Active Control of Sound Fields in Elastic Cylinders by Multicontrol Forces

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An unstiffened cylindrical model was used to study the control of sound transmission into aircraft cabins by use of multicontrol forces applied directly to the cylinder wall. External acoustic monopoles were located on each side of the cylinder to approximate the propeller noise source. This allowed the study of a dual-control system using multicontrol forces in conjunction with synchrophasing of the twin acoustic monopole sources. For acoustic resonant conditions within the cavity, a spatially averaged noise reduction of approximately 30 dB was achieved using the active control system for both in-phase and out-of-phase monopoles; however, effective reduction of the sound field was dependent upon judiciously positioning the control forces of optimal control of the sound field.

Nomenclature

a	= radius of test cylinder
A_n, B_n	= modal amplitudes for $\cos(n\theta)$ and $\sin(n\theta)$ distributions of circumferential order n, $n = 1,2,3,\ldots,N$
C_1, C_2	= angular locations of point controllers
f	= frequency
n	= circumferential mode number, $n = 1,2,3,\ldots,N$
r,x,θ	= cylindrical coordinates
S_1, S_2	= angular locations of error sensors
ϕ	= synchrophase angle between the acoustic monopole sources

Introduction

MUCH recent work has centered on development of alternative means of interior noise reduction in advanced turboprop aircraft. One proposed method is based on using vibrational forces applied to the aircraft fuselage in order to modify its response in such a manner as to reduce the interior noise levels. This technique has been designated "active vibration control," but is distinguished from the conventional meaning of this term in that the primary function of the control system is the reduction of the contained sound field, and thus does not necessarily result in (or require) a decrease in the overall vibrational response of the elastic shell.

Preliminary experiments on a closed cylindrical shell excited by an exterior monopole source have demonstrated that the new method has much potential.[1] Reductions of the order of 10 dB were found throughout the cylinder with just one control actuator (i.e, point control force). More recent work has centered on the development of a working active control system and an investigation on the nature of the control process.[2] It was demonstrated by Fourier decomposition that the main reason for the observed good performance of the system was an interface modal filtering effect (IMF). Although the exterior noise source excited a range of circumferential shell modes, only a few of these were well coupled to the interior space. Hence, as only the well-coupled structural modes of the shell need to be reduced in amplitude, the number of control actuators (i.e., control forces) required was small.

In this paper, further investigations on the performance and behavior of the active control system are described. In particular, the number of exterior acoustic noise sources is expanded to two in order to be more representative of the aircraft situation. Likewise, the number of control actuators is increased from one to two in order to investigate the nature of orthogonal control forces. With symmetrically located acoustic monopoles, the additional effects of synchrophasing is considered as the monopoles are easily varied between "in-phase" and "out-of-phase" conditions. Thus, the control performance characteristics of a dual-control system (i.e., active control in conjunction with synchrophasing) is studied. Results from modal decompositions of the shell and the coupled inte-

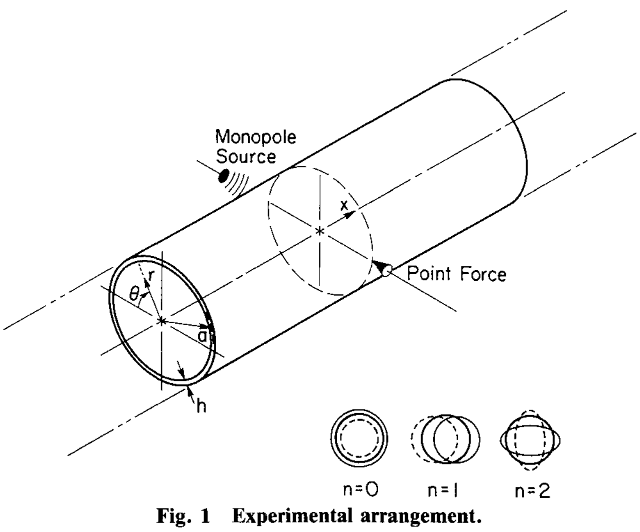

Fig. 1 Experimental arrangement.

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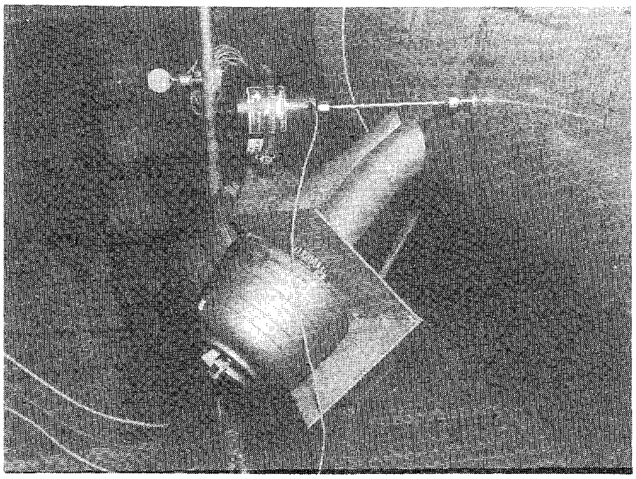

Fig. 2 Close-up view of one acoustic source and control minishaker setup.

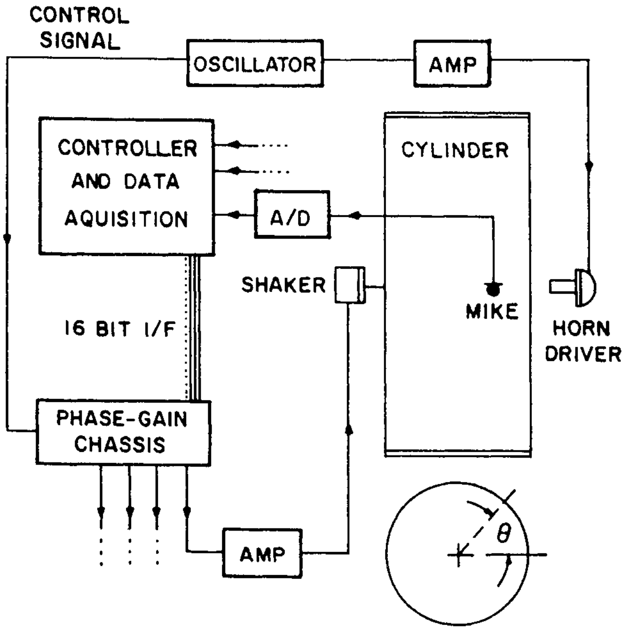

Fig. 3 Schematic diagram of the control system.

rior pressure response clearly demonstrate the mechanisms of control by the dual-control system.

Experimental Arrangement

A schematic diagram of the experimental arrangement along with the first three circumferential modes of vibration is shown in Fig. 1. Briefly, it consists of a finite unstiffened aluminum cylinder 0.508 in diameter, 1.245 m long, and 1.63 mm thick. The test cylinder was suspended in a $2.3 \times 2.6 \times 4$ m anechoic chamber to simulate the free-field conditions of flight. The cylinder was closed at its ends by wooden end caps and had rings of vibration-damping material located near each end in order to reduce the sharpness of its resonant response, thus imitating some of the damping traditionally found in aircraft cabins.

The test cylinder was excited by twin exterior acoustic monopole sources, symmetrically located just below the horizontal centerline of the cylinder so as not to interfere with the control minishakers (Fig. 2). Extension tubes were attached to the monopole sources and rotated up to 45 deg so as to closely approximate the symmetric acoustic loading on the fuselage model characteristic of a twin-engine turboprop configuration; however, as the sources were not diametrically opposite, some slight asymmetric loading was induced on the shell.

Figure 2 also shows a close-up view of the control minishaker (i.e., point controller) attachment to the test cylinder. The minishaker controllers were attached point-wise to the shell wall by use of a small swivel stinger and a 2.54 cm diameter mounting base that was machined to match the curvature of the shell wall and attached to the wall using an instant bonding glue.

To facilitate the descriptions of the differing experimental configurations, the symbols C_1 and C_2 are used to denote the angular locations of the control minishakers. Similarly, S_1 and S_2 represent the angular locations of the microphone error sensors. In both cases, the angular coordinates are consistent with θ as shown in Fig. 1. Radial and axial locations are described as a nondimensional ratio of the position with respect to the cylinder's radius (i.e., r/a and x/a). Thus, $r/a = 0$ represents the centerline of the cylinder, while $r/a = 1$ represents the principal axis of the shell wall. Similarly, $x/a = 0$ denotes the source plane.

The interior pressure response (amplitude and phase) was measured using three 13 mm (½ in.) condenser microphones mounted on a movable traverse at radial stations $r/a = 0.150$, 0.513, and 0.925. For optimization of the dual-control system, typically a single interior microphone was used as an "error sensor" to formulate a quadratic cost fuunction to be minimized. For this investigation, the cost function was defined as the time-averaged mean-square pressure averaged over the specified numbers of designated error sensors (i.e, control microphones). For the cases with a single error sensor, the sensor was located in the source plane (i.e., $x/a = 0.0$) at $S_1 = 0$ deg and $r/a = 0.925$. This location was chosen because it corresponds to an antinode of the dominant acoustic mode present in the cavity for the test frequency studied. A single differing case used an additional error sensor in the source plane at $S_2 = 45$ deg and $r/a = 0.925$. Reasons for this will be apparent later. The associated radial acceleration of shell (amplitude and phase) also was measured at various angular locations using small exterior-mounted accelerometers. Using this information, the circumferential shell and pressure responses were decomposed into their relative modal components to determine the modal character of the shell and interior acoustic field. This information was useful in identifying the fundamental characteristics of the dual-control system. All microphone and accelerometer signals were conditioned, amplified, and filtered of high-frequency noise using anti-aliasing filters before data acquisiton, postprocessing, and final output.

Control System

Figure 3 shows a schematic diagram of the data acquisition and control system, along with associated instrumentation. The multi-input/multi-output control system is centered around a "host" IBM PC computer with a high-speed data acquisition board that had both acquisition and control capabilities. An oscillator was used to generate a reference control signal for both the primary acoustic sources and the secondary control actuators. For primary excitation, the reference control signal was amplified and used to drive the twin acoustic monopole sources. The acoustic sources (including instrumentation) were phase-matched so that the relative phase between the sources (i.e., the synchrophase angle) could be easily varied between $\phi = 0$ deg and $\phi = 180$ deg by reversing the leads to one of the acoustic sources. Hence, the primary signal was specified a priori and was not subsequently varied by the control system. The secondary control signals to the minishakers were specified by the phase/gain chassis under the direction of the minimization algorithm. The phase/gain chassis divides the harmonic reference control signal into twin channels for individual modification in amplitude and phase. The phase/gain chassis was remotely controlled by the minimization algorithm via a 16-bit digital I/O port installed on the "host" IBM PC. Although the reference signal for the control actuators was generated by an oscillator, in practice this reference signal could be easily taken from an externally located microphone, as the action of the controllers does not significantly influence the external sound field.

The interior acoustic levels at the control microphones (i.e., the error sensors) were acquired using the A/D board on the IBM PC and evaluated to formulate the quadratic cost function for the minimization process. As discussed previously, the cost function was defined as the mean-square pressure amplitude spatially averaged over the specified number of error sensors. Hence, the formulated cost function was generally quadratic in each of the control variables with a single global minimum as discussed in Ref. 3. The control variables in this case were the complex amplitudes of the signals to the control actuators. The control algorithm used in this investigation was of the form of an adaptive LMS minimization technique of Ref. 4; however, the technique was modified slightly to more fully utilize the quadratic nature of the cost function to speed convergence. The minimization technique was started by arbitrarily setting initial conditions for the control parameters and evaluating the resulting cost function. Each control parameter was individually stepped and the cost function was re-evaluated. This allowed the gradient of the cost function to be calculated with respect to each control variable by difference methods. The control variables then were stepped simultaneously along the gradient in the direction of minimization, and the cost function was again re-evaluated. Movement along the gradient was repeated three additional times, doubling the step size with each change in the control parameters. Due to the known quadratic nature of the cost function, a second-order LMS curve fit was calculated based on the five points evaluated along the gradient (i.e., the initial condition and the four additional points). By setting the first derivative of the LMS curve fit to zero, the values of the control parameters that minimized the cost function along the gradient were calculated explicitly. The control variables then were changed to reflect the calculated minimum along the gradient and taken as the starting point for the next iteration. This procedure was repeated until satisfactory reduction of the cost function was achieved. Thus, the dual-control system presented above illustrates the main components of an adaptive control system.

Experimental Method

A harmonic driving frequency of 680 Hz was chosen for this investigation because it was within a range of typical scaled fundamentals of the propeller noise based on the ratio of the diameter of small-body and business aircraft to that of the test cylinder. This frequency also was chosen because it corresponded to an $n=2$ acoustic resonance within the cavity. Hence, this frequency represented a relatively simple interior acoustic sound field and was useful in demonstrating the basic control characteristics of the dual-control system.

The experimental method used in this investigation is described below. The error sensors (i.e., the control microphones) were positioned as required for each configuration studied, and the active control system was used to minimize the cost function as discussed previously. The interior pressure response of the cavity then was evaluated at 24 equally spaced circumferential positions in the source plane for each radial station by rotating the interior microphone traverse. The pressure response was evaluated for three "excitation cases" of the primary (noise) source, the secondary (control) source, and the composite "noise and control" source. Similarly, the associated shell response was evaluated at 24 equally spaced circumferential positions in the source plane for the same three "excitation conditions." The angular pressure response and associated shell response also were evaluated for one axial location out of the source plane at $x/a = -1.0$.

In postprocessing, the circumferential shell and pressure responses were decomposed into their relative modal components to determine the modal character of the shell and the corresponding pressure response for each configuration studied. The notation assumed for the modal amplitudes are A_n and B_n for $\cos(n\theta)$ and $\sin(n\theta)$ distributions of circumferential order n, respectively. As discussed previously, knowledge of the modal character of the shell and interior acoustic field is critical to understand the controlling mechanisms of this active control technique. The highly localized nature of the secondary control forces resulted in strongly excited higher-order modes; hence, the Fourier decomposition of both the shell and coupled pressure response was truncated at the $n=11$ circumferential mode. As shown in Ref. 5, the resonant frequencies of the circumferential modes greater than the $n=11$ were well above the driving frequency of interest; thus, contributions for these modes were minimal, resulting in little or no spatial aliasing.

Results and Discussion

As discussed in Ref. 5, the acoustic and structural modes of the test cylinder can be categorized into two reciprocal sets of phased modes. The even A_n modes (e.g., A_0, A_2, A_4, etc.) and the odd B_n modes (e.g., B_1, B_3, B_5, etc.) have an optimum synchrophase angle of $\phi = 180$ deg and thus were designated the ϕ_{180} modes. Conversely, the off A_n modes (e.g., A_1, A_3,A_5, etc.) and the even B_n modes (e.g., B_0,B_2,B_4, etc.) have an optimum synchrophase angle of $\phi = 0$ deg and hence were designated the ϕ_0 modes. Also discussed was the fact that synchrophasing alone can effectively control only one of the two reciprocal sets of phased modes due to their opposing control characteristics. Thus, the dual-control system of the current investigation will be used to demonstrate complementary control characteristics as synchrophasing is used to reduce one of the two sets of phased modes, while active control is jointly used to reduce members of the opposing set of modes.

In-Phase Monopoles

Figure 4 shows the circumferential pressure distribution in the source plane at $r/a = 0.925$ for the three "excitation cases" studied with in-phase monopoles (i.e., $\phi = 0$ deg). As expected with in-phase sources, a strongly excited A_2 acoustic mode is present in the cavity due to the zero phasing (i.e., $\phi = 0$ deg) corresponding to the unsynchrophased condition for the dominant A_2 mode. "Nodal response" of the A_2 mode (i.e., the response at $\theta = 45$ deg, 135 deg, 225 deg, and 315 deg) in the noise source distribution is somewhat clipped, indicative of the presence of a subordinate B_2 mode. The B_2 mode is ac-

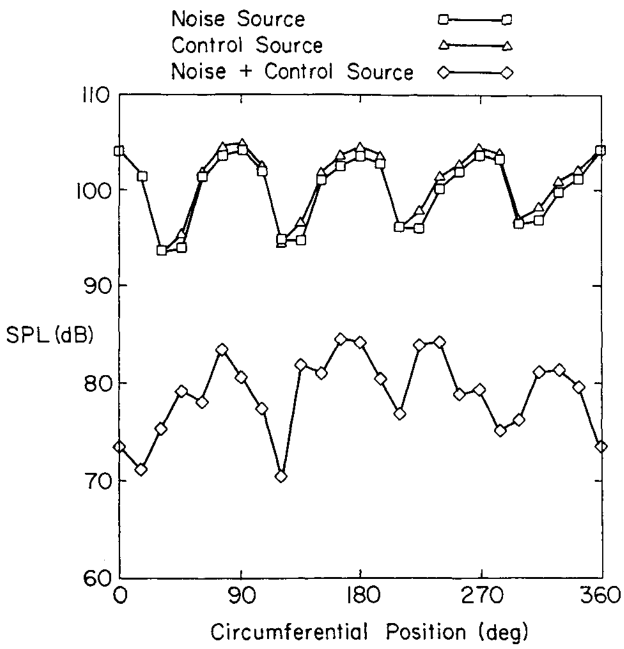

Fig. 4 Circumferential pressure distribution in the source plane at $r/a = 0.925$ with in-phase monopoles and $f = 680$ Hz.

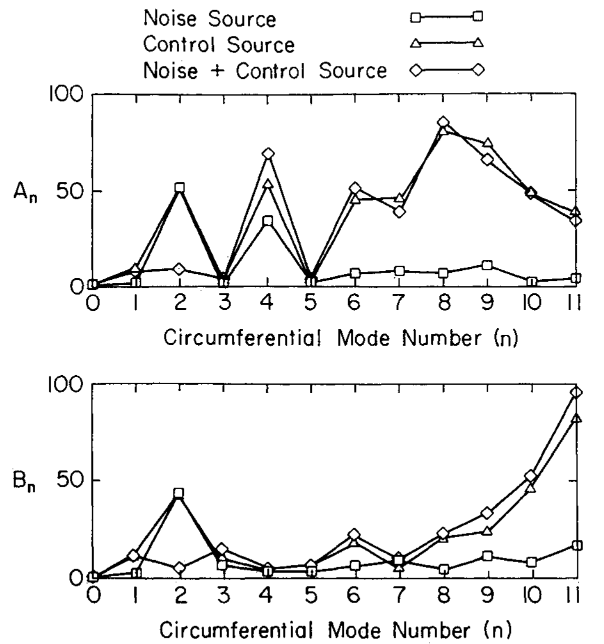

Fig. 5 Relative modal amplitudes of shell response in the source plane with in-phase monopoles and $f = 680$ Hz.

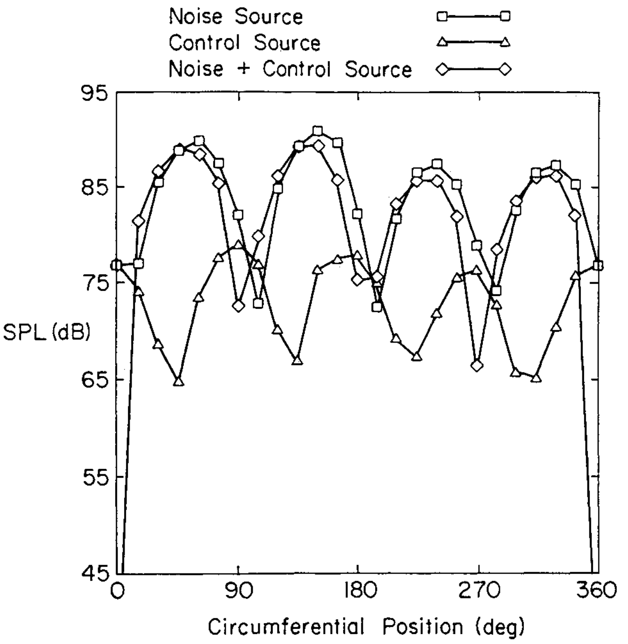

Fig. 6 Circumferential pressure distribution in the source plane at $r/a = 0.925$ with out-of-phase monopoles and $f = 680$ Hz.

tually a composite mode comprised of two elements; a coupled element, which is generated by the A_2 mode due to the coupling effect of the seam,[5] and an uncoupled element, which is generated by slight acoustic source asymmetry. For this configuration, the B_2 mode is predominantly due to the coupling effect of the seam as the uncoupled element is controlled by the synchrophasing effect. This coupled element of the B_2 mode is as yet uncontrolled because it is not directly generated by the twin acoustic sources and thus is not effectively reduced by the synchrophasing effect. The control source distribution reflects an accurate representation of the noise source distribution even near the nodes of the A_2 mode. This result is due to the fact that the excitation generated by the secondary control forces (i.e., minishakers) also exhibits the modal coupling effect associated with the seam. Hence, with synchrophasing reducing the uncoupled element of the B_2 mode and active control reducing the coupled element, excellent global attenuation of the interior sound field is now possible even though none of the controllers is independently well coupled to the composite B_2 mode.

As discussed in Ref. 5 on propeller synchrophasing, in-phase monopoles represent a worst case for the ϕ_{180} modes such as the A_2 mode. Thus, using in-phase monopoles at this frequency, synchrophasing provides little benefit in noise reduction except to reduce to the small uncoupled element of the B_2 mode. In addition, a consequence of the unsynchrophased monopoles is substantial control spillover into the well-coupled A_2 acoustic mode that is displayed by the high acoustic levels present in the cavity. Control spillover is a phenomenon that occurs when part of the control energy is "spilled" into uncontrolled modes of the shell (or coupled interior acoustic cavity), thus increasing the vibrational energy of these modes. Nevertheless, action of the control forces compensates for the acoustic spillover in the cavity and attenuates the A_2 mode dramatically. Thus, this result demonstrates the compensating nature of the composite control system that allows the constituent control systems to offset the unfavorable characteristics of each other.

Figure 5 presents the modal response of the shell in the source plane for the three "excitation cases" considered using in-phase monopoles. The shell response due to in-plane monopoles (i.e., located at $x/a = 0.0$) is governed by the A_2, B_2, and the A_4 structural modes. The distributed nature of the acoustic loading tends to excite the lower-order structural modes more strongly than the higher-order modes. From the control source distribution, the action of the control forces accurately reproduces the "controlled" A_2 and B_2 modes with a 180 deg phase shift, resulting in substantial reductions in these structural modes. However, an undesirable consequence of the control action is the substantial amount of control spillover in the shell. For 680 Hz, the control spillover is distributed over several higher order structural modes of the shell. These modes correspond to the structural resonances in the test shell that are closest to the driving frequency. For 680 Hz, these resonances (Ref. 5) are, in order of proximity of frequency, the (5,9), (5,10), (5,6) and the (5,11) structural modes. Here, the (5,9) mode, for example, denotes five axial half-waves and nine circumferential waves in the shell. It is interesting to note that a majority of the control spillover is contained in the ϕ_{180} modes (e.g., the A_4, A_{16}, A_8, and B_{11} modes). This result is a consequence of the synchrophasing effect reinforcing these modes while partially attenuating the reciprocal ϕ_0 modes. Although substantial control spillover occurs in the shell, the spillover is constrained to the shell and thus does not contaminate the interior sound field. This behavior is a result of the IMF characteristic that effectively filters the acoustic contributions of most of the uncontrolled structural modes in the shell (Ref. 2).

Out-of-Phase Monopoles

Figure 6 shows the circumferential pressure distribution in the source plane at $r/a = 0.925$ for the three "excitation cases" studied using out-of-phase monopoles. Comparing the noise source distribution due to in-phase and out-of-phase monopoles, it is immediately apparent that control performance of the composite control system using out-of-phase monopoles (i.e., $\phi = 180$ deg) is dramatically reduced in comparison to the in-phase response (i.e., $\phi = 0$ deg). Also, the pressure distribution of the out-of-phase monopoles is clearly characteristic of a dominant B_2 mode as opposed to the A_2 mode, which governs the in-phase response. By varying the synchrophasing angle of the composite control system to $\phi = 180$ deg (out-of-phase monoploes), the previously dominant A_2 mode is almost completely suppressed, leaving a subordinate B_2 mode to govern the pressure response. This reduction is a result of the synchrophasing influence of the composite control system. With out-of-phase monopoles, the control source distribution now differs significantly from that of the noise source and has

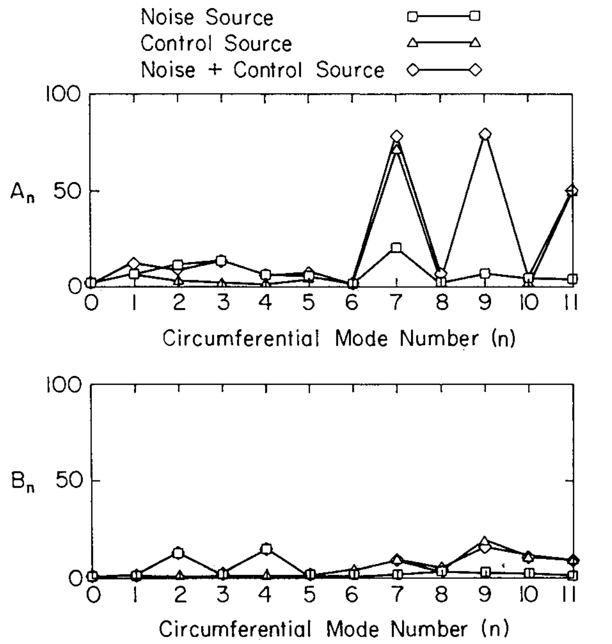

Fig. 7 Relative modal amplitudes of shell response in the source plane with out-of-phase monopoles and $f = 680$ Hz.

a modal pattern similar to an A_2 mode. Using the single sensor located at $\theta = 0$ deg (i.e., the node of the governing B_2 mode), the control system cannot effectively detect the presence of the B_2 mode. Hence, the main effect of the active control component of the composite control system is to reduce the small residual response in the A_2 mode uncontrolled by the synchrophasing effect. If a second sensor was located to detect the pressure of the B_2 mode (e.g., at an antinode of this mode), the control system still would have difficulty controlling the sound field because the controllers, being located at $\theta = 0$ deg and 180 deg (i.e., at the nodes of the B_2 mode), would not be able to effectively couple into this mode. Thus, for this configuration, noise reduction by the dual-control system is mainly due to synchrophasing that controls the resonant A_2 mode. The limited benefit of the companion active control system is principally caused by the control forces being poorly positioned. In other words, both the active control and synchrophasing systems are setup to control the ϕ_{180} modes, leaving the ϕ_0 modes (and specifically in this case the B_2 mode) uncontrolled.

It is interesting to note that although active control did not produce any additional global reduction, it did dramatically reduce the pressure response at the location of the error sensor (i.e., $\theta = 0$ deg, $x/a = 0.0$, and $r/a = 0.925$). This result is similar to that of Zalas and Tichy,[6] who demonstrated localized control of propeller-blade-passage noise in the vicinity around the error sensors. They concluded that an increased number of control sources would be required for global reduction of the sound field over a reasonable volume. For this configuration, the problem is not due to an insufficient number of control forces but rather the poor choice of the location. If the controllers were positioned at the antinodes of the remaining B_2 mode (e.g., at $C_1 = 45$ deg and $C_2 = 135$ deg), then the composite control system would likely produce an additional global reduction of 5-10 dB. Thus, to demonstrate the companion control capabilities of the dual-control system for out-of-phase monopoles, this experiment was repeated with the two controllers located at $C_1 = 45$ deg and $C_2 = 135$ deg. Results of this experiment will follow immediately after further discussion of the present configuration.

Figure 7 shows the modal decomposition of the shell response for the three "excitation cases" considered using out-of-phase monopoles. A comparison of the shell response results using in-phase monopoles (Fig. 5) and out-of-phase monopoles (Fig. 7) indicates several interesting characteristics. With in-phase monopoles, the structural response of the shell is governed by the A_2 and the A_4 modes. Conversely, using out-of-phase monopoles, the A_2 and A_4 modes as well as other lower order ϕ_{180} modes are clearly suppressed, while the opposing ϕ_0 modes (such as the A_7 mode) are comparatively enhanced. Hence, the synchrophasing component of the dual-control system provides excellent control characteristics for one of the two reciprocal sets of phased modes. Also, since the input mobilities of the ϕ_0 modes are generally lower than the ϕ_{180} modes, only minimal control spillover occurs in the shell, predominantly within the A_7 modes. Thus, the distributed nature of synchrophasing effect has the favorable characteristic of lower spillover in the shell, which has significant importance in application, as increased vibrational levels of the fuselage could increase the probability of fatigue failure within the structure.

Comparing the modal shell distributions of the control source for in-phase and out-of-phase monopoles (Figs. 5 and 7, respectively) again indicates substantial control spillover within the shell due to the highly localized nature of the control forces as previously discussed. The control spillover for in-phase monopoles is comparatively larger due to an increase in the control energy required by the point forces for reduction of the contained sound field. For this frequency, the control spillover is distributed over a number of higher-order shell modes. These modes, as discussed previously, correspond to the closest structural resonances in the test shell. It is interesting to note that for out-of-phase monopoles, the synchrophasing effect of the joint control system reduces control spillover associated with the secondary controllers for the ϕ_{180} modes (such as the A_6, A_8, and A_{10} modes), while enhancing control spillover in the reciprocal ϕ_0 modes (such as the A_7 and A_9 modes). Conversely, for in-phase monopoles, the ϕ_0 modes appear to be somewhat more strongly excited than the ϕ_{180} modes. Although control spillover is substantial for both in-phase and out-of-phase monopole configurations, the spillover is predominantly constrained to the shell by the IMF effect and thus does not contaminate the interior sound field. Hence, in the joint control system, the synchrophasing effect can be used to effectively control a series of modes in the shell and coupled acoustic cavity, given that all the modes have similar optimum synchrophase angles. In contrast, "active vibration control" generally requires an equivalent number of point controllers as modes to be controlled.

As shown by Lester and Fuller,[3] the task of active control methods is to reproduce the interior pressure field with a 180 deg phase shift. Rather than using several acoustic sources spatially distributed within the cavity as used in more conventional active control techniques, the reproduction is possible by synchrophasing with a single symmetric source located exterior to the shell. This result appears to violate control theory, which states that to effectively control a specified number of modes, at least an equal number of secondary controllers as modes to be controlled are required. However, this limitation does not hold if the secondary (control) sources are well matched in model distribution (both amplitude and phase) to the primary sources. In other words, if the forcing function of the controller on the shell induces a similar spatial distribution to that of the primary source, then the controller could be symmetrically positioned to control a series of modes generated by the primary acoustic source. This symmetric location is dependent on the set of modes to be controlled. However, generally speaking, the primary and secondary source distributions are dissimilar; thus, control theory dictates the use of at least an equal number of secondary sources as modes to be controlled for effective reduction of the sound field.

Figure 8 shows shaded contour maps for the primary (noise) and composite sound fields for both in-phase and out-of-phase monopoles. Here, areas of darker shading represent lower pressure levels, while areas of lighter shading (or the white unshaded areas) represent higher pressure levels. How-

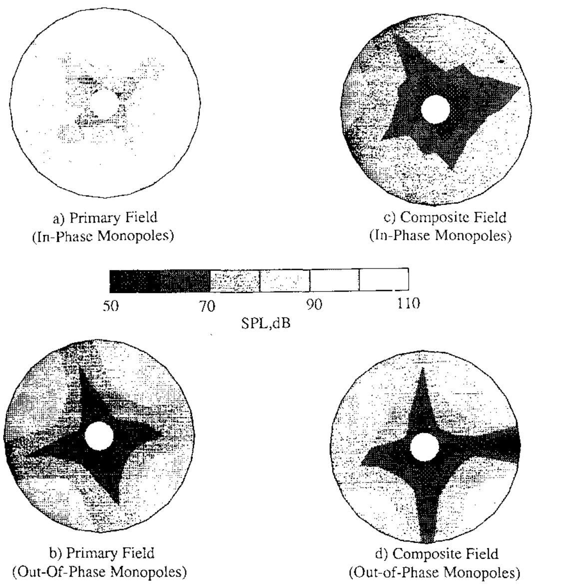

Fig. 8 Contour maps of the primary and composite sound fields in the source plane for in-phase and out-of-phase monopoles and $f = 680$ Hz.

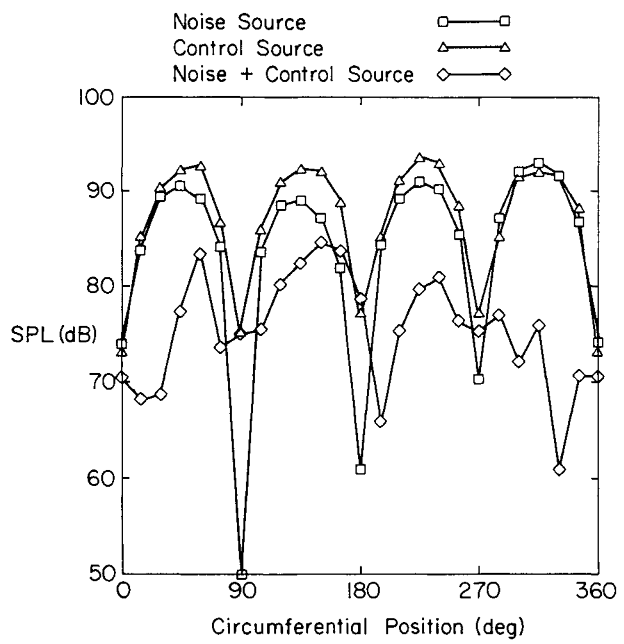

Fig. 9 Circumferential pressure distribution in the source plane at $r/a = 0.925$ with out-of-phase monopoles and $C_1 = 45$ deg, $C_2 = 135$ deg, and $f = 680$ Hz.

ever, the contour region only extends between the limiting radial stations of $r/a = 0.925$ and $r/a = 0.150$; thus, the small unshaded hole at the center of each contour plot (i.e., $r/a < = 0.150$) represents an unevaluated region and not an area of high pressure response.

The in-phase and out-of-phase primary sound fields represent the unsynchrophased and synchrophased conditions of the dominant A_2 mode *without* active control. A comparison of the two primary sound fields demonstrates the substantial noise reduction possible by synchrophasing. For the out-of-phase sound field, there is some distortion in the nodal lines from the expected $\theta = 0$ deg and $\theta = 90$ deg locations. This distortion is associated with the presence of some residual response in the controlled A_2 mode, along with the governing response of the uncontrolled B_2 mode.

The in-phase and out-of-phase composite sound fields represent the unsynchrophased and synchrophased conditions of the dominant A_2 mode *in conjunction with* active control. A comparison of these contour maps indicates noticeably better control performance using in-phase monopoles than out-of-phase monopoles. However, this result is misleading because the control forces are optimally located for the resulting pressure distribution associated with in-phase monopoles but not for that of the out-of-phase monopoles. The action of the point controllers for the out-of-phase monopoles clearly reduces the residual A_2 mode but is unable to couple to the governing B_2 mode. This result is characterized by the nodal lines now along $\theta = 0$ deg and $\theta = 90$ deg, indicative of a dominant B_2 mode. In other words, the noise reduction using out-of-phase monopoles is largely due to the synchrophasing effect, with little benefit from active control. For this case, the optimal location of the control forces would be at the antinodes of the uncontrolled B_2 mode rather than its nodes. Thus, the out-of-phase results do not fully reflect the noise reduction capabilities of the composite control system.

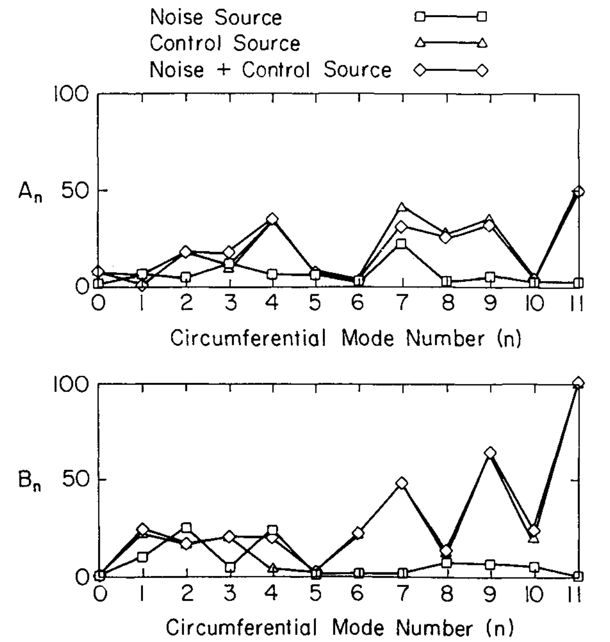

Fig. 10 Relative modal amplitudes of shell response in the source plane with out-of-phase monopoles and $C_1 = 45$ deg, $C_2 = 135$ deg, and $f = 680$ Hz.

Out-of-Phase Monopoles With Controllers Located at $C_1 = 45$ deg and $C_2 = 135$ deg

In order to clearly demonstrate the complementary characteristics of the companion control systems, the two control forces were relocated at $C_1 = 45$ deg and $C_2 = 135$ deg as discussed above. In addition, two error sensors located at $S_1 = 0$ deg and $S_2 = 45$ deg were used to detect the presence of A_2 and B_2 modes, respectively. Thus, with this configuration, synchrophasing should reduce the dominant A_2 mode, whereas active control jointly reduces the subordinate B_2 mode.

Figure 9 presents the circumferential pressure distribution in the source plane at $r/a = 0.925$ using out-of-phase monopoles in conjunction with two control forces located at $C_1 = 45$ deg and $C_2 = 135$ deg. It is immediately apparent that by optimally locating the control forces, the performance of the dual-control system using out-of-phase monopoles is enchanced, resulting in a lower and more uniform composite source distribution. For this configuration, effective utilization of the control forces increases the spatially averaged noise reduction by approximately 10 dB. The composite source distribution indicates that the control forces provide the complementary benefit of controlling the remaining B_2 mode as predicted. Hence, by independently controlling the two orthogonal modes present in the acoustic cavity simultaneously, synchrophasing and "active vibration control" clearly

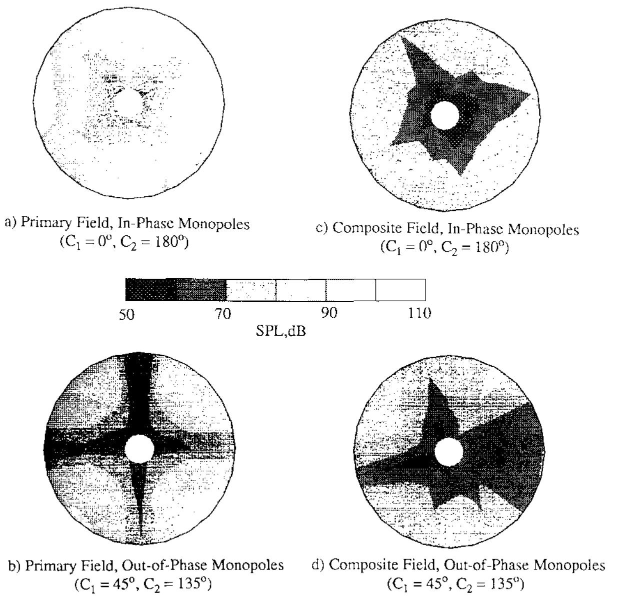

Fig. 11 Contour maps of the primary and composite sound fields in the source plane for in-phase and out-of-phase monopoles with optimally located controllers at 680 Hz.

exhibit complementary control capabilities when using out-of-phase monopoles as well as in-phase monopoles.

Figure 10 shows the associated modal decomposition of the shell response using the optimally located control forces. As in the previous cases, the composite control system still produces control spillover in the shell; however, due to the relocation of the control forces, the spillover is contained mostly in the higher order B_n modes. As expected, the action of the control forces produces some reduction in the B_2 structural mode; however, considering the rather dramatic reduction in the acoustic response of this mode, the minor reduction in the shell response seems inconsistent. The reason for this behavior may be associated with the nonlinear characteristic of the resonant B_2 acoustic mode. The coupling effect between the shell and the contained acoustic cavity has a threshold response level above which the shell will effectively couple to the interior acoustic field. However, below this threshold level the coupling will be substantially lower. Thus, near this threshold level small reductions in the shell response potentially can produce substantially larger reductions in the acoustic cavity.

Figure 11 shows the primary and composite shaded contour maps for in-phase monopoles with $C_1 = 0$ deg and $C_2 = 180$ deg, and out-of-phase monopoles with $C_1 = 45$ deg and $C_2 = 135$ deg.

As discussed previously, the in-phase and out-of-phase primary sound fields represent the synchrophased and unsynchrophased conditions *without* active control. Similarly, the in-phase and out-of-phase composite sound fields represent the synchrophased and unsynchrophased conditions *with* active control. With the control forces optimally located for both configurations, this figure now demonstrates the full benefits of the composite control system. The overall level of reduction using out-of-phase monopoles is now equal to that of in-phase monopoles. The excellent control performance using both in-phase and out-of-phase monopoles demonstrates the complementary characteristics of the dual-control system, as synchrophasing and active control are used to control the A_2 and B_2 modes, respectively, without any significant spillover in the acoustic cavity. In addition, the considerable increase in control performance of out-of-phase monopoles with optimally positioned control forces in comparison to nonoptimally positioned control forces demonstrates the importance of controller location on the effectiveness of a composite control system.

All the results presented above for the aircraft model configurations were evaluated in the source plane. However, for each of these configurations, similar out-of-plane measurements were acquired at $x/a = -1.0$. Results from these measurements were in all cases nearly identical to the source plane (i.e., $x/a = 0.0$) results and thus are not shown. Hence, the discussions presented above for the source plane measurements apply globally throughout the test cylinder.

Concluding Remarks

A simplified model of an aircraft fuselage was used to perform an experimental investigation of a dual-control system that used "active vibration control" in conjunction with synchrophasing. The characteristics of the control system were studied for both in-phase and out-of-phase monopoles. The results of this experimental work demonstrated several important conclusions.

Using active control in conjunction with synchrophasing, the dual-control system displayed enhanced control performance, as the two constituent systems clearly demonstrated complementary control capabilities. Using the dual-control system, spatially averaged reductions on the order of 30 dB were achieved. However, control of off-resonant excitation would likely be more difficult, as the modal distribution of the sound field would become increasingly complex. Thus, global noise reduction under these conditions probably will be less dramatic and require additional control actuators and sensors judiciously positioned to maximize noise reduction throughout the cavity.

Experimental studies by Silcox et al.[7] and Abler and Silcox[8] have demonstrated the application of active acoustical control (i.e., active control using acoustic transducers) in conjunction with synchrophasing inside a flexible cylinder. Similar to the results presented in this investigation, the companion control systems exhibited complementary characteristics that enhanced control performance beyond that of the individual systems. However, active acoustical control was shown to require twice the number of interior secondary acoustic sources as the circumferential order of the mode to be controlled. This conclusion is noticeably different from that of "active vibration control," which requires only one point controller per mode regardless of circumferential order. This difference is associated with the distributed nature of the radiating shell wall. For example, if an A_2 mode is governing the acoustic response of the cavity (as in the case presented), then the angular distribution of contained sound field has a spatially distributed four-lobed pattern characteristic of the A_2 mode. Thus, the requirement of four acoustic control sources (i.e., $2n$ control sources, where n is the circumferential order of the mode to be controlled) to effectively reproduce the four-lobed pattern is not surprising. However, in contrast, "active vibration control" uses point controllers on the shell wall to reduce the structural response of the "well-coupled" modes that are transmitting their energy into the acoustic cavity. By controlling the response at the shell wall, a single point-controller can be used to reduce the distributed A_2 structural mode and hence its coupled acoustic mode. In other words, a single point-controller applied to the shell wall can reduce the structural response of the well-coupled A_2 mode, thus decreasing acoustic transmission by the A_2 mode into the cavity. Therefore, "active vibration control" generally will require fewer controllers than active acoustical control for reduction of a contained sound field. However, an undesirable consequence of the point actuators is control energy spillover into other uncontrolled structural modes of the shell. Yet, because of the IMF effect discussed previously, the spillover energy is predominantly constrained to the shell and thus does not contaminate the acoustic space. This discussion of active control techniques is not intended to imply that "active vibration control" is superior to active acoustical control. In fact, in some applications, the converse may be true. The purpose of this discussion is to identify and explain some of the similarities and differences between the two techniques.

Along with the discussion above, several important conclusions can be identified:

1) Location of the control actuators was shown to strongly influence the performance of the dual-control system.

2) Localized control action of the point actuators resulted in substantial control spillover in the shell. Spillover tended to be contained in the uncontrolled structural modes whose resonant frequencies were closest to the driving frequency. However, control spillover was predominantly constrained to the shell because acoustic contributions from the higher order uncontrolled modes of the shell were filtered by the IMF effect.

3) The increase in vibrational energy in the shell is an undesirable consequence of the point-controller action because of the increased potential for fatigue failure in the structure. However, spillover can be controlled by application of additional controllers.

4) "Active vibration control" and synchrophasing demonstrated complementary control characteristics that allowed the companion systems to simultaneously control orthogonal modes.

5) The active control system performed equally well using either in-phase monopoles or out-of-phase monopoles, as synchrophasing was employed to reduce one of the two reciprocal sets of modes present in the cavity, whereas "active vibration control" was employed to reduce the opposing set of modes.

6) Due to its distributed nature, control spillover in the shell associated with synchrophasing tended to be substantially less than that of "active vibration contol."

The simplified experimental model used in this investigation is instructive in identifying the characteristics and mechanisms of a dual active control system for application in reduction of low-frequency sound transmission into cylindrical cavities.

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