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Control-Nonlinear-Nonstationary Structural Response and Radiation near a Supersonic Jet

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This paper is on the control of nonlinear-nonstationary vibration of a frame-stringer structure resulting from high levels of excitation from a nearby supersonic jet exhaust. The structure exhibits periodic, chaotic, or random behaviors when forced by high-intensity sound from a supersonic jet exhaust with "shock" loading superimposed on a broadband response. The time history of the pressure, showing the rotation and flapping of the shock structure in the jet column due to large-scale instabilities, indicates that the response is not only nonlinear but also nonstationary. The acoustic pressure radiated by the structure also contains shocks and the formation of harmonics with distance. Control of the structural response is achieved by actively forcing the structure with an actuator at the shock oscillation frequency whose amplitude is locked into a self-control cycle. Results show that the peak power level is reduced by a factor of 63, or 18 dB. As a result, new broadband components emerge with at least four harmonics. At accelerating and decelerating supersonic speeds, the exhaust from the jet induces higher transient loading on the nearby flexible structure due to the occurrence of multiple shocks from the jet.

I. Introduction

A SUPERSONIC transport starts from takeoff, accelerates to a constant cruising speed, and then decelerates for landing. During the flight, the vehicle's surfaces, such as the fuselage, wing, and control surfaces, are forced by unsteady loading in both space and time from the boundary layer, inlet noise, jet noise, and shock noise or screech. This paper concerns a laboratory investigation of the excitation and control of structural vibration forced by a nearby supersonic jet. Accelerating, decelerating, and constant speed jets are examined. The strong coupling between the unsteady pressure from the supersonic jet exhaust and the nearby flexible structure necessitates experimental study to quantify the nonlinear behavior of both the structure and the resulting sound radiation.

In his early experiments on jet noise, Powell[1] recognized that the instability of the jet column due to the feedback loop between fluid flow and sound is the cause of a powerful acoustic tone. Later works by Lassiter and Hubbard,[2] Westley and Lilley,[3] Westley and Wooley,[4] Norum,[5] Harper-Bourne and Fisher,[6] Dosanjh et al.,[7] Seiner,[8] Seiner et al.,[9] Tam et al.,[10] Tam,[11] Ponton and Seiner,[12] Ponton,[13] and Powell et al.,[14] as well as others, showed that the self-excited oscillation involved the transfer of energy from one wave to another and the spinning of the shock cells associated with the large-scale instability and sound. These are the sources causing nonlinearity due to periodic doubling and shock harmonics and nonstationary effects due to amplitude modulation in the structural vibration and in the resulting acoustic radiation.

Early experiments on the control of the noise from jets were started in England by Westley and Lilley[3] and in the United States by the Boeing and Douglas companies. Also, early theory on the noise produced by shock-turbulence interaction was reported by Ribner[15] and Ram and Ribner.[16] Controlling the noise produced by the jet, rather than controlling the response of the structure excited by the noise of the jet, is being investigated by Maestrello[17] using a porous plug nozzle.[18] The shock-free nozzle reduces the structure response and the acoustic radiation levels significantly. Because of the distributed porosity on the plug, the shock structure is weakened. Controlling the noise using a plug-type nozzle had been investigated earlier by Dosanjh et al.,[7] and recently, also using a porous plug, by Kibens and Wlezien[19] and Das and Dosanjh.[20]

The most significant aircraft maneuvers are those with variable rather than constant speeds. Hence, it is essential to examine the time-varying jet velocity due to the changing mass flux, with the formation and the dissipation of shocks, resulting from the change in aircraft speed.[21] Theoretical analysis for structural acoustic interaction with a panel in unsteady motion was initiated by Ting.[22] Previous work on nonlinear waves penetrated on a structure were reported by Dowell,[23,24] Vacaitis et al.,[25] Nayfeh,[26] Ginsberg,[27] Maestrello et al.,[28] and Frendi et al.,[29] as well as others. This work shows that the changes in response behavior are due to the changes in input conditions triggered either naturally or by the modulation of the incident waves.

This paper deals with an experimental study of aircraft-type structural vibration forced by acoustic waves from a supersonic jet. A model jet is used with a full-scale frame-stringer structure. The response of the structure at constant supersonic jet speed as well as accelerated and decelerated speeds is studied experimentally. The paper also deals with active control of the structure response induced by the acoustic load, including shocks (shock noise from a jet or screech as referred to by Powell). Control is obtained by actively changing the amplitude, frequency, and phase of a periodic point load on the structure. The technique developed for the control is based on the feedback loop and has been used to control high-amplitude turbulence triggered by a pure tone acoustic incident wave (Maestrello[30,32]). The controller is adaptable to follow the nonlinear behavior of the oscillation. Other techniques to control nonlinear systems have been developed by de Figueiredo and Chen[33] and Auerbach et al.[34]

II. Experimental Apparatus

The experimental investigation of sound from a jet exciting a structure was carried out inside an anechoic chamber. The structure consists of six full-size aluminum aircraft-type panels, 18 × 7 × 0.040 in., with frames and stringers, mounted on

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a rigid baffle and placed in the vicinity of the jet exhaust (Fig. 1). The baffle is inclined at an angle of 12 deg with the jet axis such that the jet plume will not interact with the baffle. The structure represents a section of a full-scale aircraft sidewall. A convergent nozzle with diameter $D = 2$ in. is used at a constant pressure ratio, p_o/p_a, of 3 and stagnation temperature of 520°R, with corresponding Reynolds number $UD/\nu = 1.3 \times 10^6$ and Strouhal number $fD/U = 0.28$, where p_o and p_a are the stagnation and atmospheric pressure and f is the shock frequency. Experiments are also initiated for constant accelerating and decelerating jet velocities.

The acoustic pressure radiated from the jet and from the structural vibration is measured by arrays of unvented, phase-amplitude matched pressure transducers capable of dc response. The vibration response of the structure is measured by strain gauges located at the midpoint of the top, bottom, and side edges of the panels, as well as on the adjacent stringers.

The measurement locations are shown in Figs. 2 and 3. An array of pressure transducers is placed along the jet axis at an angle of $\varphi = 12$ deg. The transducers are placed 3.0 in. apart

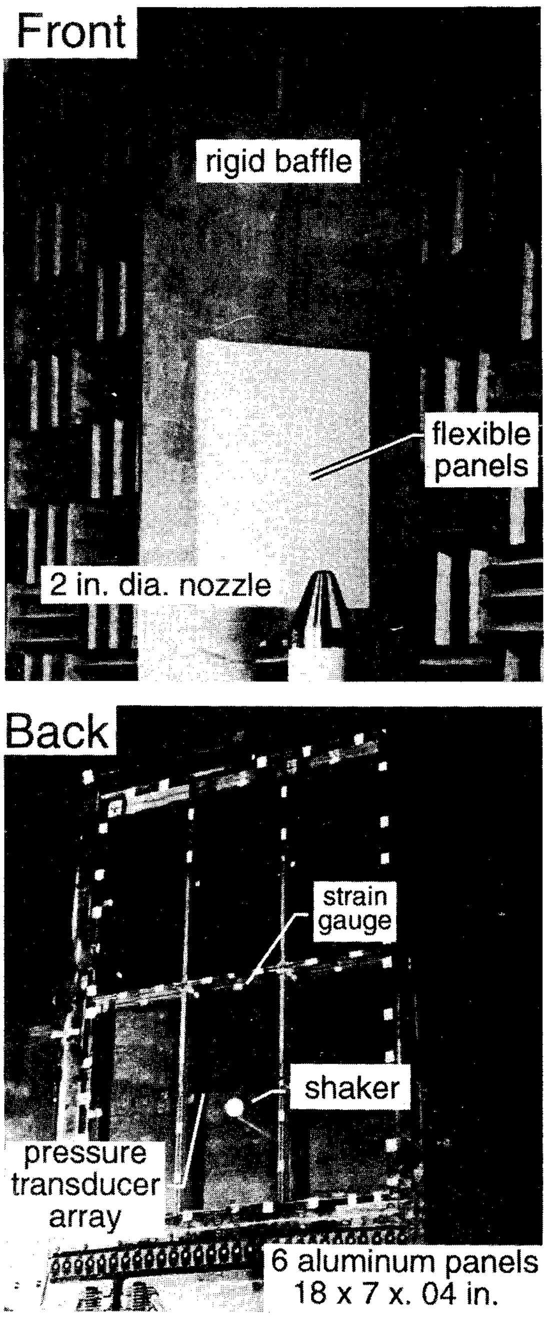

Fig. 1 Frame and stringer structure.

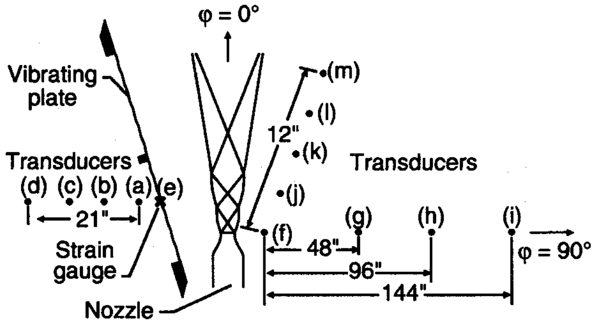

Fig. 2 Experimental setting.

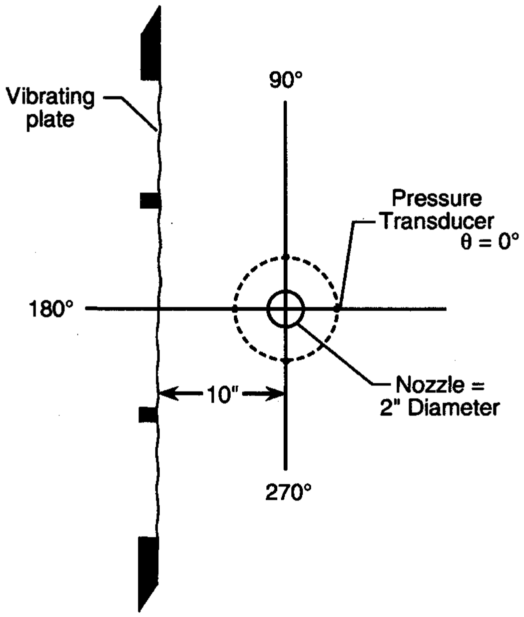

Fig. 3 Pressure transducer around the nozzle at $\varphi = 90$ deg.

from location (f) to (m). The transducer (f) is positioned at the nozzle exit plane (Fig. 2). The second array of transducers stretches 72 nozzle diams between the near field and the far field at $\varphi = 90$ deg. The first transducer is located at position (f) and the last at position (i). The third array is placed around the nozzle exit at $\varphi = 90$ deg. The transducers are located at $\theta = 0$, 60, 90, 120, 180, and 270 deg (Fig. 3). The fourth array of transducers, (a) to (d), is used to measure the acoustic pressure transmitted via the structure and is located behind the bottom-center-lower panel (Fig. 2). The first transducer, (a), is placed 1 in. from the center of the panel. A strain gauge is placed at the midpoint of the top edge of the panel (Fig.1). This is the most sensitive location for capturing the passage of the shock during a rotation and flapping cycle.

The active control method used concentrates on actively reducing the response of the lower center panel measured by the strain gauge during the passage of the shock. This is achieved by using a shaker freely suspended by a string from its center of mass such that the horizontal load supplied by the shaker to the panel is independent of the mass of the shaker. The strain gauge is placed in line with the shaker in the direction of the jet axis (Fig. 1). The shaker is activated by a feedback loop from the strain gauge supplemented by dc bias and a phase filter (Maestrello[30]). A versatile feedback control mechanism is adopted. This mechanism chooses the highest amplitude in each shock cycle and then forces the panel response to follow the chosen orbit in the phase plane by the application of shaker loading. The feedback loop consists of a feedback signal from a strain gauge, a bandpass filter, a phase filter capable of shifting the phase continuously from 0 to 360

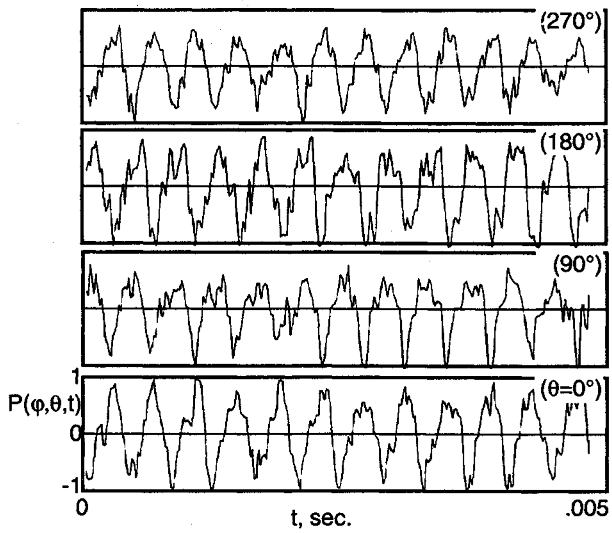

Fig. 4 Instantaneous near-field pressure about the nozzle exit at $\varphi = 90$ deg, between $\theta = 0$, 90, 180, and 270 deg.

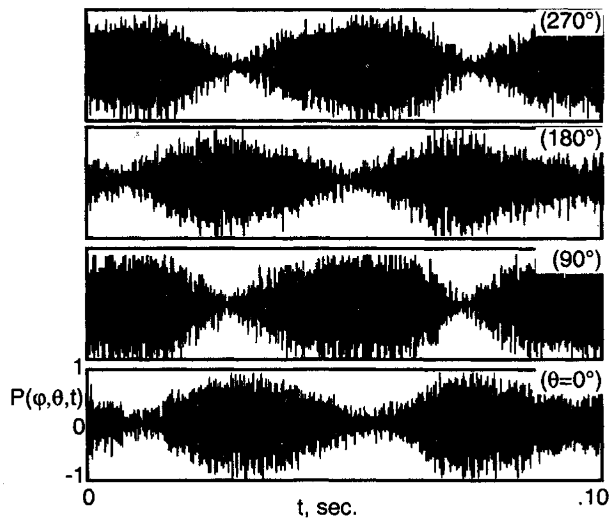

Fig. 5 Instantaneous near-field pressure about the nozzle exit at $\varphi = 90$ deg, between $\theta = 0$, 90, 180, and 270 deg.

deg, and a power amplifier. Although this feedback circuit is the same in principle as that used previously, several modifications were made to improve the controller's dynamic range.

III. Sound Radiation from the Jet

The investigation of the acoustic pressure radiated from a jet at a pressure ratio of 3 is carried out in two parts. The first part contains information on the nearfield, whereas the second part contains the wave propagation to the far field.

Near-Field Pressure

Figure 4 shows the pressure fluctuation in real time at $\varphi = 90$ deg, $\theta = 0$, 90, 180, and 270 deg for a short time interval of 0.005 s. Extensive measurements are reported in Ref. 31 for different azimuthal angles and different times. The data show that the occurrence of peaks and valleys is nearly periodic, but the waveform is not. We can trace the occurrence of a peak (or valley) at different angular locations and illustrate the rotation or the asymmetry of the shock wave from the jet. In the data of short time intervals, we do not see any regularity in the rotation of the trace of the peaks in the circumferential direction or correlation in the pressure fluctuations at different θ.

Figure 5 shows the pressure fluctuations in the same locations as Fig. 4c, but over a much longer interval of 0.1 s, 50 times longer than that in Fig. 4c. In Fig. 5, we see that the envelope of the pressure fluctuations is nearly periodic in time, and there is good correlation between the data at two diametrically opposite points, $\theta = 0$, 180 and 90, 270 deg. This suggests a flapping motion in the jet. This phenomenon will be further illustrated by the power spectrum, phase, probability, and coherence analyses shown in Figs. 7 and 8. Further evidence has been given by Ponton,[13] Ponton and Seiner,[12] and Westley and Wooley.[4]

Figure 6 shows the real-time pressure fluctuation in the meridian plane, $\theta = 0$, at stations (j) to (m) along a line parallel to the jet surface (see Fig. 2). The time interval in Fig. 6 is 0.1 s and has many oscillations. The figure shows the envelope of the oscillations in a time interval of 0.012 s, indicative of very low rotational speed toward the nozzle from downstream between (m) and (j), whereas in the upstream direction between (j) and (m), the envelope indicates a much larger rotational velocity with a time interval of 0.003 s. This winding and unwinding motion of the jet column comes through amplitude and bandwidth changes due to the spreading of the shear layer as the velocity varies. The slow drift of the modes could be attributed to the convection rotation and counter-rotation effects, a result of the helical modulation of the pressure field. One pattern observed is a spontaneous, randomly occurring switch from a clockwise-dominated mode to a counterclockwise-dominated mode, leading to partial rotations (clockwise or counterclockwise) of the helical modes, shown also by Ponton[13] and Westley and Wooley.[4]

Two apparently different instabilities have been observed. These are 1) a rapid flapping or pulsation of the jet to each side and 2) a helical disturbance propagating along the jet column. The flapping can be expressed as a pulsation of the jet boundary of the form $r = D/2 + \eta(t, x, \theta)$, where η represents the position-dependent deviation of the jet boundary. Typically η varies abruptly as θ varies around the jet, leading to a flapping motion of the jet column. This is illustrated in Figs. 5 and 6. The second instability, that of slowly modulated helical modes, is manifested by pressure disturbances propagating along the jet column in a helical fashion. This phenomenon can be modeled by assuming that the pressure fluctuation has a slow periodic modulation. In cylindrical coordinates, $\tilde{x}$, $\tilde{r}$, and θ can be represented by the functional forms

$$P_{\pm} \approx A_{\pm}(t, \tilde{r}, \tilde{x}, \theta) e^{i(\omega t \pm \theta)} + \text{complex conjugate} \tag{1}$$

where $A_{\pm}$ depends only weakly on t and θ, corresponding to counterclockwise and clockwise waves. Since the observation

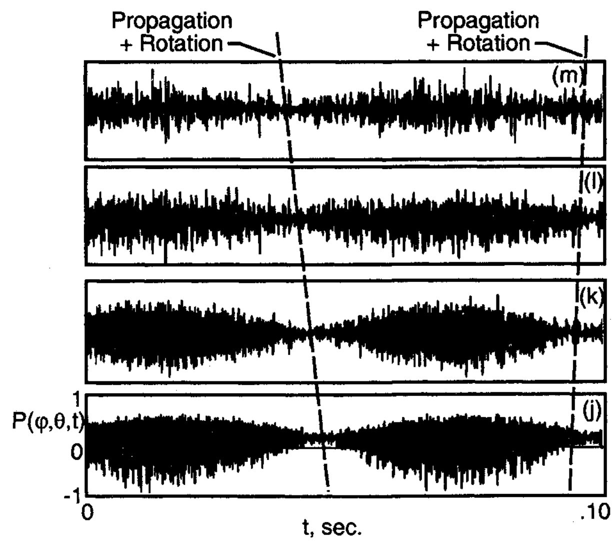

Fig. 6 Instantaneous near-field pressure along the jet column, $\varphi = 12$ deg. See Fig. 2.

remains fully correlated only for points 180 deg apart, we consider only the first mode of θ.

Because the measurements of the pressure were made at the edge of the jet, ($r \gtrsim D/2$), we first neglect r in the form of Eq. (1),

$$P_{\pm} \approx A_{\pm}(t, \tilde{x}, \theta)e^{i(\omega t \pm \theta)} + \text{complex conjugate}$$

Measurements suggest that the pressure has a helical form as x varies along the jet column. We model this by

$$P_{\pm} \approx A_{\pm}(t + \kappa\tilde{x}, \theta) \exp\{i[\omega(t + \kappa\tilde{x}) \pm \theta]\} + \text{complex conjugate}$$

where κ represents the degree of winding of the helix. Here we assume that the modulation depends on the convected coordinate $t + \kappa\tilde{x}$. Setting $r = t + \kappa\tilde{x}$, i.e., transforming to a moving frame, we have

$$P_{\pm} \approx A_{\pm}(r, \theta)e^{i(\omega r \pm \theta)} + \text{complex conjugate} \qquad (2)$$

The experiments indicate that the modulations generally depend weakly on r, θ and are generally unequal. This suggests that $A_{\pm}$ may evolve according to coupled, complex, nonlocal, Ginszburg-Landau equations that have been derived in other applications, e.g., Matkowsky and Volpert.[35] These equations exhibit a variety of complex spatial and temporal patterns, in particular, shocklike behavior and chaotic dynamics (Aranson et al.[36]).

Additional data from different runs for the pressure fluctuations at the same set of stations show that the rates of rotation (or counter-rotation) and flapping are irregular and

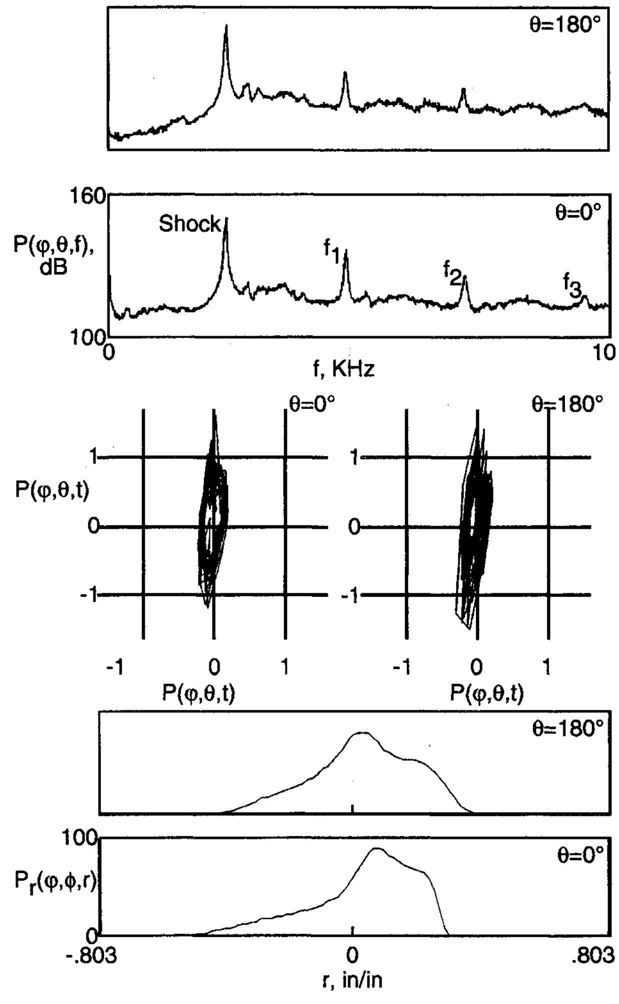

Fig. 7 Power spectral density, phase, probability of the pressure at the nozzle exit, $\varphi = 90$ deg.

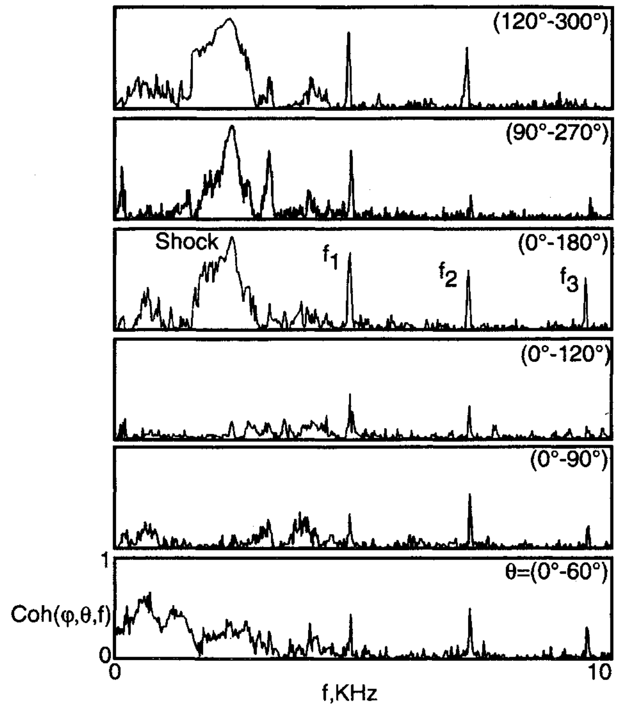

Fig. 8 Coherence of the pressure at the nozzle exit, $\varphi = 90$ deg.

different from those shown in Figs. 4–6. Therefore, these figures give only a qualitative description of the phenomenon. Similar tests made for the jet alone (without the panels) show the same near-field pressure fluctuation. This indicates that the panel is sufficiently far away from the jet and has no significant effect on the near-field behavior of the jet. In fact, the near-field behavior for a jet alone was observed in early experiments by Ponton[13] and Westley and Wooley.[4] They suggested that this behavior was caused by rotating helices and spinning shock cells. Since 1962, Davies and Oldfield[37] have identified two distinct modes of oscillation: one emitting axisymmetric sound and the other emitting antisymmetric sound, coupled to helical disturbances in the jet. Chan and Westley[38] were able to calculate the near field and the strength of the convected wave with remarkable accuracy in the manner suggested by Ribner.[39] Recently, noise from choked jets has been reviewed by Powell et al.[14] who originally identified the screech tone sound.

The corresponding pressure power spectral density $P(\varphi, \theta, f)$, the phase $P(\varphi, \theta, t)$ and $\dot{P}(\varphi, \theta, t)$, and probability plots $Pr(\varphi, \theta, r)$, at two stations, $\theta = 0$ and 180 deg, are shown in Fig 7, where $\dot{P}$ indicates the time derivative of the pressure. The power spectrum shows the presence of shock and higher harmonics superimposed on a broadband response. The phase plots are skewed, indicative of rotation in the azimuthal plane similarly observed in the previous real-time data. The probability plots indicate that the pressure has a nonzero mean, whereas the skewness indicates once more the jet column rotation.

Additional knowledge of the pressure fluctuation at the jet exit came from the coherence measurement about the azimuthal plane, $\varphi = 90$ deg, in Fig. 8. The coherence function $\mathrm{Coh}(\varphi, \theta, f)$ at four pairs of angular positions, $\theta = 0$ and 60 deg, 0 and 90 deg, 0 and 120 deg, and 0 and 180 deg, and two additional pairs, $\theta = 90$ and 270 deg, and 120 and 300 deg, show that the pressure is coherent only at a 180-deg interval around the nozzle exit. This confirms the flapping motion of the jet column noted from Fig. 5.

Far-Field Pressure

The wave propagation to the far field is captured by an acoustic array in the space domain over time. The nonlinear

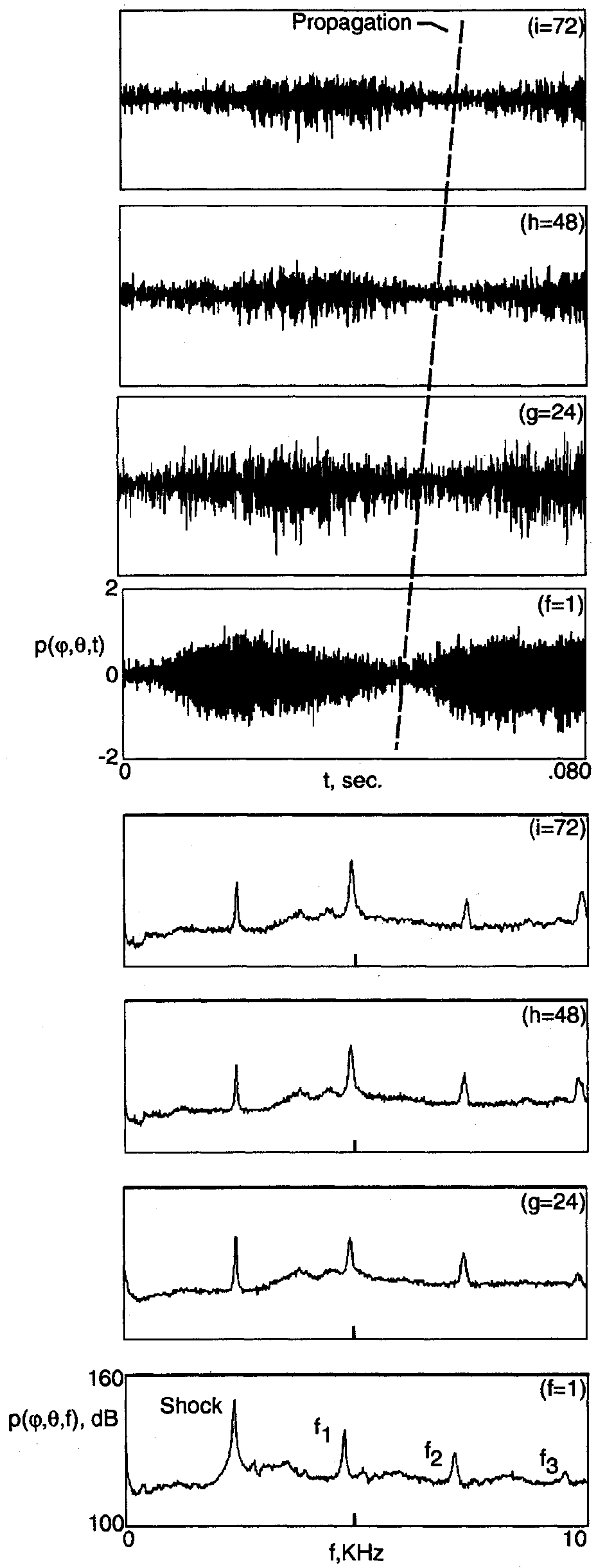

Fig. 9 Radiated pressure field of the jet, $\varphi = 90$, $\theta = 90$ deg, at 1, 24, 48, and 72 nozzle diameter; instantaneous and power spectral density plots.

wave propagation and shocks are observed at $\varphi = 90$ deg and $\theta = 0$ deg by four pressure transducers placed at 48-in. intervals 144 in. from the jet (from 1 to 72 nozzle diam) (Fig. 2). Real-time pressure and power spectral density are shown in Fig. 9. The nonlinear-nonstationary behaviors observed in the near field at the exit plane, shown in Fig. 7, are observable in Fig. 9 from the near field to the far field. The temporal modulation of the amplitude and the phase shift toward the far field are shown in the real-time plots. The corresponding spectrum plots show that the amplitudes of the higher harmonics relative to the fundamental mode increase with distance. The amplitude modulation is also maintained over a large distance. We are not aware of similar experimental observations made previously, for both near field and far field. However, the present near-field measurements are consistent with those of Westley and Lilley,[3] Westley and Wooley,[4] and Ponton.[13] Observations on the energy transfer from the fun-

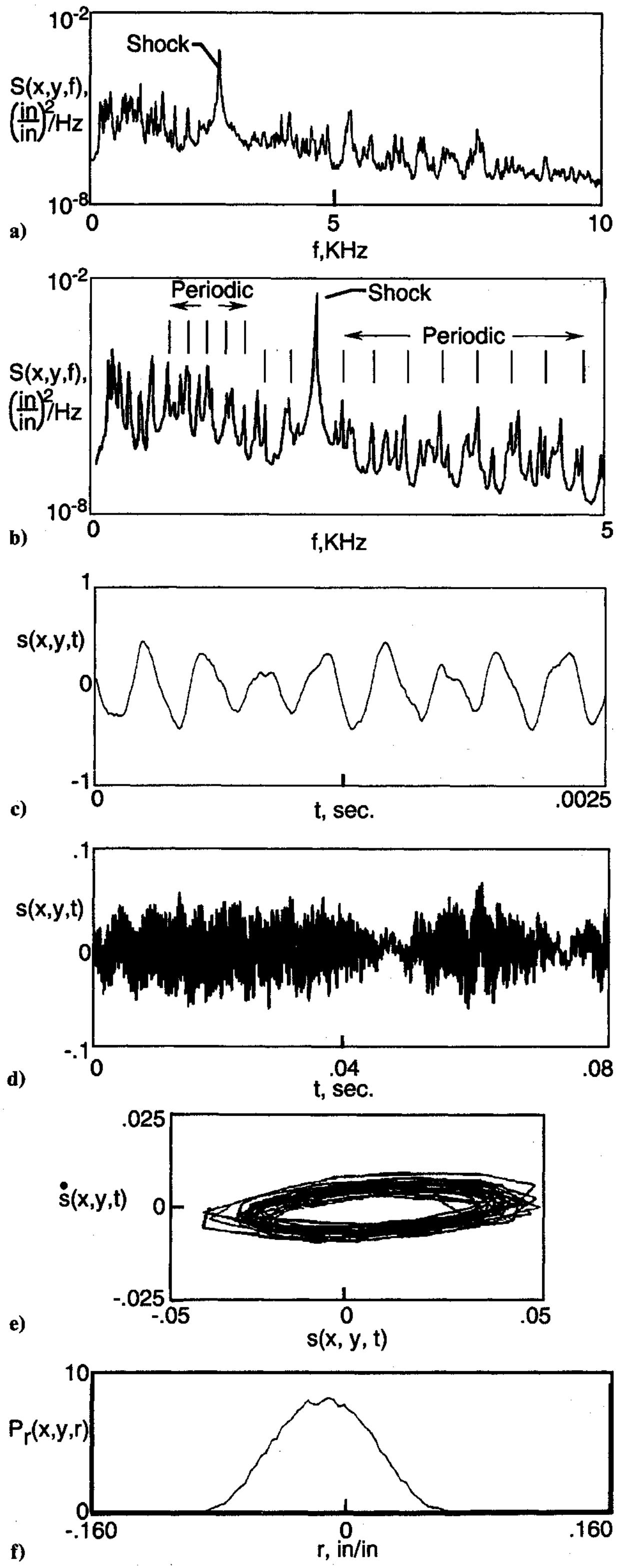

Fig. 10 Panel strain: a) power spectral density, b) power spectral density, c) time history, d) time history, e) phase plane, and f) probability.

damental into the harmonics as the distance increases were discussed by Blackstock[40,41] and recently by Nayfeh,[26] Ginsberg,[27] Foda,[42] Lauterborn and Parlitz,[43] Frendi et al.,[29] and Lighthill.[44] In an actual engine installation, there are interests in the noise generation by the jet reaching the far field, as well as noise and response from structural oscillation induced by the acoustic waves from the jet.

Powell[1] described the screech process as a feedback loop consisting of flow disturbances and a sound wave. Recently, this mechanism has been associated with the nonstationary effects in the jet column. Results from experiments, shown in Figs. 5, 9, and 10d, illustrate the phenomena of self-excitation associated with the transfer of energy from one wave to another at the nozzle exit. Results indicate that jet noise in the presence of shocks is far more complex than previously described. The mechanism is rich in variety of dynamical behavior, including periodicity and chaotic behaviors. Thus, the jet flow-noise problem, with unsteadiness, nonlinearity, etc., is a challenge to be met.

IV. Response of and Sound Radiation from the Structure

Determining the energy input and the power output of the panel motion requires information about the real-time events over the entire structure (Dowell[24] and Ginsberg[27]). In our preliminary experimental work to estimate these quantities, we used a distributed array of pressure transducers between the jet stream and the structure. To avoid interference between the transducers and the structure, we used a single pressure transducer to establish the relationship in real time between pressure input, panel response, and radiation field output. These results are discussed later.

The strain response exhibits broadband behavior with a sharp, distinct, high-amplitude spike due to shock impingement. The power spectral density, $S(x, y, f)$ vs f; amplitude in real time, $s(x, y, t)$ vs t; phase, $s(x, y, t)$ vs $\dot{s}(x, y, t)$, where $\dot{s}$ indicates the time derivative of the strain; and probability, $Pr(x, y, r)$ vs r, are shown in Fig. 10. The strain gauge response is dominated by the shock-induced oscillation, as shown in the spectra (Figs. 10a and 10b) and in the phase plots (Fig. 10e). The strain is measured at two different time intervals and different bandwidths, from 0 to 5 kHz and 0 to 10 kHz. The results show that the two independently measured spectra exhibit different dynamics; one is characterized by random broadband or chaotic behavior with shock, whereas the other is characterized by periodic response behavior with shock. The panel responds with either one or the other of the two behaviors, whereas switching occurs within the rotation and flapping of the shear layer. As shown previously, the acoustic pressure from the jet is also nonlinear. In addition, Figs. 10c and 10d show the real-time plots. Figure 10c shows the strain variation in a short duration of 0.0025 s, resolving the structural response due to shock impingement. Figure 10d shows the strain response over a longer time interval of 0.08 s, resolving the slow modulation of the panel response due to the rotation and flapping of the jet column. As a result of the modulation, the panel response is not only nonlinear but also nonstationary. The modulation period varies slowly with time due to the random flapping of the jet column. The probability shown in Fig. 10c is nonsymmetric due to the nonsymmetry of the pressure load on the structure (Fig. 7). It has been observed that the underlined dynamic measurements can lead to a dramatic manifestation of random deterministic chaos. The switching in and out between periodic and chaotic behaviors and the random response processes from complex dynamic systems may be the cause of deterministic chaos.

The acoustic pressure transmitted via the structure is measured by the array of pressure transducers located at stations (a) to (d) behind the panel, as shown in Fig. 2. The radiated

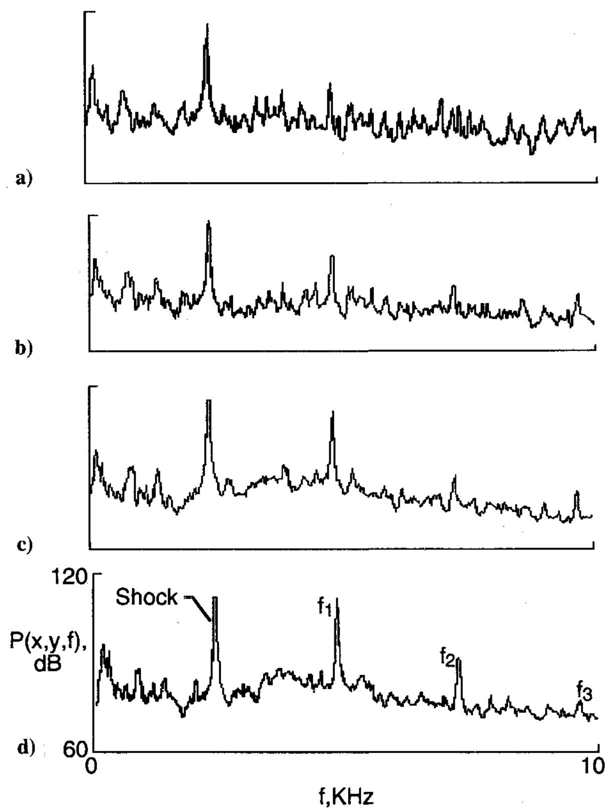

Fig. 11 Panel radiated pressure, power spectral density plots. See Fig. 2.

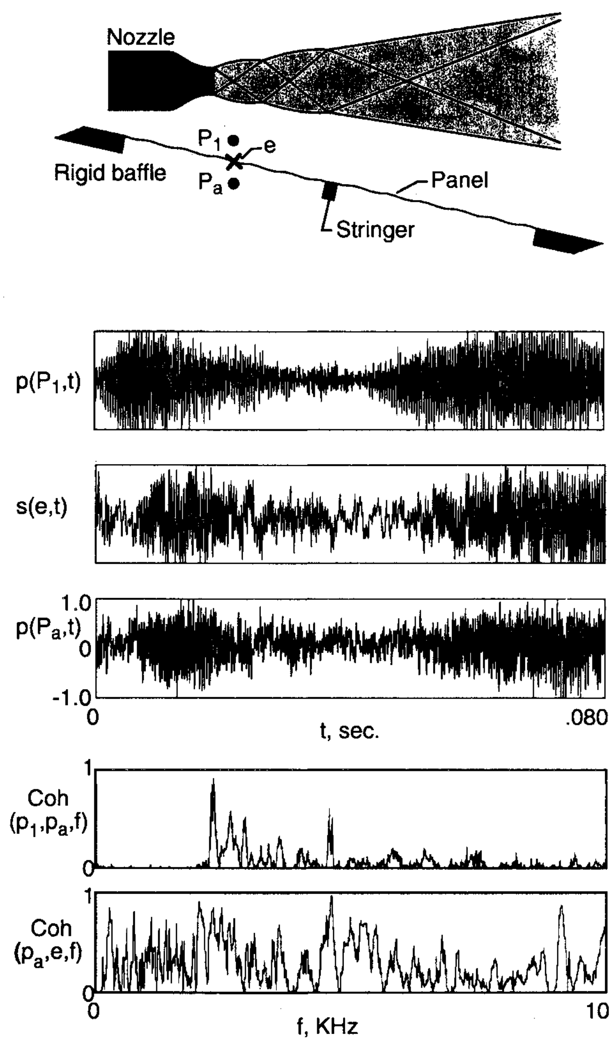

Fig. 12 Time plot of the incident and transmitted pressure across the panel surface, panel strain and coherence.

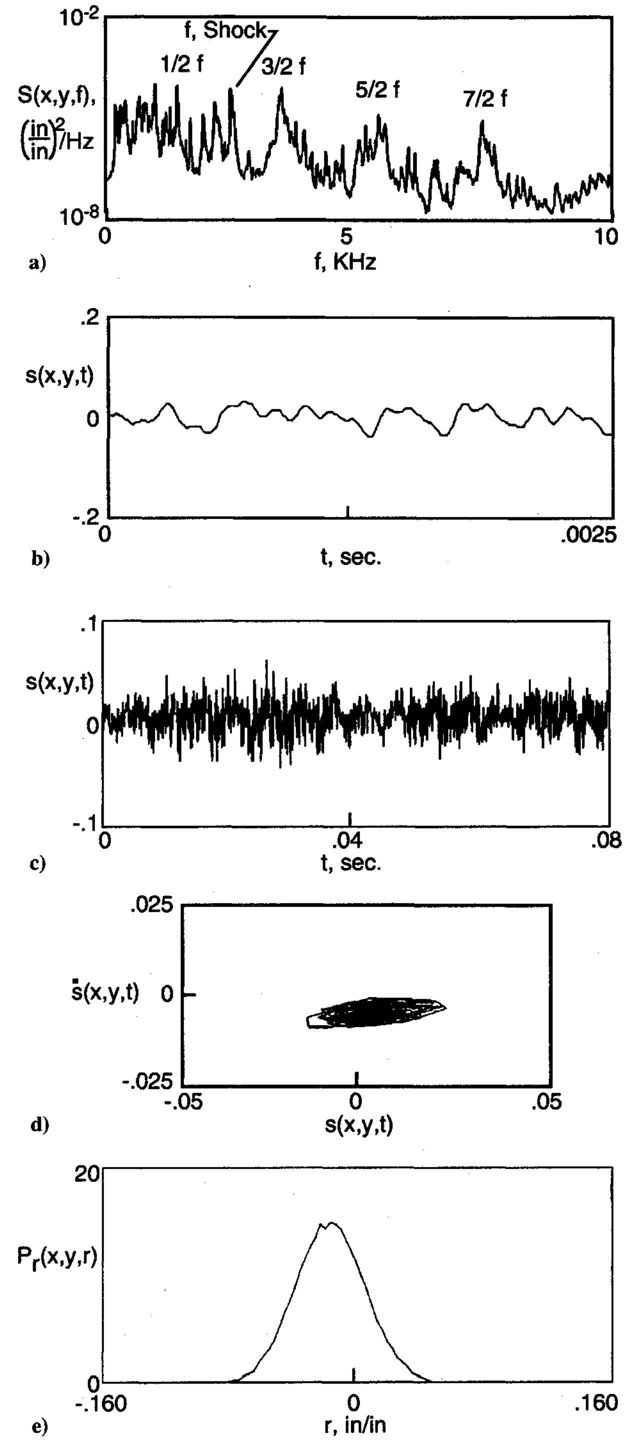

Fig. 13 Control of panel strain: a) power spectral density, b) time history, c) time history, d) phase plane, and e) probability.

pressure field is created by the panel oscillation, which is forced by the acoustic waves from the jet on the incident side of the panel. The radiated pressure power spectral density, shown in Fig. 11, retains the features of shocks and harmonics. It also shows that the amplitudes of the harmonics relative to the fundamental increase with distance. In the amplitude time plots in Ref. 32, the pressure is modulated similar to the strain response, showing that even the transmitted acoustic field is nonlinear and nonstationary.

V. Coupling Between the Incident Pressure, Structure Strain, and Pressure Radiated from the Structure

The experimental results described earlier indicate strong coupling between the sound from the jet, the response of the structure, and the sound radiation from the structure.[45] Therefore, simultaneous and time-averaged measurements are made of the pressure radiated by the jet and that by the structure on the other side of the jet and of the strain of the structure. Results from the pressure transducer located at $\theta = 180$ deg (see Fig. 3), the strain at point (e) on the panel, and the pressure at (a) are shown in Fig. 12. Two independent real-time measurements[31] indicate the variability of the pressure input signal with time. A single real-time datum in Fig. 12 shows strong coupling between pressure and strain across the structure. The modulation of pressure from the jet, including the shock, is fully reproduced by the strain response and by the radiated pressure on the opposite side of the structure. The pressure from the shock and its harmonics coupled across the structure is indicated by the coherence plots. In addition, strong coherence is shown between panel strain and pressure transmitted on the opposite side. One can conclude from these results that the nonlinear and nonstationary pressure field emanating from the jet is coupled with the structure oscillation, which in turn is coupled with the radiation field.

VI. Control of Structural Response and Sound Radiation from the Structure

The active control technique was tested in an experiment designed to control periodic motion of a panel structure containing harmonic and subharmonic modes (Maestrello et al.[28] and Maestrello[31,32]). Control was applied to the fundamental mode through a forced perturbation of time-dependent phase shift. The energy is transferred from the fundamental mode to

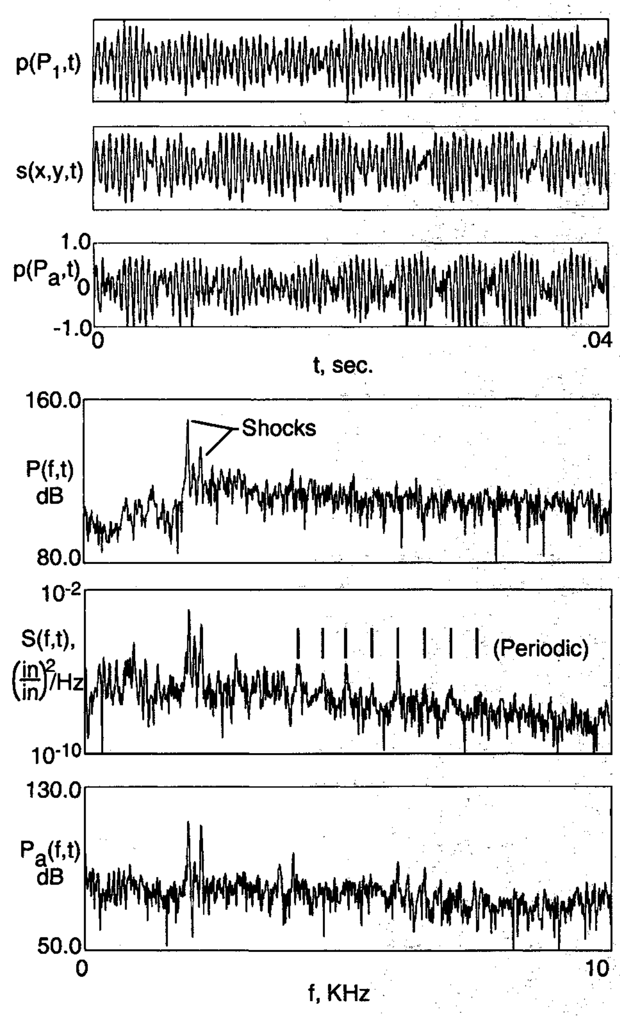

Fig. 14 Accelerated jet; instantaneous and power spectral density of the incident and transmitted pressure across the panel surface, and phase. See Fig. 12.

the harmonic and the subharmonic modes as the control process evolves. This transfer is accomplished by maintaining conservation of energy with very little acoustic damping.

The current experiment is to control the nonlinear-nonstationary vibration response of the structure due to shock impingement. Control is imparted to the high-amplitude level of the panel due to shock impingement as the time evolves. The controller, a shaker, is placed at the center of the panel and is triggered by the strain gauge (Fig. 1). The shaker is driven by the filtered output of the strain gauge. The output from the controller produces an interference that attenuates the panel amplitude response. By exploring the complexity inherent to the mechanism of generation of harmonics, it becomes possible to design a simple controller that reduces the maximum amplitude response induced by the convective acoustic loading from the jet.

The amplitude response level in the structure is reduced as a result of a phase-amplitude mismatch between input from the shock, superimposed on the broadband response, and the controller. The control system is robust and can be maintained through the unevenly modulated cycling and reverse cycling of the jet column instability. The controller output is reported in Ref. 31. In this experiment, there is no conservation of energy, as was observed in the first periodic nonlinear control experiment. Control of the major peak came at the expense of an increase in the level of the harmonics, apparently as an energy exchange mechanism, but with a net overall reduction in power (see Figs. 10 and 13). The spectrum peak shows a reduction by a factor of 63, corresponding to a power level of 18 dB in strain response. The experimental results demonstrate that one can convert the quasiperiodic motion of the panel with an impinging shock to a new periodic state without shock by controlling the shock modulation. It was obtained using a shaker loading with time-dependent amplitude from the controller output. The acoustic radiation level from the structure is also reduced; the amount of reduction, however, is difficult to determine because the adjacent panels radiate sound while the control is applied. In conclusion, the control mechanism has succeeded in controlling a highly complex system with substantial reduction of the peak amplitude response.

Results from strain gauges placed at other locations indicate that the control system also removes the shock. However, we see in Fig. 13 an increasing complexity due to the appearance of several broadband harmonics in the spectrum. Controlling these harmonics requires multiple controllers on the panel surface.

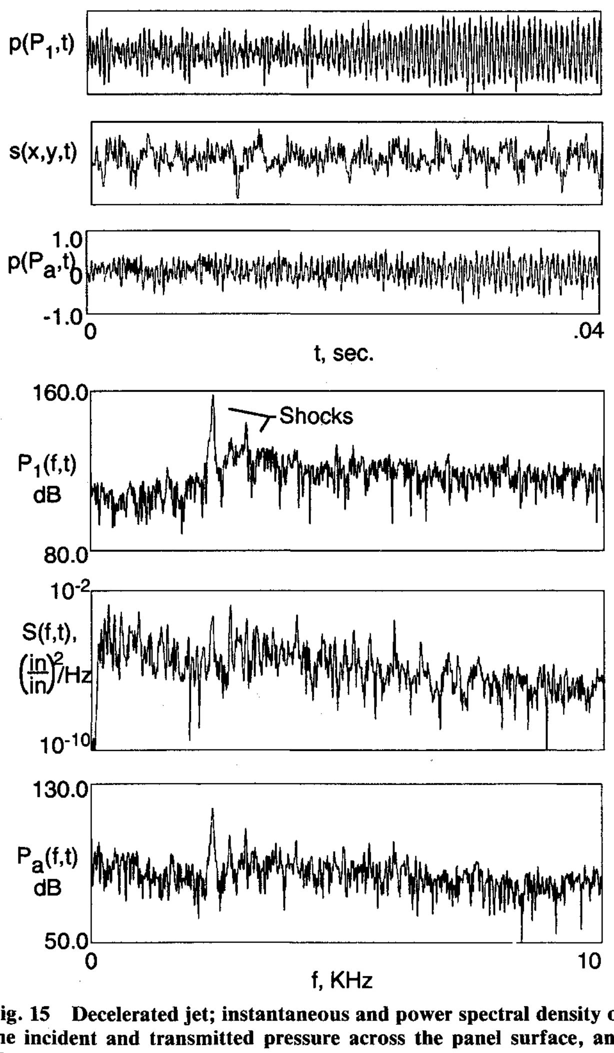

Fig. 15 Decelerated jet; instantaneous and power spectral density of the incident and transmitted pressure across the panel surface, and phase. See Fig. 12.

VII. Response and Radiation from the Structure at Accelerated and Decelerated Supersonic Speeds

We made preliminary studies on the effects of jets at accelerated or decelerated speed on the structure. The runs started at the initial pressure ratio of 2.5 with constant acceleration of 16.1 ft/s^2, or half of the gravitational acceleration, up to a pressure ratio of 3.5. The deceleration runs started in reverse order of the pressure ratios, with -16.1 ft/s^2. The objective is to compare the results with the data for a jet at constant speed and a pressure ratio of 3.

Samples of the experimental data at the instant when the pressure ratio is equal to 3 are shown in Figs. 14 and 15 for the accelerated and decelerated cases. In each figure we show the power spectral density of the near-field pressure on the incident side and that of the panel strain and the corresponding real-time data for a short interval of 0.040 s, whereas the duration for an accelerated or decelerated run is about 10 s. The data show that jet flow exiting from the nozzle and the resultant pressure exhibit a variety of behaviors different from the data with constant speed, characterized by a family of shocks of higher amplitude than the constant-speed condition (Fig. 10). The jet exhaust has less rotation or flapping oscillations than the constant-speed jet. Additional runs show similar characteristics but not the same quantitative results.

VIII. Discussion and Conclusion

The main results of this investigation are as follows.

1) Measurements show that the pressure emanating from the axisymmetric convergent nozzle at a pressure ratio of 3 and a stagnation temperature of 520°R is broadband, nonlinear, nonstationary, and modulated by shocks.

2) The acoustic pressure radiating to the far field contains shocks. The ratio of the amplitudes of the harmonics to the fundamental increases with distance. The propagating pressure signal from the jet is randomly modulated in time, indicating nonstationary behavior of the source field.

3) The pressure from the jet interacting with the nearby flexible aircraft structure leads to an energy exchange. The waves generated in the structure give rise to a variety of nonlinear responses, namely, nonlinear-nonstationary broadband responses with periodic behaviors, and shock harmonics.

4) Active control of the structural response at the shock-oscillating frequency is an achievable goal in the laboratory. As a result, the peak power spectrum of the strain is reduced by a factor of 63. The resulting spectrum response displays a new family of harmonics at a lower level.

5) The sound radiation from the structure is also nonlinear and nonstationary. There are noticeable increases in the ratios of the amplitudes of the harmonics to the fundamental with distance.

6) At accelerated and decelerated jet speeds, a new family of moving shocks is created at the exhaust and transmitted to the structure, and the structural response also exhibits multishock behavior.

Nonlinearity is an undesirable state of the jet flow, structural response, and the resultant radiation; the nonstationary effect is an added complexity. In high-speed flow, nonlinearity leads to temperature oscillations, drag increases, and structural fatigue. Controlling nonlinearity reduces the structural response and the resultant acoustic radiation. It can also reduce the nonstationary effects. Clearly, the ability to control nonlinearity is of much practical importance. Control technology currently developed is unable to simultaneously control this multiplicity of nonlinearity behaviors. Those that are relatively simple lead to the establishment of a linear response, as in the experiment by Maestrello.[32] Global nonlinear structural problems, as observed in the present experiment, are far more complicated. Full control technology has yet to be developed. For example, after controlling the nonlinearity response due to shock impingement, the structure responds with a new family of harmonics. This new family of periodic waves emerges without shocks into broadband harmonics. These harmonics will be difficult to suppress because they are highly damped.

Techniques are now developed to the state that one can distinguish periodic from quasiperiodic, chaotic, or even random behaviors. It is necessary to recognize at least some of the most common types of nonlinearity that occur in a given experiment, a necessity for the interpretation of the experimental data. However, a number of potential difficulties can be anticipated in forecasting response of, and radiation from, nonlinear-nonstationary structures forced by high-speed jets.

No technique is currently available to rescale the structural response to a larger nozzle diameter without experimentation. The structure is an accurate reproduction of a fuselage sidewall panel-stringer construction. In an engine installation, an essential prerequisite is the assessment of the noise from the jet and the response of the nearby structure. The noise power in a supersonic transport exceeds 0.01 of the engine power. This acoustic power level is, by far, too high for a standard sidewall fuselage construction and thus requires significant reduction to insure a long structural life for commercial vehicles.

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