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Control of Panel Response to Turbulent Boundary-Layer and Acoustic Excitations

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Nonlinear response of a panel structure results when forced by a subsonic turbulent boundary layer and pure-tone sound in a wind tunnel. It is a coupled problem, where flow, structure, and sound interact. The structure exhibits a broadband response typical of turbulent boundary-layer loading with superimposed pure tone and harmonics over the band, a process which is statistically stationary, but non-Gaussian. The mechanism is an energy transfer process: the amount of energy supplied to the harmonics is removed from the low-frequency band and the fundamental tone. The objective is to control the nonlinear wave using a time-harmonic actuator tone. Full control is almost achieved using a single controller. Two steps are taken: first, control the harmonics by feeding the energy back into the fundamental and low-frequency band, and second, control the fundamental tone to shift the energy further back into the low-frequency band. Consequently, the response of the panel is reduced to the broadband level of the turbulent boundary-layer excitation, a reduction in peak amplitude power level by 20 dB or more. The experiments are motivated by considerations for aircraft interior noise and structural response.

I. Introduction

THE paper addresses the problem of nonlinear vibration and vibration control of a panel structure forced by the interaction of a turbulent boundary layer with pure-tone sound in a wind tunnel. It is well known that the response of a structure interacting with high-speed fluid flow, flow-sound, or random loading is essentially nonlinear.[1–8]

Demand for higher performance aircraft is increasing. This means that we are required to operate in a region where linearity is not a good approximation for describing the dynamic behavior of the structure. Industrial power plants and aircraft companies have been concerned for many years about the response of a structure forced by a turbulent boundary layer with a wideband random excitation and sound with narrowband tone harmonics. For instance, passengers seated along the sidewall next to the engine inlet or propeller experience a greater amount of noise than those seated elsewhere in the aircraft. A reduction in noise and vibration will certainly enhance the passengers' comfort level and reduce the structural fatigue.

The dynamic complexity of the forcing field induces the flexible structure to respond nonlinearly. Without the pure tone, the response of the panel is linear when excited by a convected subsonic turbulent boundary-layer loading. In the 1950s to the 1970s, the structural response to a turbulent boundary-layer excitation was widely reported.[9–20] It was established analytically and experimentally in subsonic and supersonic flows that when the boundary-layer thickness is much less than the longitudinal length scale of the panel, the response is in the form of convective waves. When the waves in the structure match the wave speed in the turbulent boundary layer, aerodynamic coincidence occurs.[9] As a result, this excitation mechanism has profound effects on the response of a structure and acoustic power radiated into the cabin of modern high-speed aircraft.

Conventional signal processing or time-series analysis has been limited for many years by the linearity assumption. In reality, in a laboratory this assumption is far from being reasonable. We were unaware of the possibility that the so-called random noise may in fact be a manifestation of the system dynamic behavior, i.e., chaos. As a result, recent effort has been directed toward the understanding of how to analyze nonlinear and nonlinear-nonstationary signals.[21] Experiments and analysis on nonlinear interactions of the acoustic and flowfields with a flexible structure under harmonic excitations were studied.[22–29] In their analyses,[23,30] special emphasis is given to the formation of shocks.

In the present experiment, when the acoustic forcing of the turbulent boundary layer is at a low level, the panel response tends to remain in the linear range. As the level increases, more and more nonlinearity action occurs. Accordingly, we have chosen the excitation that induces a nonlinear response in the panel. The panels in the wind tunnel are a replica of an aircraft sidewall structure and are tested in a flight simulation under the action of two independent loadings: one the static due to the local pressure difference across the panel, and the time-dependent one due to turbulent boundary layer and pure-tone sound loading. As the level of the pure tone superimposed on the turbulent boundary layer increases, various harmonics are formed throughout the bandwidth. The panel will eventually drift into an aperiodic and then into chaotic state. A technique is developed to control the nonlinear oscillations in two steps: the first is to control the amplitude of harmonics and the second is to control the amplitude of the fundamental one. For the first step, the controller actively forces the fundamental frequency with proper amplitude and phase such that the energy from the coupled harmonics shifts back into the fundamental and low-frequency band, a reverse to the process that produces such harmonics. Thus, the acoustically excited nonlinear response is controlled by forcing the panel at the fundamental frequency through amplitude/phase adjustments. For the second step, the level of the fundamental tone is brought back to the broadband level of the turbulent boundary layer by additional phase-shift adjustments. The control is achieved by using a well-tuned controller: an externally mounted actuator on the panel surface. In the past experiments, the author utilized controllers that yielded desirable behavior of a system whose uncertainties were characterized deterministically, such as in controlling the response of a flexible structure and flow transition on a flat plate.[21,29,30] In the present experiment, the nonlinear state of the system is periodic and the controlled response is linear. Many have suggested methods for controlling periodic, aperiodic, and chaotic systems by combining direct or delayed self-controlling feedback, even without the use of any external force.[31–36] These methods do not require a priori knowledge of the system dynamics and are applicable to experiments.

II. Experimental Apparatus and Instrumentation

The experiment is conducted in a low-speed wind tunnel at Reynolds number per meter (Re/m) $= 3.67 \times 10^6$ and speed (U_e) $= 61.58$ m/s. The structure is mounted on the sidewall and

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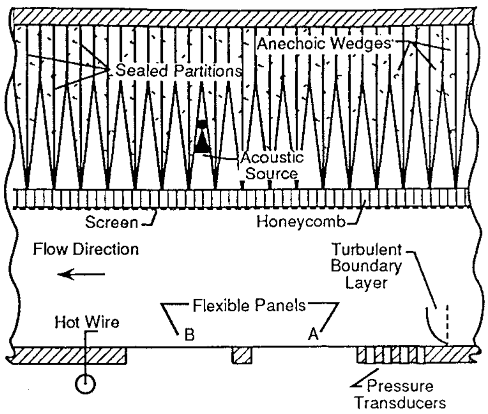

Fig. 1 Wind tunnel setup with anechoic test section.

consists of two aluminum aircraft type panels joined by a stringer. The panel sizes are 0.65 by 0.20 by 0.001 m, and the stringer is 0.013 by 0.013 m mounted on a rigid baffle (Fig. 1). The panels are subject to the turbulent boundary-layer excitation and to a superimposed pure-tone sound. The boundary-layer thickness downstream of the second panel is 0.062 m, where the flow is turbulent. The wind-tunnel sidewall opposite the panel is anechoic (a unique construction), to prevent the 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 downstream of the panel are measured by a hot-wire anemometer and pressure transducers. The pressure transmitted through the panel to the outside is measured by pressure transducers not shown in the figure. The vibration response is measured by miniature accelerometers. All measurements are made from the dc response. The instrumentation was checked out in real time by monitoring the measurement conditions, saturation, noise, nonlinearity, etc. The accuracy of the pressure measurements using the transducers is within 0.5 dB, and the accuracy of the acceleration using accelerometers is 3×10^{-5} m/s^2. A 100-W acoustic source is mounted in the opposite side wall facing the center of the panel, and a pressure transducer is mounted on the horn of the source, to monitor the output and the waveform (Fig. 1). The active controller mounted at the center of the downstream panel B is designed to control nonlinear periodic waves on the downstream panel. Time-continuous control combining feedback with periodic external forces has been derived in other applications.[32] In the present experiment, control is achieved by actively forcing the panel with an electromagnetic actuator at the pure-tone fundamental frequency. An accelerometer placed at one-quarter length of the panel (Fig. 1) provides the output signal from the panel motion $z(t)$, and the actuator generates a signal proportional to the acceleration of the shaker $z_i(t)$. The difference $D(t)$ between the input signal $z_i(t)$ and the output signal $z(t)$ is used as a control signal:

$$F(t) = K[z_i(t) - z(t)] = KD(t)$$

where K is an adjustable amplitude. Also, we can control the time shift of $z_i(t)$ with respect to $z(t)$. The control is introduced into the system input as a negative feedback ($K > 0$). By selecting amplitude K, one can achieve equilibrium; it implies that the output signal $z(t)$ is very close to $z_i(t)$ and the forcing term $F(t)$ becomes very small.

A single actuator located at the centerpoint on the surface is sufficient to control multinonlinear dimensions of the surface motion. When the electrical driving force is turned off from the shaker, there is no measurable force input, since the shaker is independently suspended from the panel. The controller matches the amplitude and frequency of the surface motion at the point of control. Complete control is achieved when the spectrum of the panel response is reduced to that obtained from the turbulent boundary-layer forcing alone. The low-frequency band plays a major role in the transfer of energy to the harmonics as a result of the instability created by the pure tone. In reverse order, the energy is pumped back to the low-frequency band when control is applied.

III. Results

The methods for analyzing the measured linear and nonlinear signals are substantially different. This section is devoted to examining these differences. The tools used for the interpretation of the experimental observations start with the time trace of the measured quantities. One of the critical questions is the identification of the system being measured. In order to generate high-order harmonics (Fig. 9b) with an amplitude enhancement of at least 20-dB power above the broadband level of the panel response (Fig. 9a), one needs to excite the excitable, tunable states of the boundary layer by the pure tone. These tunable states that generate harmonics in the panel forced by turbulence and pure-tone sound are associated with aerodynamic coincidence waves [9,14] on the structure. The paper addresses this mechanism.

A. Turbulent Boundary-Layer Response

The mean velocity distributions at the zero pressure gradient with and without pure-tone sound measured downstream of the second panel are reported in Ref. 36. The Reynolds numbers are $Re = U_e\delta/\nu = 4.44 \times 10^5$ and 4.65×10^5 for the turbulent boundary layer with and without pure-tone sound, respectively. Hence, ν is the kinematic viscosity, δ is the boundary-layer thickness, and U_e is the freestream velocity. The presence of the pure-tone sound at $f = 505$ Hz locally enhances the thickness of the boundary layer, but how it develops downstream of the test section or how it may become affected at different frequencies is not known. Expectations are that the boundary layer will become thicker downstream. We have also observed that the local boundary-layer thickness is affected as shown earlier by the presence of a pure-tone sound when the acoustic intensity exceeds the level of the boundary-layer pressure fluctuations.

At the entrance of the test section, the boundary layer is artificially thickened by sandpaper on the tunnel sidewall. Thus, the panel structure, the boundary-layer thickness, and the Reynolds number are parameters that are consistent in scale with the current aircraft fuselage flow-structure relationship, a necessary scaling for studying the dynamic responses and the acoustic radiation of such a structure.

The normalized time-average, two-point, space–time correlation $Re_P(X_1, X_2; \tau)$ of the wall-pressure fluctuations over the rigid surface in the absence of sound is shown in Fig. 2. The convective velocity U_c can be expressed as the ratio of the streamwise separation $(X_2 - X_1)$ and temporal separation τ, which makes $Re(X_1, X_2; \tau)$ a maximum. The maximum can be located at a fixed time delay or a fixed spatial separation.[14] The wall pressure correlates up to about two boundary-layer thicknesses along the direction of flow with the

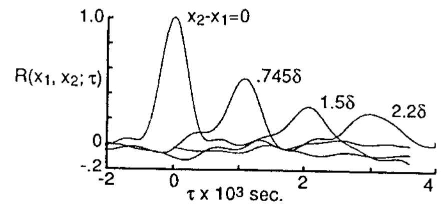

Fig. 2 Space–time correlation of the wall-pressure fluctuations along the direction of flow.

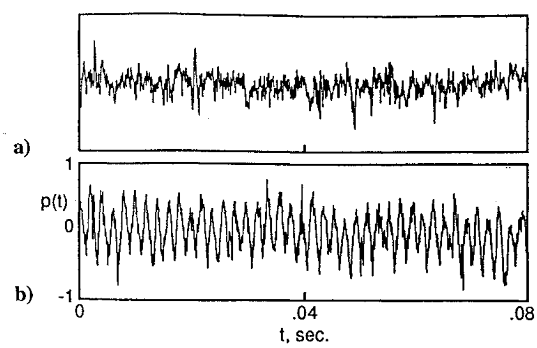

Fig. 3 Instantaneous wall pressure fluctuations: a) turbulent boundary layer and b) with pure-tone sound.

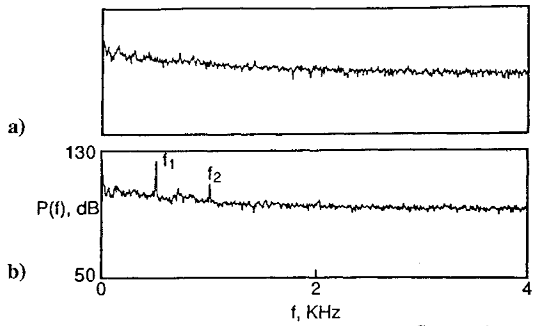

Fig. 4 Power spectral density of the wall-pressure fluctuations: a) turbulent boundary layer and b) with pure-tone sound.

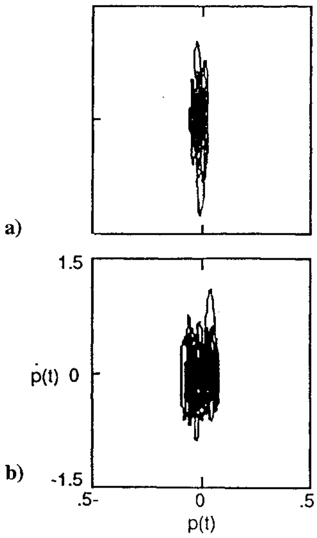

Fig. 5 Wall pressure fluctuations phase: a) turbulent boundary layer and b) with pure-tone sound.

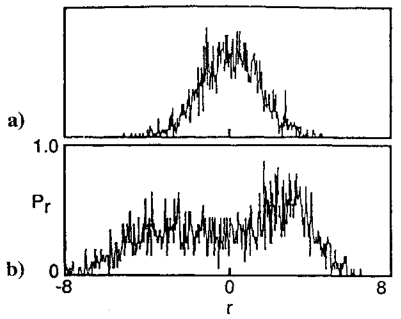

Fig. 6 Wall-pressure probability: a) turbulent boundary layer and b) with pure-tone sound.

average convection velocity $U_c = 0.7U_e$. The space–time correlation over the complete surface can be used as the forcing field for the flexible structure response. The wall-pressure fluctuation in the presence of a turbulent boundary layer and pure-tone sound is fully correlated over the entire surface and, thus, the results are not shown. This indicated that the loading over the structure significantly increases with the added pure-tone sound, since both amplitude and correlation area increase.

The real-time wall-pressure fluctuations over the rigid surface $p(t)$, power spectral density $P(f)$, phase $\dot{p}(t)$ vs $p(t)$, and probability P_r, are shown in Figs. 3–6. The wall pressure indicates distinct differences in power and distribution levels when forced by pure-tone sound. The real-time wall-pressure fluctuations become dominantly periodic, and the power spectral density is characterized by a broadband response with superimposed tonal harmonics. Both the real-time and spectrum plots show the presence of subharmonics, one by the modulated amplitude in the time plot, and the other by the presence of highly damped broadband peaks in the spectrum. The damping is attributed to the time-averaging processes. The phase plots are skewed, indicating convection and rotation. The probability plot from the turbulent boundary layer alone has a quasizero mean and is symmetric, whereas the plot with the superimposed pure tone has a nonzero mean. The large skewness indicates once more the convection and nonlinearity effects. Thus, the superposition of a pure-tone sound on a turbulent boundary layer significantly changes the distribution of the pressure fluctuations over the rigid surface.

B. Panel Response and Active Control

The static deflection of the panel at the test section is on the order of the panel thickness. Hence, the panel oscillation is governed by the nonlinear plate equations.[23] The deflection is exerted by the static pressure difference between the pressure in the tunnel test section and the ambient pressure outside. The broadband space–time correlation of the acceleration response is measured with four equally spaced accelerometers along the panel centerline. The first accelerometer is located 0.076 m from the stringer, and the others are spaced 0.183 m apart. The correlation coefficient of the acceleration $Re_g(X_1, X_2; \tau)$ indicates that the panel response is prominently excited by convected waves along the line $(X_2 - X_1) - U_c\tau = \text{const}$ (Fig. 7). The results show that the convected wave velocity in the panel motion matches the convected wave velocity of the boundary-layer pressure fluctuation (Fig. 2). The result reproduces the previously well-known fluid structure coupling effect, known as the aerodynamic coincidence effect, the transfer mechanism of energy between the flow and the structure. The space–time correlation of the panel response exhibits a quasilocal action, due to the forced input from the turbulent boundary-layer convected loading: whereas with the superimposed pure-tone sound loading, the pressure became fully correlated over the entire surface of the panel. Thus, the presence of sound significantly enhances the structural loading.

Figure 8 shows the instantaneous panel acceleration $g(t)$ obtained from the accelerometer located on panel B (Fig. 1). The normalized power spectral density $G(f)$, phase $\dot{g}(t)$ vs $g(t)$, and the probability P_r are shown, respectively, in Figs. 9–11. In Figs. 8–11 there are four plots: a) turbulent boundary layer alone, b) with pure-tone sound, c) with partial control, and d) with total control. The pure-tone frequency of 505 Hz and the harmonics exceed the broadband level induced by the turbulent boundary layer in excess of 20-dB power. The panel response from the turbulent boundary layer is a typical broadband random response.[9] Results are shown in Figs. 8–11. In the presence of sound, the acceleration response spectrum shown in Fig. 9b is characterized by the broadband response with seven harmonics superimposed, because the amplitude of the fundamental tone (driven frequency) is saturated. The figure reveals the presence of rich harmonic content, which does not exist at the source. The

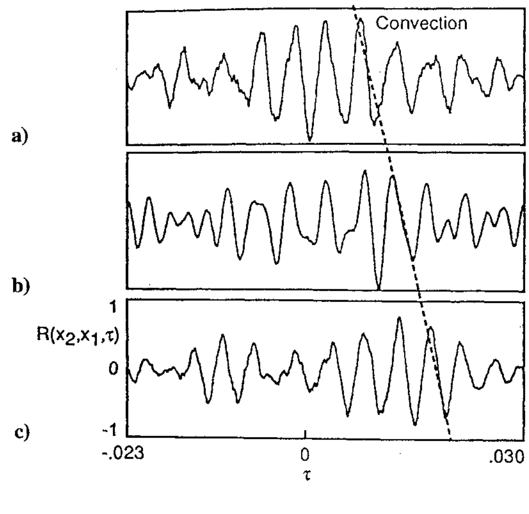

Fig. 7 Panel broadband space–time correlation of the acceleration response: a) $(X_2 - X_1)$ = 0.183 m, b) $(X_2 - X_1)$ = 0.366 m, and c) $(X_2 - X_1)$ = 0.549 m.

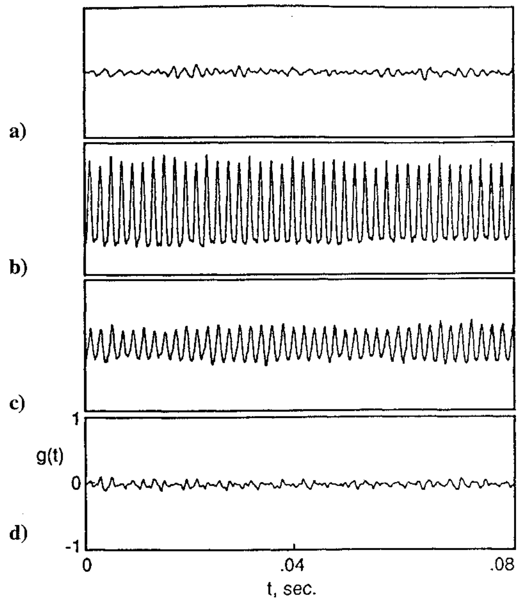

Fig. 8 Instantaneous panel acceleration: a) turbulent boundary layer, b) with pure-tone sound, c) partial control, and d) total control.

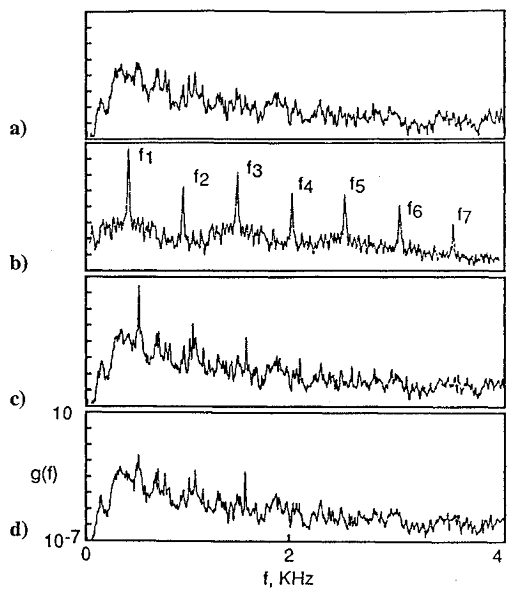

Fig. 9 Power spectral density of the panel acceleration: a) turbulent boundary layer, b) with pure-tone sound, c) partial control of the harmonics, and d) total control.

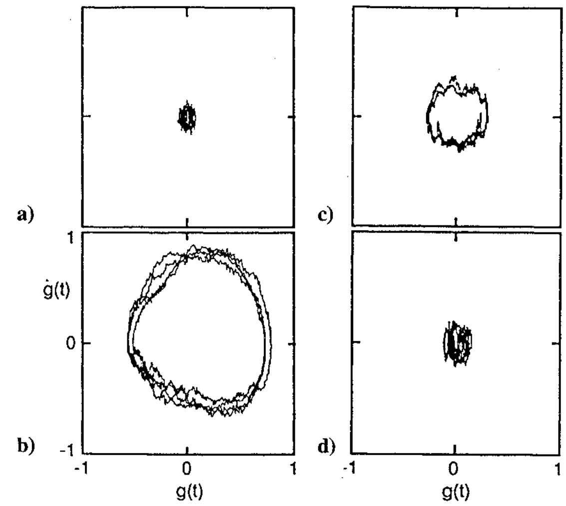

Fig. 10 Power spectral density of the panel acceleration: a) turbulent boaundary layer, b) with pure-tone sound, c) partial control of the harmonics, and d) total control.

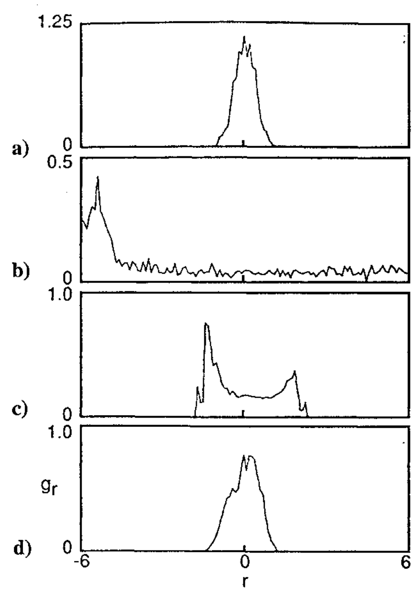

Fig. 11 Acceleration response probability: a) turbulent boundary layer, b) with pure-tone sound, c) partial control, and d) total control.

presence of harmonics f_2–f_7 is an indication of the energy transfer from the fundamental and low-frequency band to the harmonics due to the panel boundary layer. The nonlinear transfer of energy from the low-frequency broadband to the harmonics of the panel motion and vice versa is coupled to the mechanism that induces broadband response in the turbulent boundary layer itself via aerodynamic coincidence, as shown in Figs. 2 and 7.[9,14] This coupled energy transfer between flow and structure can be utilized most beneficially in reducing the noise transmission and the structural fatigue. Even in the absence of flow, we have observed that the higher harmonics have amplitudes that are a sensitive function of the driven amplitude of the fundamental.[23] Thus, conclusively we can state that the high-intensity sound is the cause of nonlinear behavior in the structure and is manifested by the presence of harmonics, period doubling, and the non-Gaussian probability multidistributions, as shown in Figs. 8–11. In addition, the panel response does not scale linearly with the input level, and for this reason, switching occurs from periodic to aperiodic and back to periodic state in time.

As a result of the nonlinear behavior of the panel response, it is also advisable to analyze the data using higher order statistics when the process is stationary. This requires the decomposition of the third and fourth moments to get the bispectrum and trispectrum information. The analysis will provide some new and useful information.

The control of the panel response is obtained by forcing the structure at the pure-tone fundamental frequency through a phase and amplitude tuning procedure. The control technique is developed in two stages. In the first stage, the controller operating at the fundamental frequency forces for panel with proper amplitude and phase such that the energy of the harmonics is shifted back into the fundamental tone and the low-frequency band (Figs. 8b and 8c). This is the reverse process of forming the harmonics by the acoustic excitation. The second stage is to control the fundamental amplitude level (Fig. 8d) by further increasing the phase angle. In this exchange, the energy shifts from the fundamental tone back to the low-frequency band. As the spectrum level of the damped low-frequency band increases, it resembles the original wall-pressure fluctuation spectrum in the absence of pure-tone sound, both in shape and amplitude (compare Figs. 9a and 9d). The redistribution of energy is very similar to that obtained in an earlier simple experiment without flow for the control of the subharmonics.[21]

The total control, which includes the control of both harmonics and the fundamental, requires a higher degree of sophistication in the controller operation, accompanied by fine tuning of the system. Experiments were carried out using two controllers. The results are not as good as a single controller placed at the center of the panel. This shows that a single controller with a single incident forcing frequency is an efficient device for controlling the harmonics in the panel response. Note that in the experiment the incident wave is of a single frequency. If there is a complex forcing field with several frequencies not integral multiples of each other, we may need more than one controller.

C. Transmitted Wave Through the Panel

The panel oscillation induces an acoustic wave in the ambient medium outside the tunnel as shown in Figs. 12–15, when the panel oscillation is forced by a) turbulent boundary layer alone, b) turbulent boundary layer with pure-tone sound, c) partial control, and d) total control. The acoustic radiation behavior follows the panel response behavior observed in real-time $p(t)$, power spectral $P(f)$, phase $\dot{p}(t)$ vs $p(t)$, and probability distributions P_r. These results indicate coupling between response and radiation. The power spectral density is a continuous broadband associated with turbulent boundary-layer excitation, with spikes from the pure tone and its harmonics when the tone is superimposed. The variation of the pressure with superimposed pure tone leads to successive doubling of the period in the phase plot (Fig. 14b). Partial control reduces the phase to a single double loop; correspondingly, the power spectrum shows a dominant fundamental peak. Full control acoustic pressure level reduces to the broadband response and relatively close to that induced by the turbulent boundary layer alone. The transmitted field from the panel is linear. The weakly nonlinear effect will appear only at large distances from the panel, much larger than the size of the panels (or the size of an aircraft fuselage).

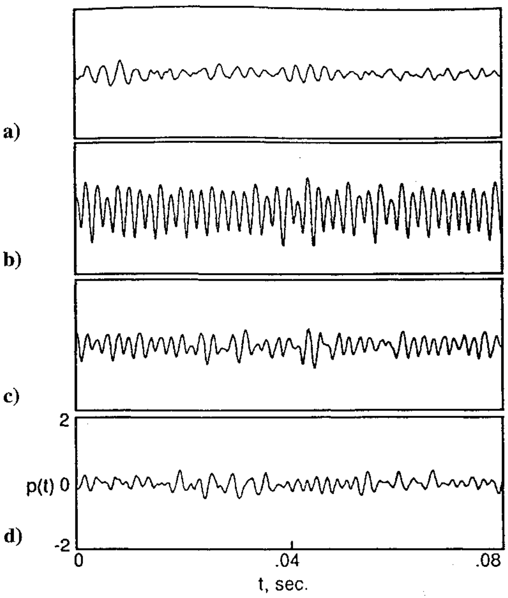

Fig. 12 Acceleration response probability: a) turbulent boundary layer, b) with pure-tone sound, c) partial control, and d) total control.

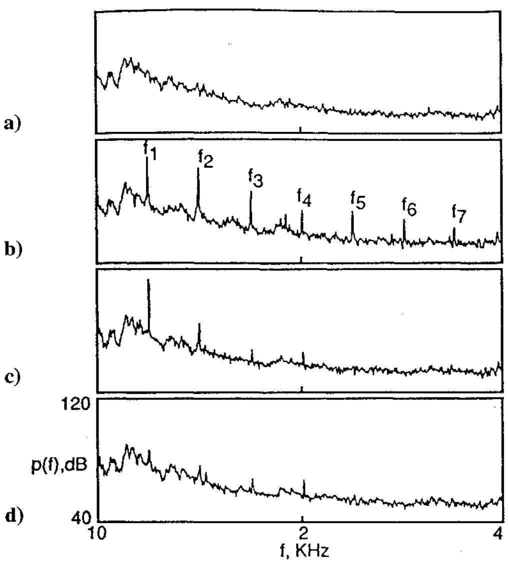

Fig. 13 Power spectral density of the near-field pressure fluctuations: a) turbulent boundary layer, b) with pure-tone sound, c) partial control, and d) total control.

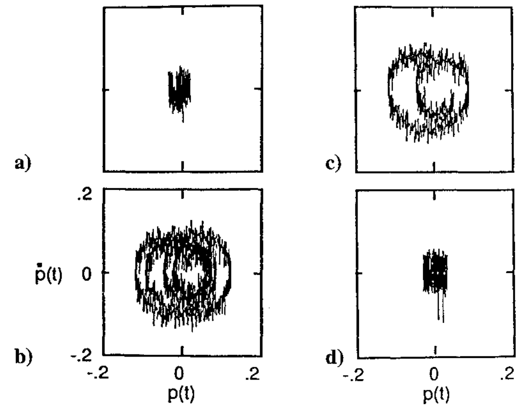

Fig. 14 Near-field pressure phase: a) turbulent boundary layer, b) with pure-tone sound, c) partial control, and d) total control.

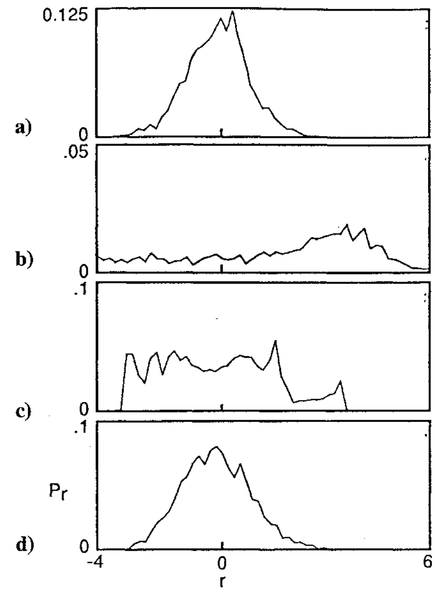

Fig. 15 Near-field pressure phase: a) turbulent boundary layer, b) with pure-tone sound, c) partial control, and d) total control.

IV. Discussion and Conclusion

Results on the boundary-layer, flexible panel, and sound interactions are essential for doing real dynamic analysis in an aircraft structure. The methods are of direct utility for extracting the physical mechanism at work in these measurements, since it is doubtful that a purely theoretical approach will generate engineering answers to the problem of nonlinear structural response induced by flow and sound. When the pure tone and harmonics emerge out of the broadband response of the panel, they provide a signal synthesis equivalent to that of an aircraft fuselage sidewall panel in flight with tone harmonics from the power plant.

The mechanism by which harmonics form becomes clear as the amplitudes of the fundamental and low-frequency band decrease with increasing level of the harmonics. The nonlinearities in the system are responsible for redistribution of the signal energy to the higher harmonics as the harmonics are phase coupled to the fundamental. This is a manifestation of energy exchange. The mechanism that generates harmonics is activated when the level of the fundamental tone reaches saturation, and then, the energy in the fundamental and low-frequency band is redistributed. The reverse procedure takes place when the control is applied.

To control the nonlinear response of the structure, one needs to assess the transfer of energy from the low-frequency band and the fundamental to the harmonics and vice versa. The dynamics of the turbulent boundary layer with superimposed pure tone on the panel are the loading of the panel creating a non-Gaussian probability distribution to the response statistics. For control, however, one requires only a single controller, since the multidimensional response of the surface motion can be simultaneously controlled by a weak periodic external input. Thus, the feedback system achieves control with a smaller number of variables than the system dimensions. The applied external force produces striking changes in the dynamics of the panel, and restores the panel response to that of the turbulent boundary-layer forcing alone.

The stability of the pure tone and its harmonics can also be achieved by a delayed self-control feedback without an external input. A delay line is required for this feedback. To achieve stability, two parameters, the time delay τ and amplitude K, of the feedback need to be adjusted in the experiment. The method consists of substituting the external signal $z_i(t)$ of the method used in the experiment for the delayed input signal $z(t - \tau)$, and using the forcing term of the form

$$F(t) = K[z(t - \tau) - z(t)] = KD(t)$$

By choosing an appropriate K of the feedback and time delay τ, one can achieve full control. Thus, the control can be achieved either by the use of an externally applied periodic oscillation or by the use of delayed self-control feedback.

The results obtained for the panel response, transmitted wave, and control of the panel have potential engineering significance. The problem is a simulation of a realistic dynamic input coupling on an aircraft type panel structure in terms of the Reynolds numbers, the boundary-layer flow parameters, and the acoustical loading. The technique developed in these studies can be used to control structural response on aircraft, and should be widely applicable to coupled fluid-structure-acoustic loading problems in industries at large.

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