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Active Control of Panel Oscillation Induced by Accelerating Boundary Layer and Sound

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Measurements are made of the response and acoustic radiation of a panel structure forced by a constantly accelerating subsonic turbulent boundary layer with superimposed pure-tone sound in a wind tunnel. Both panel loading and response exhibit convective instability and high-dimensional complex behaviors because of nonlinear coupling between the convective short-scale instability wave in the boundary layer and the localized intense long scales of the pure-tone sound and its harmonics. In each run, the panel response exhibits unique dynamics, indicating a dependency on the initial conditions characteristic of a temporal chaotic system. Pure-tone and harmonic response over the broadband are stabilized and suppressed by a local external fixed temporal oscillator system. The controller almost suppresses the nonstationary multiharmonics in the panel. The response reduces to that of an accelerated turbulent boundary layer loading in the absence of sound. The experiments are motivated by considerations of aircraft interior noise and structural response during initial acceleration.

I. Background

IT is known that a pure-tone acoustic excitation superimposed on a turbulent boundary layer along a flexible structure alters the boundary layer and the structure response. The incident wave acts as a trigger mechanism that transfers energy from the broadband response to the pure tone and then the harmonics. This transfer of energy was reported for the boundary layer and panel interaction for a flow at constant speed.[1] In this coupled system, the convective instability of the turbulent boundary layer triggers convective waves in the flexible structure, and when the superimposed pure-tone amplitude exceeds a certain threshold value, the flexible structure exhibits chaotic and periodic response behaviors. The experiments present several challenges, one of which is characterization of the observed dynamics.[2–4] One such characterization is synchronization of the system by linking some of the dynamic variables and using them in feedback control of the system variables during the acceleration state of the motion. Synchronization does not work when the initial state is not uniquely specified.[5–8] Synchronism was necessary when a large number of driving oscillators were distributed over the surface of a structure whose forcing scale was smaller than the response scale. The control strategy then becomes dependent on the existence of a stable direction at each trajectory point.[9–14] In the present investigation, the structure is forced by an accelerated boundary layer with superimposed pure-tone sound, representing a typical loading over an aircraft fuselage panel near an engine during the takeoff stage. Now in the absence of a stable direction, a new strategy for active control is adopted. In this system, control is achieved over the acceleration stage but the active control process varies with time.

Pure-tone acoustic forcing of a jet shear layer has become widely used for investigating the stability of a shear layer.[15,16] When the acoustic forcing is applied on the jet shear layer, the broadband far-field pressure decreases while the pure tone and harmonics exceed the broadband level of the undisturbed jet shear layer. We shall show in this paper that acoustic forcing of a turbulent boundary layer over a flexible structure also produces a decrease in broadband level at the same time that the amplitudes of the pure tone and harmonics exceed the level by several orders of magnitude. This mechanism of energy transfer is due to nonlinear coupling between the turbulent boundary layer and pure-tone sound.

It is known that in an accelerated flow in the absence of sound, the turbulent boundary layer along a rigid wall relaminarizes[17]; therefore, the loading on a rigid structure will be lower than that in the corresponding steady flow. As we shall see in this paper, in the presence of sound the boundary layer acoustic loading on a flexible structure can exceed the boundary layer acoustic loading on a rigid structure for constant speed flow at the same instantaneous speed.

Procedures to control transient nonlinear waves on structures in the absence of a flow were reported in 1991 and 1993 (Refs. 18 and 19). This paper describes how a low-energy feedback control signal can be successfully utilized to suppress nonlinear-nonstationary responses on an aircraft-type panel structure. This study involves measurements of the aerodynamic and acoustic loading on the panel, the panel response, acoustic radiation transmitted across the panel, and control of the panel response.

II. Experimental Apparatus, Instrumentation, and Test Conditions

The apparatus and some of the techniques used in these experiments have been described in a recent publication.[1] The data presented in this paper are taken at a constant acceleration of 3.27 m/s^2, or one-third of the gravitational acceleration, from the initial velocity of 3.05 m/s to terminal velocity Ue of 66 m/s in 19.4 s. Results of the accelerating flow at the instant when $Ue = 58$ m/s are compared with the corresponding results for a constant speed of 58 m/s for a Re/m value of 3.6×10^5.

The experiment is conducted in a low-speed wind tunnel. The structure is mounted on a side wall and consists of two aluminum aircraft-type panels joined by a stringer (Fig. 1). The panel sizes are $0.65 \times 0.20 \times 0.001$ m, and the stringer cross section is 0.0128×0.0128 m mounted on a rigid baffle. The wind-tunnel side wall opposite the panels is anechoic, a unique construction, to prevent formation of standing and reflecting waves in the test section over a broad range of frequencies. The mean velocity profile and the wall pressure fluctuations are measured with an array of hot-wire anemometers and with an array of pressure transducers. The pressure transmitted through the panel to the outside is also measured by a pressure transducer. The vibration response is measured by miniature accelerometers. All measurements are from dc response. An acoustic source generating 500-Hz pure-tone sound at a power level of 128 dB is mounted on the opposite side wall of the tunnel facing the center of the downstream panel. A pressure transducer is mounted on the horn of the source to monitor the output waveform.

The active controller, an electromagnetic actuator, is mounted at the center of the downstream panel, for example, the origin (0,0), and is freely suspended. Two accelerometer signals are notch-filtered around the fundamental tone frequency. One accelerometer placed at

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one-quarter length, a, of the downstream panel, i.e., at $(-a, 0)$, provides the output signal from the panel motion $Z(t) = g(-a, 0, t)$. Another accelerometer is placed at the shaker-panel interface and provides signal $Z_i(t) = g(0, 0, t - b)$, where b denotes the time delay or phase shift. The difference, $D(t)$, between input and output is used as a control signal:

$$F(t) = K(t)[Z_i(t) - Z(t)] = K(t)D(t)$$

where $K(t)$ is an adjustable amplitude. Also, we can control the time shift $b(t)$ of $Z_i(t)$ with respect to $Z(t)$. The control is introduced into the system input as a negative feedback ($K > 0$). When the control is accomplished, the output signal $Z(t)$ is close to $Z_i(t)$, and hence the controlling force $F(t)$ becomes small. Like the control used for constant speed, a single actuator is sufficient to control the response of the panel by suppressing the harmonics and then the fundamental. For the accelerating stage, at least two and up to four control level adjustments of K and the phase lag b are made by the feedback system.

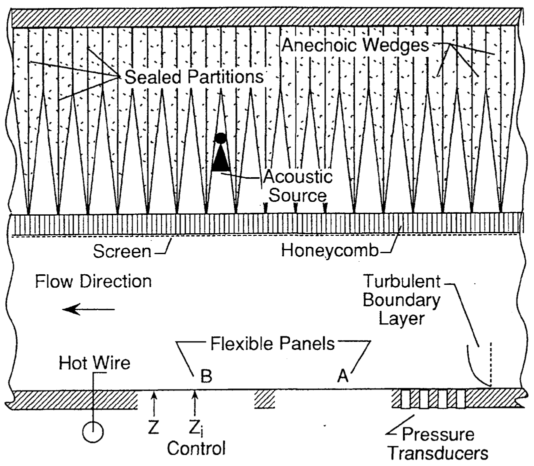

Fig. 1 Top view of wind tunnel setup with anechoic test section.

III. Results

Similar to a previous work for a constant speed flow,[1] we describe the experimental data, the coupling with the pure-tone sound, the formation of the harmonics, the energy exchanges, and the mechanism that controls the harmonics and then the fundamental. But in an accelerating flow, the time history of the dynamics of the system and the panel response depend on the initial data. Thus, we represent the real time measurements and the active control of the panel response as successive small time-dependent perturbations of the panel surface dynamics. Several runs are made to study the system response to broadband and tonal loading so that we can identify the response to the appropriate control adjustments of $K(t)$ and $b(t)$ for the accelerated flow. The experimental investigations are presented in the following sequence: the response of a turbulent boundary layer along a rigid wall with or without an incident pure-tone sound, the interaction of the boundary layer with flexible panels with or without active control, the effect of the initial conditions on the control adjustment, and waves transmitted across the panels into the far field.

A. Turbulent Boundary Layer Response

Measurements of the wall pressure fluctuations from a turbulent boundary layer along a rigid surface at a constant speed of 58 m/s are compared with those in the flow accelerating at one-third the gravitational acceleration when the speed reaches 58 m/s. The incident pure-tone sound is at a frequency of 500 Hz and a power level of 128 dB. At the point of pressure measurements, the turbulent boundary layer is 0.059 m thick for the constant speed flow and 0.034 m thick for the accelerating flow. The real time wall pressure $p(t)$, the power spectrum density $P(f, t)$, the phase plots $\dot{p}(t)$ vs $p(t)$, and the probability density $Q(r, t)$ are shown in Figs. 2a and 2b for the turbulent boundary layer at a constant speed of 58 m/s, without and with pure-tone sound, respectively. Figure 2c shows the corresponding plots for an accelerating flow in the presence of pure-tone sound. The instantaneous power spectrum density $P(f, t)$, phase $\dot{p}(t)$ vs $p(t)$, and probability $Q(r, t)$ are at the instant T when the accelerating flow reaches the speed of 58 m/s to compare with the corresponding constant speed data. The real time $p(t)$, shown for an interval of 0.08 s near the instant T, is used for evaluation of the instantaneous plots of the spectrum phase and probability.

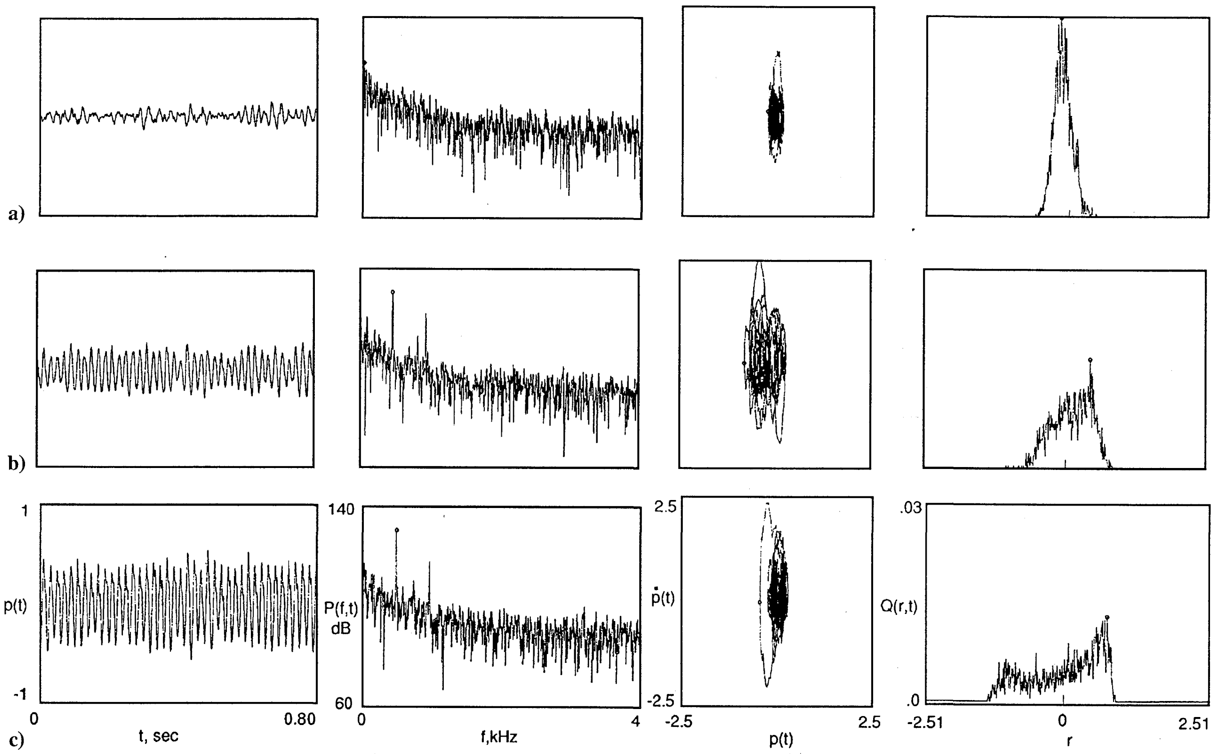

Fig. 2 Pressure fluctuation on a rigid wall: turbulent boundary layer in constant speed flow a) without external sound and b) with pure-tone sound; and c) accelerating turbulent boundary layer with pure-tone sound.

For the nonstationary signal $p(t)$, we define the power spectral density $P(f, t)$ as the power spectral density of the signal $p(s)$ restricted to the interval $t - I/2 \leq s \leq t + I/2$, where I is chosen from experimental considerations. Thus,

$$P(f, t) = |\hat{p}(f, t)|^2$$

where

$$\hat{p}(f, t) = \int_{t-(I/2)}^{t+(I/2)} \exp(i 2\pi f s) p(s)\, ds$$

Figures 2a and 2b show distinct differences between the wall pressures of a turbulent boundary layer of a constant speed flow without and with pure-tone sound, respectively. The real time pressure in the presence of pure-tone sound is significantly amplified. The power spectral density plots in Fig. 2a show the broadband response, whereas Fig. 2b shows a spike of 20 dB at the pure-tone frequency and a relatively lower level above the broadband level at the next harmonic. Because the amplitude of the incident wave exceeds the threshold value, we see the presence of the next harmonic as an indication of saturation of the fundamental due to the acoustic flow coupling. This behavior is also reflected in the real time plots in Fig. 2b, where the presence of the pure tone and the next harmonic can be observed. The phase plots in Fig. 2b are less flattened than those in Fig. 2a, showing the difference in wall pressure as the pure-tone sound changes the effect of convection in the flow. The probability distribution from the turbulent boundary layer Fig. 2a has a quasizero mean and is almost symmetric, whereas the plot in Fig. 2b has a nonzero mean and is asymmetric. Figure 2c shows the corresponding four plots for the interaction of the pure-tone sound with an accelerated boundary layer at the same instantaneous speed. Comparing Figs. 2c and 2b, we see the effect of acceleration. In Fig. 2c, the amplitudes in real time and the spectrum peaks are larger and the phase plots are more skewed and flattened, whereas the probability plot is more asymmetric with wider spread.

B. Panel Response and Active Control

The static pressure in the tunnel is below the ambient pressure outside, simulating aircraft panels in flight. Thus, the aircraft-type panels in the tunnel deflect toward the moving stream and the mean static deflection is on the order of the panel thickness. Because of the difficulty of mounting a transducer on the moving surface without changing the inertia, we measure instead the panel acceleration. The location of the accelerometer is shown in Fig. 1. Note that the panel acceleration is related to the loading, i.e., the wall pressure. The real time panel acceleration response $g(t)$, the power spectral density $G(f, t)$, the phase $\dot{g}(t)$ vs $g(t)$, and the probability $\hat{Q}(r, t)$ at a constant speed are shown in Figs. 3a and 3b without and with pure-tone sound forcing on a turbulent boundary layer, respectively. These values for an accelerating flow with pure-tone sound without and with active control are shown in Figs. 3c and 3d, respectively. A short time history of the response in Fig. 3a shows a random modulated amplitude with nearly Gaussian probability distribution. The power spectral density of the panel acceleration is smooth and continuous, and the phases are the typical phases of random broadband response. The power spectral density with the pure-tone sound in Fig. 3b shows a spike at the forcing frequency of 500 Hz exceeding the amplitude of the broadband level by 20 dB and the spikes of seven harmonics above the broadband. The energy transfer from the fundamental to the harmonics indicates that the forcing amplitude exceeds the threshold value. Note that in Fig. 2b, for the rigid wall, there is only one harmonic above the broadband. This implies that the threshold value for a rigid wall is higher than that for a flexible wall, and hence there are more harmonics in the latter case. Comparing the real time plots in Figs. 3a and 3b, we see that the high amplitudes of the fundamental and harmonics dominate

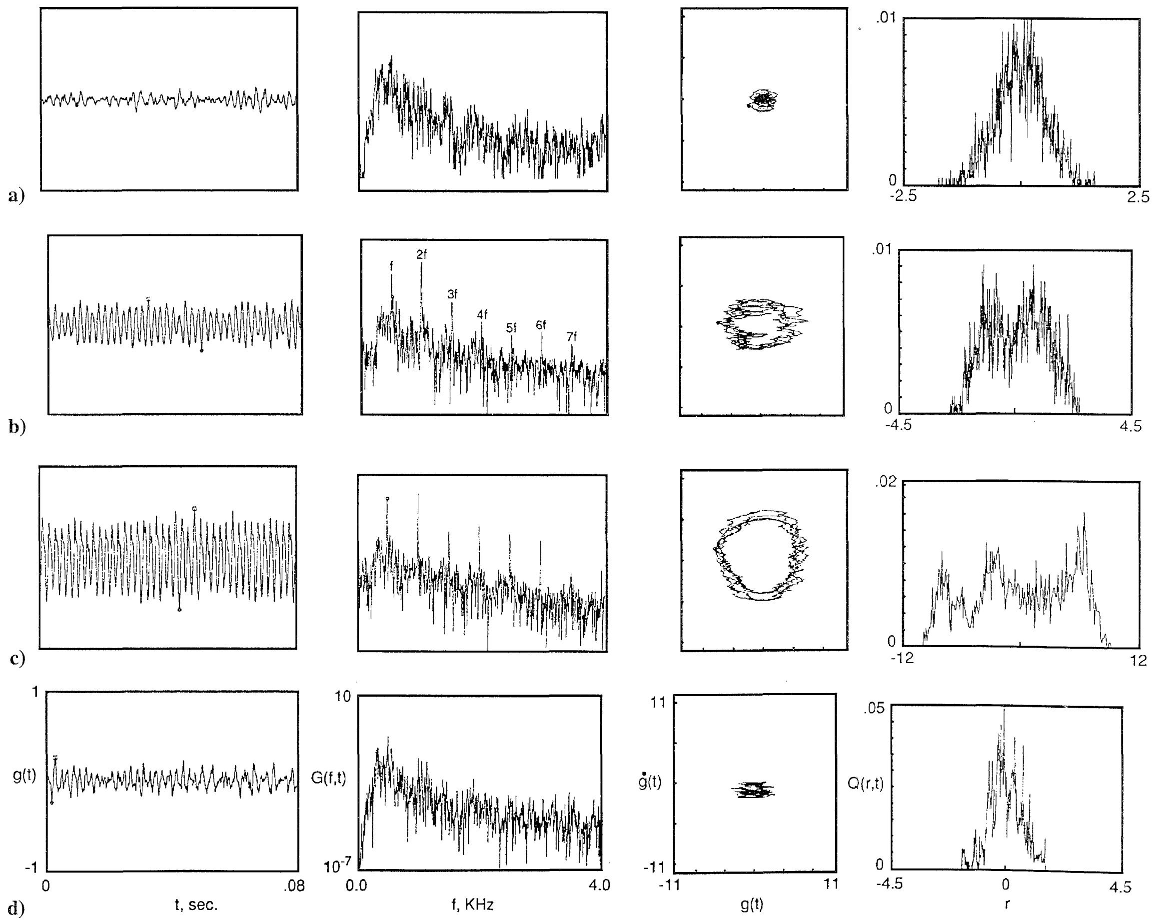

Fig. 3 Panel acceleration response: turbulent boundary layer in constant speed flow a) without external sound and b) with pure-tone sound; and accelerated turbulent boundary layer c) with pure tone and d) with pure-tone sound and active control.

the broadband in the latter. The probability distribution in Fig. 3b no longer maintains Gaussian-type distribution. The phase plot is modulated, an indication of coupling between competing unstable waves with the instability waves in the boundary layer.

The wall pressure on a rigid wall for an accelerating boundary layer flow is known to be lower than that at the corresponding constant speed if there is no external sound forcing. The present experiments for a rigid wall, shown in Figs. 2a–2c and for a flexible wall in Figs. 3a–3c, show that with high-intensity external sound the responses are much higher than those without the external sound, whereas the responses for an accelerating boundary layer are of the same order of magnitude as those for the corresponding constant speed.

The panel response is controlled by forcing the structure at the pure-tone fundamental frequency through a phase and amplitude tuning procedure in two stages similar to those used for a constant speed flow. In the first stage, the controller forces the panel with amplitude and phase variations $K(t)$ and $b(t)$ so that the energy in the harmonics is shifted back into the fundamental tone. In the second stage, the controller reduces the amplitude of the fundamental by increasing the amplitude and phase. Control of the panel in accelerating flow is not as straightforward as it is in constant speed flow, and full control is not always achieved in the initial stage of the accelerating flow. It requires at least some foreknowledge of the temporal dynamics during the initial stage. For a given accelerating flow, it takes several tries to achieve a systematic feedback control, i.e., $K(t)$ and $b(t)$, applicable for all initial stages (Fig. 3d). By comparing the plots in Fig. 3d with those in Figs. 3c and 3a, we see the remarkable changes in the panel responses. With active control, the real time panel response to an accelerating boundary layer with pure-tone sound in Fig. 3d reduces by several orders of magnitude from that without the control in Fig. 3c to nearly the level of constant speed flow without external sound in Fig. 3a. Similar changes occur in power spectral density, phase, and probability. Thus, one can effectively control the system dynamics with a small applied force via a single controller. The panel response is controlled in effect by reversing the mechanism that generates the high-amplitude fundamental and harmonics shown in Fig. 3c.

C. Effects of Initial Condition in an Accelerating Flow

With each test run of the accelerating boundary layer with pure-tone sound, the panel response exhibits different characteristics, indicating the dependence on the initial conditions unpredictable in each run. We demonstrate this dependency with the data from six test runs. The active control is applied only to the sixth run. The pure-tone sound is absent in the fourth run. The power spectral densities of the panel response of the first three runs are shown in Figs. 4a–4c. The spectrum of the first run (Fig. 4a) consists of the fundamental tone and seven harmonics well above the broadband level. In the second run (Fig. 4b), only the harmonics are observed while the broadband level is higher than that in Fig. 4a for the frequencies near and below the fundamental. In the third run (Fig. 4c), the fundamental tone and the next harmonic are not observable as the broadband level becomes higher for the frequencies near and below the next harmonic. This shows that different initial conditions inherent with different runs produce different power spectra.

Next, we use the data from the remaining three runs to demonstrate the temporal responses of the panel over the entire acceleration period as the velocity increases from 3.05 to 66 m/s. Figure 4d shows the panel response without an external sound, Fig. 4e shows response with pure-tone sound, and Fig. 4f shows response with pure-tone sound and control. In Fig. 4f, the control is applied at 12.5 s, which is less than T for the data at which the power spectrum, etc. were presented in Fig. 3d. The response in the uncontrolled interval is different from that in Fig. 4e, showing again the effect of the initial conditions. The response in Fig. 4f is close to that in Fig. 4d and

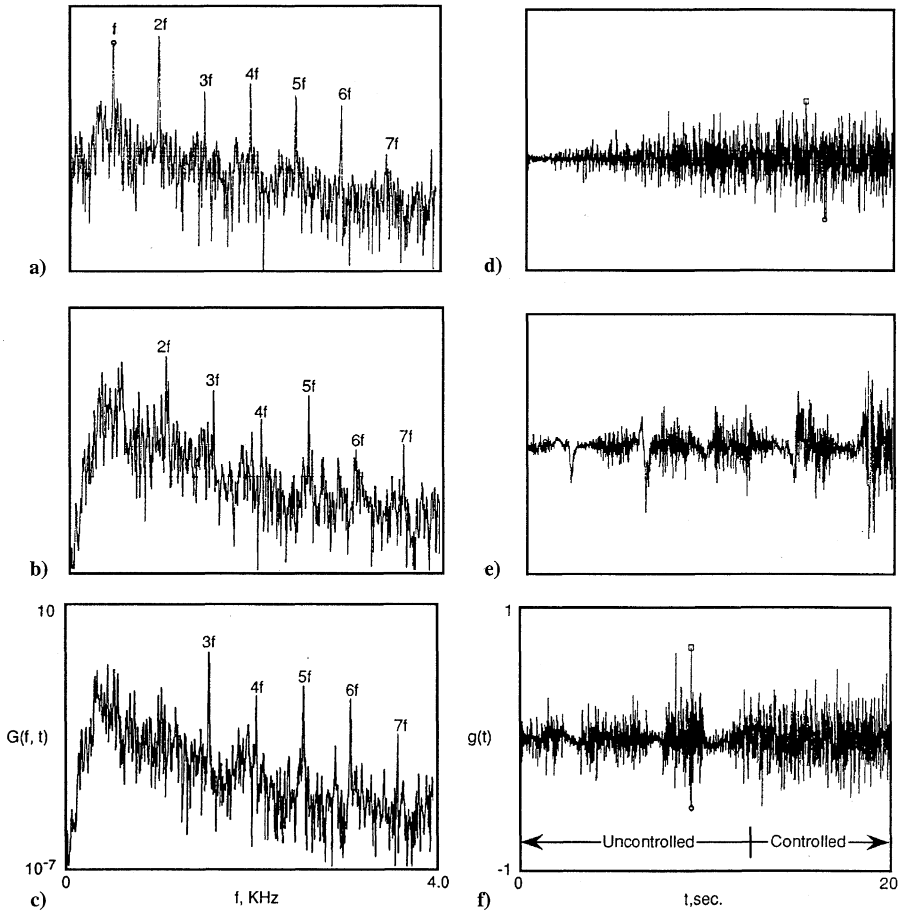

Fig. 4 Panel acceleration responses for six test runs of an accelerated turbulent boundary layer: a)–c) power spectrum density with pure-tone sound for three runs; and real time pressure for a run d) without external sound, e) with pure-tone sound, and f) with pure-tone sound and active control.

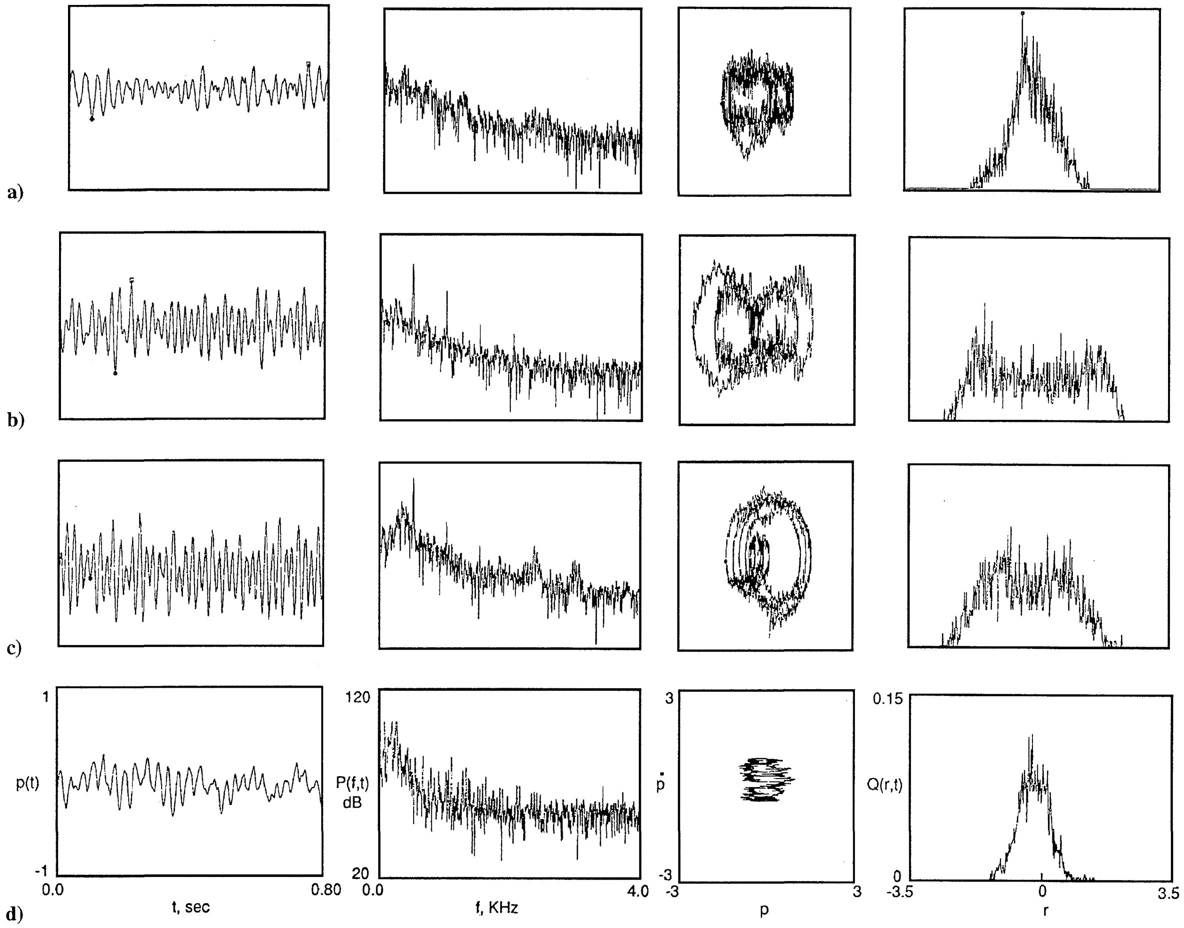

Fig. 5 Panel transmitted pressure: turbulent boundary layer a) without external sound and b) with pure-tone sound; and accelerated turbulent boundary layer c) with pure-tone sound and d) with pure-tone sound and active control.

shows the effect of control in reducing the maximum amplitude in Fig. 4e to that in Fig. 4d. Thus, the control functions $K(t)$ and $b(t)$ are effective independent of the initial conditions.

D. Wave Transmitted Through the Panel

The accelerating turbulent boundary layer and pure-tone sound induce panel vibration, which in turn induces acoustic pressure in the ambient medium outside the tunnel, simulating the cabin noise. A pressure transducer is placed 0.81 m from the downstream panel center outside the flowfield. Figure 5 shows these results: turbulent boundary layer at constant speed without external sound (Fig. 5a) and with pure-tone sound (Fig. 5b) and accelerating turbulent boundary layer with pure-tone sound (Fig. 5c) and with pure-tone sound and active control (Fig. 5d). The plots include the following: real time response $p(t)$, power spectral density $P(f, t)$, phase $\dot{p}(t)$ vs $p(t)$, and probability density distributions $\tilde{Q}(r, t)$. The coupling of the turbulent boundary layer with pure-tone sound induces harmonic response on the panel and on the radiation response. Because the transmitted wave is induced by the panel oscillation, the differences shown in Fig. 3 for the panel response are qualitatively similar to those shown in Fig. 5 for the transmitted pressure. For example, the fundamental tone level of the transmitted wave is higher for the accelerating than for the constant speed boundary layer. Both the fundamental and the harmonics are observed above the broadband level in the transmitted field. By comparing Fig. 5d with Figs. 5c and 5a, we see that as a result of controlling the panel acceleration the acoustic pressure in Fig. 5d reduces from that in Fig. 5c to the broadband level in Fig. 5a, which is the level of the pressure radiated by the panel from the turbulent boundary layer at constant speed without external sound. Also, the probability distribution in Fig. 5d assumes a nearly Gaussian distribution similar to that in Fig. 5a. Thus, the active control on the panel is effective for reducing the panel response and the transmitted acoustic pressure.

IV. Discussion and Conclusion

Experiments were carried out to study the interaction of a turbulent boundary layer in a constant speed flow or in an accelerating flow with a normal incident pure-tone sound along a rigid wall. We then studied the interaction of the turbulent boundary layer along a wall with flexible panels, the panel oscillations, and the transmitted waves across the panels without or with an active control.

Figure 1 shows the experimental setup. Figure 2 shows the wall pressure data for a turbulent boundary layer along a rigid wall (without flexible panels) in a constant speed flow and for the boundary layer interacting with a normally incident pure-tone sound in a constant speed or accelerating flow. Figure 3 shows the response corresponding to the cases in Fig. 2 when there are two flexible panels mounted on the wall. Also shown is the effect of an active control acting on the panel. Figure 5 shows the transmitted wave induced by the panel oscillation corresponding to the cases in Fig. 3. Figure 4 demonstrates the differences in the panel response for an accelerating boundary layer in different test runs due to the uncontrollable initial conditions and the effectiveness of control functions independent of the initial conditions.

From these figures, we see the following:

1) An external pure-tone sound can excite high-amplitude fundamental and harmonics above the broadband level for a turbulent boundary layer in a constant speed flow as well as in an accelerating flow.

2) A single active controller on the panel can effectively reduce the amplitudes of the fundamental and harmonics to the broadband level and hence is effective in reducing the transmitted wave.

To seek a theoretical understanding of our experimental data, we note that a mathematical model was introduced in Ref. 14 to demonstrate the feasibility of active control of nonlinear panel vibration by applying an unsteady distributed load. The optimum distribution is defined by minimizing the mean acoustic radiation energy. The plate oscillation is two-dimensional and is governed by the nonlinear beam equation. The beam is simply supported. This condition, rather than a clamped support, was introduced only to simplify the construction of the optimum load distribution by Galerkin's method, with the beam oscillation and load distribution expressed as Fourier sine series. The numerical results show that active control of the structural sound radiation is highly effective.

In conclusion, the control of a complex chaotic system consisting of a turbulent boundary layer and acoustic loading on a flexible structure in a constant speed or in an accelerating flow is of practical interest in reducing panel fatigue and cabin noise. The ability of a single control device to control such a complex system and result in substantial reduction in panel response and the transmitted wave deserves further investigation, both theoretical and experimental. Also, the feasibility of applying this device to control other systems of practical importance in areas such as engineering, chemistry, biology, and medicine should be exploited.

The results presented here can best be understood when viewed in real time. Thus, segments of the experiments have been recorded on video tapes, illustrating the dynamics of the response and response-control of the panel at constant and accelerated speeds. These tapes were presented at the second AIAA/CEAS Aeroacoustics Conference (State College, PA) in 1996.

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