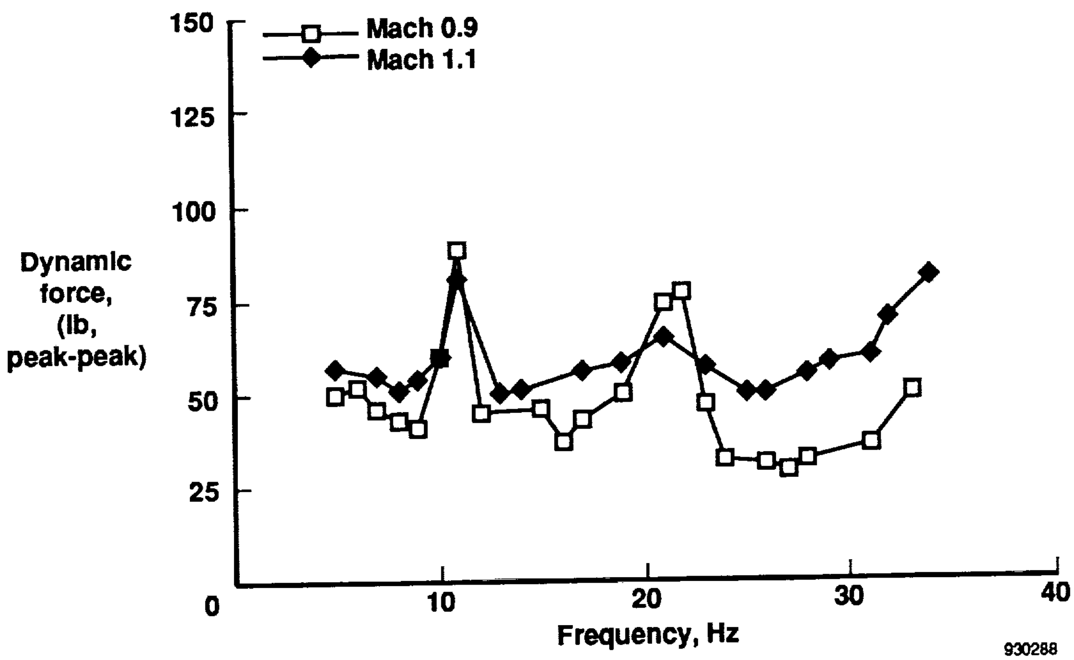
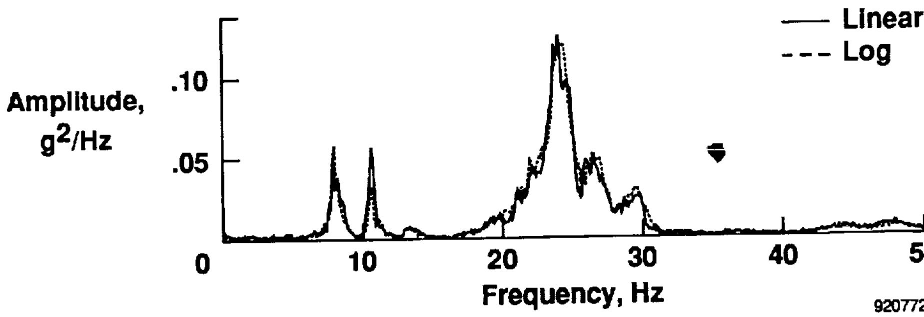
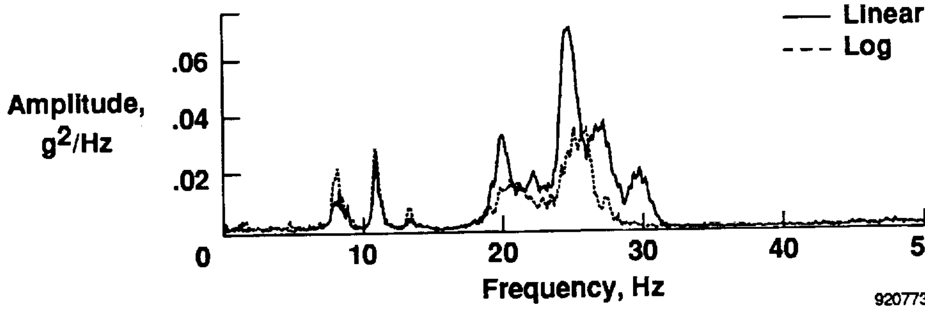


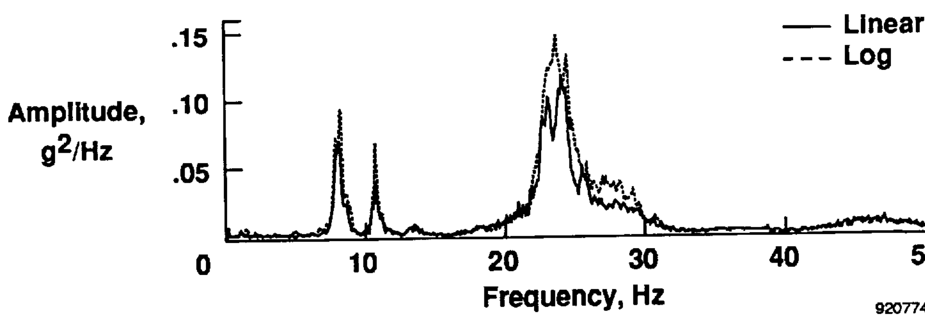
Fig. 13. Exciter dynamic force amplitude as a function of sweep frequency.



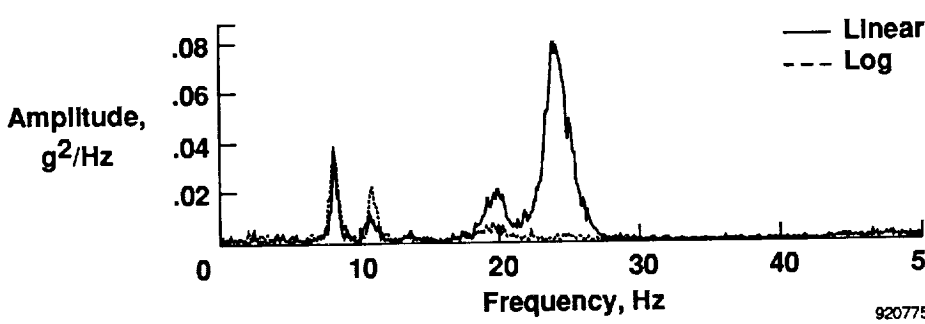
(a) Mach 0.9, 60-sec sweeps.



(b) Mach 1.1, 60-sec sweeps.

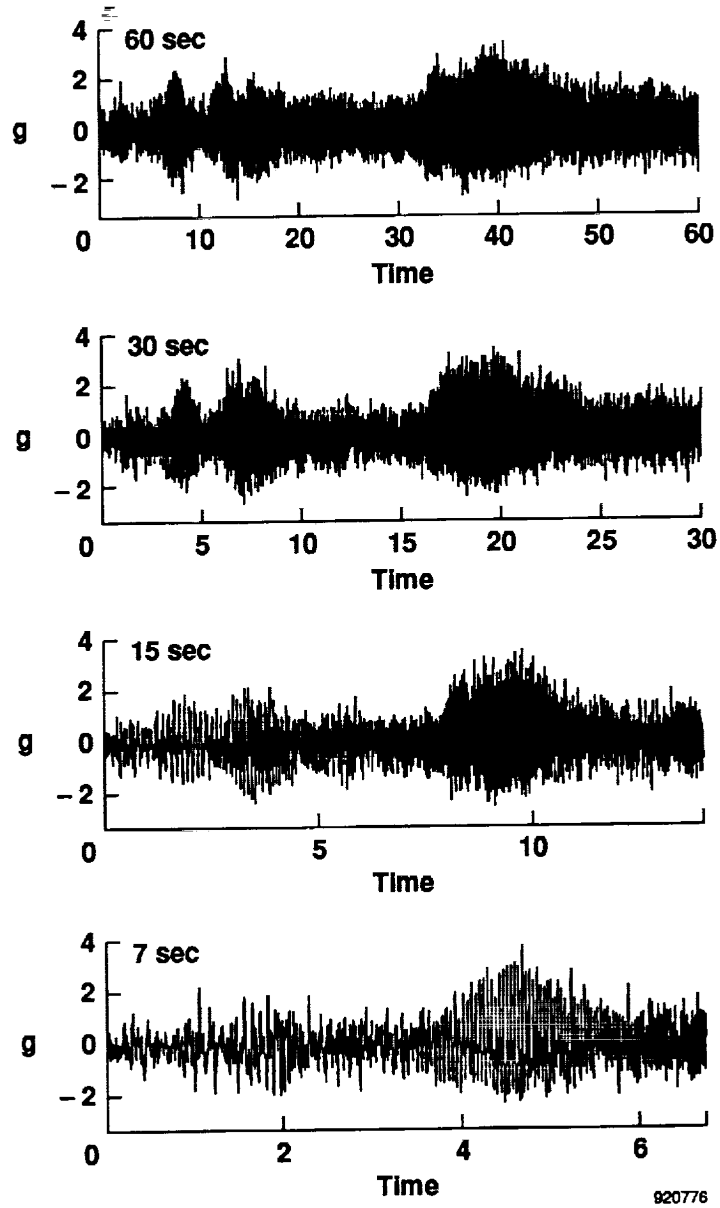


(c) Mach 0.9, 30-sec sweeps.



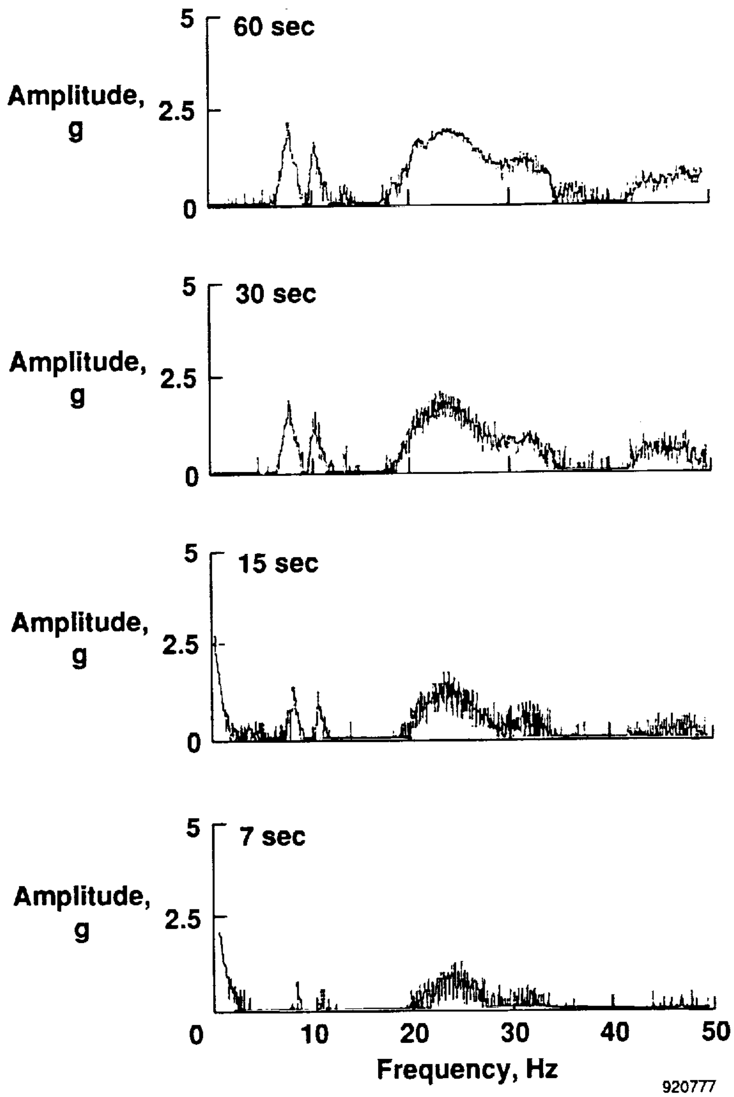
(d) Mach 1.05, 30-sec sweeps.

Fig. 14. Comparison of linear and logarithmic sweeps at various Mach numbers.



(a) Time history plots.

Fig. 15. Linear sweep duration variations, Mach 0.8 at 30,000 ft, left-wing aft accelerometer, high-force mode.



(b) Power spectral density plots.

Fig. 15. Concluded.

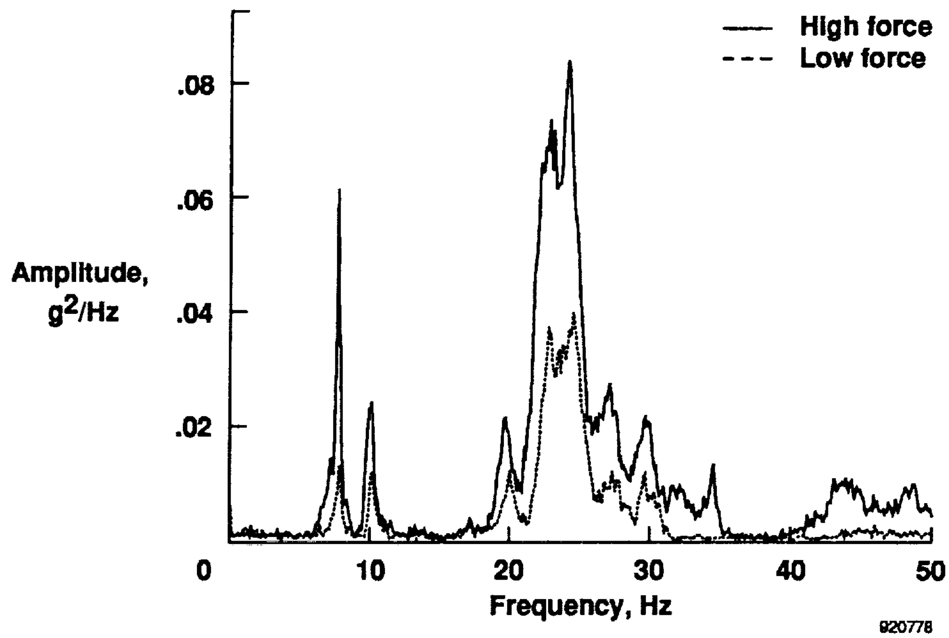


Fig. 16. Comparison of high- and low-force mode exciter sweeps, Mach 0.9 at 30,000 ft, left-wing aft accelerometer.

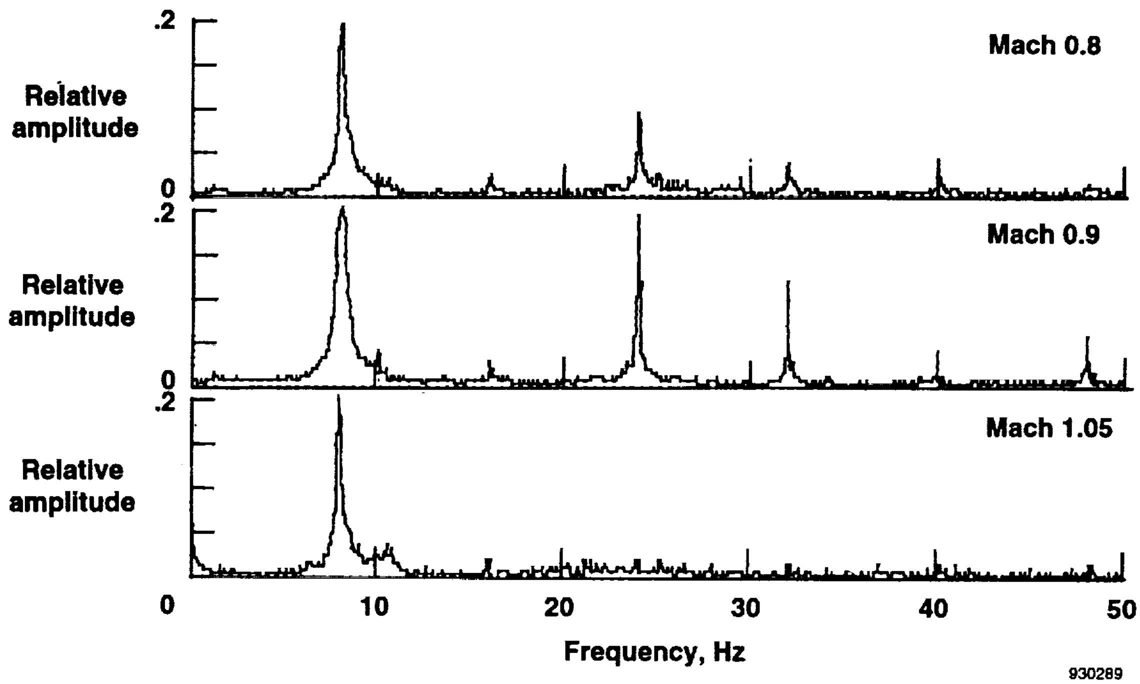


Fig. 17. Right wing aft response showing exciter harmonics from an 8.0 Hz frequency dwell.

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13. ABSTRACT (Maximum 200 words)

A research excitation system was test flown at the NASA Dryden Flight Research Facility on the two-seat F-16XL aircraft. The excitation system is a wingtip-mounted vane with a rotating slotted cylinder at the trailing edge. As the cylinder rotates during flight, the flow is alternately deflected upward and downward through the slot, resulting in a periodic lift force at twice the cylinder's rotational frequency. Flight testing was conducted to determine the excitation system's effectiveness in the subsonic, transonic, and supersonic flight regimes. Primary research objectives were to determine the system's ability to develop adequate force levels to excite the aircraft's structure and to determine the frequency range over which the system could excite structural modes of the aircraft. In addition, studies were conducted to determine optimal excitation parameters, such as sweep duration, sweep type, and energy levels. The results from the exciter were compared with results from atmospheric turbulence excitation at the same flight conditions. The comparison indicated that the vane with a rotating slotted cylinder provides superior results. The results from the forced excitation were of higher quality and had less variation than the results from atmospheric turbulence. The forced excitation data also invariably yielded higher structural damping values than those from the atmospheric turbulence data.

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