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AN EVALUATION OF ACTIVE NOISE CONTROL IN A CYLINDRICAL SHELL

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SUMMARY

This paper examines the physical mechanisms governing the use of active noise control in an extended volume of a cylindrical shell. Measured data was compared with computed results from a previously derived analytical model based on infinite shell theory. For both the analytical model and experiment, the radiation of external monopoles is coupled to the internal acoustic field through the radial displacement of the thin, elastic cylindrical shell. An active noise control system was implemented in the cylinder using a fixed array of discrete monopole sources, all of which lie in the plane of the exterior noise sources. Good agreement between measurement and prediction was obtained for both internal pressure response and overall noise reduction. Attenuations in the source plane greater than 15 dB were recorded along with a uniformly quieted noise environment over the entire length of the experimental model. Results indicate that for extended axial forcing distributions or very low shell damping, axial arrays of control sources may be required. Finally, the Nyquist criteria for the number of azimuthal control sources is shown to provide for effective control over the full cylinder crossection.

INTRODUCTION

Requirements for the control of low frequency noise in enclosed spaces, especially for aerospace applications, have recently taken on more importance. This can be attributed to the need for increased noise reduction with a minimum of additional weight. Traditional methods for low frequency noise control dictate a mass law dependence for increased transmission loss through the sidewall. Aerospace vehicles such as the advanced turboprop aircraft, helicopters and space station are extremely weight sensitive in their implementation and all suffer from noisy interiors, particularly at low frequencies. One innovative technique currently under study is active noise control. This technology utilizes additional interior noise sources to provide control of the acoustic cabin environment. Recent developments in digital signal processing hardware allow this technology to be utilized for noise control in the audio range upwards to 1000 Hz. Furthermore, advances in adaptive control techniques will allow control to be maintained in complex, time-varying, spatial domains.

The work of Zalas and Tichy[1] was the first active noise control system to be implemented in an aircraft flight test. The complex structure of the aircraft however, tended to mask the underlying mechanisms of structural-acoustical coupling. Bullmore et al[2], examined the nature of the noise environment and the necessary placement of control sources, but did not consider the true distributed nature of the pressure excitation over the exterior of the fuselage. More recent results[3] demonstrated the interface modal filtering (IMF) effect of the radiation mechanism for noise fields excited by a cylindrical shell. Finally, the work of Lester and Fuller[4] showed how the coupled acoustic-structural problem may be modelled and evaluated the theoretical performance of active noise control in a fuselage model.

The work to be reported here is an initial experimental validation of the analytical work reported in reference 4 as well as an evaluation of the physical mechanisms that govern the operation of an active control system in a finite length cylinder. Descriptions of the analytical model used and the laboratory apparatus are given. A comparison of predicted and measured pressure fields inside the cylinder are shown with and without the control sources operating. For the same case, the measured extent of noise control within the finite cylinder is shown. Analytically, the effect of the number of sources on the noise suppression is demonstrated and related to the nature of the externally versus internally driven acoustic fields.

MODELS AND APPARATUS

The approach to this research was a balance of analytical modeling and experiment. The analytical approach allowed investigation of the theoretical limits of the concept and an experimental program of reasonable scope to be defined. The experimental program provided a validation of the theory as well as an evaluation of mechanisms inherent only in true physical systems with discrete control system characteristics.

Analytical Model

Figure 1 shows the model used for the analytical development. A complete description of the analytical model was given in reference 4. Here, the fuselage was represented as an infinitely long, uniform, elastic cylinder of radius a and thickness h. The cylinder was driven into vibration by two exterior monopole sources representing propeller noise sources. The analytical solution assumed a steady state response and the exterior and interior acoustic fields were coupled by the radial displacement of the cylinder wall. This approach preserved the fluid loading and radiation damping effects. Both the shell response and the interior acoustic response were expressed as finite series of modes.

Interior control sources were placed judiciously within the interior space in the plane of the exterior sources. The coupled structural-acoustical response relations for these sources were then superimposed on that for the interior solution due to the exterior sources. An expression for the sound power integrated over the source plane was then minimized with respect to the complex control source inputs. This yielded a set of complex matrix equations for the optimum control inputs which were solved and substituted into the pressure response expressions to produce the minimized composite interior noise field.

Experimental Apparatus

Figure 2 is a photograph of the experimental apparatus. An existing model cylinder of length 1.22 meters, a diameter of 0.8 meter and wall thickness of 1.02 mm was used. Two acoustic drivers (one hidden in the photograph) on either side of the cylinder (fig. 2a) approximated the monopole sources used in the analytical model. These two sources were always driven at identical amplitudes but were either in-phase (0 degrees) or out-of-phase (180 degrees) with respect to one another. Finally, the reference microphone was used to set the levels of the external sources as well as to sample the pressure distribution on the exterior of the cylinder. The interior view (fig. 2b) shows four interior drivers (control sources) configured at 90 degree increments on the vertical and horizontal axes. The source locations may be adjusted as conditions warrant but for this work were configured as shown. In all cases investigated these sources were placed 2.54 cm from the interior wall in the same cross sectional plane as the exterior drivers. The internal sources were placed close to the wall in these locations in order to have maximum interaction with the radiation of acoustic energy into the internal volume. The microphone array was a linear arrangement of 10 sensors oriented on a vertical diameter at radial locations of 6.5, 14.5, 22.5, 30.5, and 38.5 cm from the centerline. Since the primary acoustic field was known to have peak levels at the source plane, the error microphone array was placed on antinodal lines 2.54 cm from the source plane. This moveable sensor array was used to map the interior pressure field.

Structural damping material on both the inside and outside walls at either end (see fig.2a) provided damping of the wall vibrations. A similar treatment with acoustical material on the interior end caps as shown in figure 2b helped damp acoustic reflections. This was intended to more closely approximate the infinite cylinder analytical model. In addition, larger transport aircraft have been found to display strong axial damping of both structural vibrations and interior sound pressure levels[5] as one moves away from the propeller plane. This is attributed to the large inherent damping of the built up fuselage structure and the interior treatment designed to reduce the cabin noise levels. Thus, a damped infinite cylinder may more closely approximate real transport aircraft than a finite cylinder without treatment.

The operation of this experimental apparatus was similar in concept to that of the analytical model. The exterior sources excited a harmonically varying interior pressure field which was mapped at various planes of the interior space with no control source input. Locating the microphone array at a fixed position, an error function was constructed by summing the mean square pressure of each microphone. Using a least mean square (LMS) steepest decent algorithm[6], the error function was minimized to some acceptable level by optimizing the control source inputs. This reduced the sound levels in some region of the interior space. Fixing the control source inputs at their optimum values, the pressure field was again mapped and the system performance determined.

Besides providing the effect of finite model length, the experimental apparatus demonstrated the effect of damped structural and acoustical systems and real sources; i.e., finite size and discrete [redacted]ed over an entire surface by integrating the mean squared pressure. Here, the spatially limited and discrete nature of the error sensor array made the control system susceptible to minimizing the pressure field at only these discrete sensor locations. The sound pressure may even increase at locations away from the sensor array. Additional work is required to identify a universal sensor configuration for arbitrary source conditions. Here this problem was addressed by locating both error sensors and control sources at pressure antinodes as determined from a subjective evaluation of the primary pressure field.

RESULTS

Figure 3 shows the exterior sound pressure level measured along the exterior axial length adjacent to the shell wall. The exterior sources are 16 cm (0.4a) from the shell wall. The pressure, as expected, is a maximum in the source plane (x=0) and is seen to fall off about 14 dB to either end, similar to typical aircraft results[5]. The model itself was suspended in a semi-reverberant environment which accounts for the slight asymmetry in this pressure distribution. The effect of operating another external source on the opposite side of the cylinder, regardless of its phase relation, had a negligible effect on the measured SPL on this side due to both shielding and near field radiation effects.

The first case to be presented is for in-phase exterior source excitation at 475 Hz. This frequency scales to a blade passage frequency of 125 hz in a 3 meter diameter fuselage, typical of present day turboprop aircraft. This will be shown to have excited a dominant acoustic mode of 2nd order in the azimuthal plane. This was predicted by theory and resulted from the symmetrical compressions and rarefactions on either side of the cylinder. This frequency was between two resonant cavity mode frequencies with a n=2 azimuthal distribution and would therefore be expected to exhibit some degree of resonant cavity behavior. The second case was a prediction of the interior field with out-of-phase source monopoles. In theory, this excited only odd modes (i.e. n=1,3,5...) but in the experiment, the 2nd order mode was only a few dB down due to its resonant character and the coupling due to slight asymmetries in the geometry and excitation. However the results in this case focus on the analytical model where the effects of control source distribution were studied in isolation from the above contaminating factors.

In-Phase Exterior Source Excitation

A comparison between prediction and measurement is presented in figure 4 for the in-phase external excitation. The pressure fields inside the cylinder are plotted as color contour plots ranging from 50 to 100 dB as shown by the color bar. The primary field represents the pressure due only to the exterior sources. The primary+control field represents the composite of the response due to both interior control and exterior sources and, relative to the primary field, demonstrates the suppression obtained. As stated, the four interior sources were placed at locations 90 degrees apart on vertical and horizontal diameters in the plane of the exterior sources. The exterior monopoles were operated in-phase at 475 Hz corresponding to a non-dimensional shell driving frequency of 0.22 and a free space acoustic wave number of 3.48. As shown in the figure for the primary field, the measured interior pressure was well predicted by the analytical model. They were both dominated by a 2nd order circumferential mode with essentially the same distribution of sound pressure level. The operation of the control sources yielded dramatic suppressions of 10 to 25 dB in SPL over the interior space as demonstrated by comparing the primary and composite (primary+control) noise contour plots. This is indicated by the change in dominant color from white to red and yellow. The prediction retained the dominant second order mode, whereas the measurement was affected by residual modes that arose in practice. The suppressions were however comparable.

Figure 5 demonstrates the global nature of the measured noise suppression of the previous case. Here, the primary field is compared to the composite field at three different axial planes. The suppression was optimized close to the x/a=0 (source) plane and the resulting performance mapped at two additional cylinder cross sections. The primary field remained fairly strong away from the source plane with the same dominant second order circumferential mode. The composite field at x/a=0 is identical to that of the previous figure. At x/a=0.5 (20 cm) the suppression remained comparable with some minor deterioration close to the wall. At x/a=0.75 (30 cm) the composite interior levels remained comparable to the previous axial station although the actual suppression had decreased. This was due to decreased interior sound levels from the primary sources at this axial location rather than an increased residual noise field. It is important to note that, although the noise suppression was optimized with the error sensor array at x/a=0, comparable noise levels were attained over the entire interior space. Thus a uniformly quieted interior space was attained.

In the two composite acoustic fields (fig. 5) at x/a=0.5 and 0.75, a 2nd order circumferential acoustic mode was discernible. This effect is illustrated further in figure 6. The axial distribution of the n=2 circumferential mode coefficient is shown for the three conditions: primary sources alone, control sources alone, and finally the composite field. These modal coefficients were determined from a 1-dimensional spatial decomposition of the pressure field near the interior wall. Note that the terms mode and mode coefficient are used only in the azimuthal domain and are not to be confused with a true 3-dimensional mode representation. The phase for the control case was shifted 180 degrees to correlate with the primary source. The n=2 circumferential mode dominated the primary noise field by 25 dB as illustrated by the previous contour plots. In the plot of the amplitude level for this acoustic mode (fig. 6a), the interior level due to the primary sources remained fairly constant for the first 0.5a length from the source plane. If this is compared to the decay of the modal field due to the interior sources, for which the decay rate is nearly linear, it may be concluded that the shell motion forced the interior acoustic field over this axial length. This effect was confirmed for the primary excitation by the small change in phase, figure 6b, of the n=2 mode over this same length. This is characteristic of the long wavelength of the structural wave compared to the cylinder length. Between x/a=0.5 and 0.75, the slope of the primary n=2 mode amplitude and phase tended to that exhibited by the n=2 mode driven by the interior sources indicating a decay of the structural excitation and a more dominant propagating acoustic field. Note that the axial wavelength of a freely propagating n=2 acoustic mode in a hard walled duct at 475 hz exhibits a 24 degree phase change over 0.25a (10 cm), very close to the phase change shown for the control source case. For axial locations greater than x/a=0.5, damping inherent in the cylinder structure, coupled with the reduced exterior forcing amplitude (fig. 3) reduced the vibrational energy such that acoustic propagation was the prime transmitter of acoustic energy.

It was this extended structural excitation driving the interior acoustic field to respond in the n=2 mode that was responsible for the reduced suppressions of the n=2 mode at locations away from the source plane. This was indicated by the increase of over 10 dB in level in the composite field n=2 mode level from x/a=0 to 0.25. The interior acoustic field of the control sources decayed at too high a rate and propagated with too short of a wavelength compared to the structurally excited wavefield to maintain control over this mode. The n=2 mode was the dominant mode at axial stations away from the source plane. However due to the axial decay of the exterior driving force as well as the shell damping, this shell excitation of interior noise was down significantly in level away from the source plane and the resultant composite interior levels were nearly uniform over the axial length of the cylinder. It should be noted that at this frequency the n=2 mode was expected to display some resonant cavity behavior, but was apparently heavily damped by the acoustic treatment on the end caps. For other cases where the resonant response is less, the matching of the exterior and interior excited pressure fields may deteriorate faster and the uniformity of the axial suppression may be significantly reduced. This would necessitate the use of an axial distribution of control sources in order to maintain effective control.

Out-of-Phase Exterior Source Excitation

The next case involved exciting the cylinder with out-of-phase exterior sources at the same 475 Hz frequency. Noise level predictions inside the cylinder are presented in figure 7 for two control source configurations. With this excitation, the primary field was dominated by the 3rd order circumferential mode thus departing dramatically from the previous in-phase case that responded in a 2nd order mode. This was due to the cylinder responding only in the odd azimuthal modes because of the inverted symmetry of the exterior source phasing. Shown in figure 8 is a 1-dimensional azimuthal modal decomposition of the interior pressure field. With all values normalized to the n=3 primary field mode amplitude, the next strongest mode in the primary field was the n=5 mode, which was 15 dB down from the n=3 mode. Referring back to figure 7, the composite field for two control sources is presented in the right insert.

The control sources were configured on the horizontal axis and provided 5 to 8 dB of attenuation in the immediate vicinity of their location but actually increased the sound level in other regions. If six control sources were used, placed at 60 degree increments starting at the horizontal axis, a much improved noise environment resulted as shown in the lower inset. Reductions in the regions where the sound was loudest amount to 10 dB or more and a much more uniformly suppressed field resulted.

In order to provide insight on why six interior control sources were needed it is necessary to refer to figure 8. In this figure, the modal pressure levels for each of the first 5 odd modes is plotted for the primary, control and composite source fields. This is plotted for both control source configurations: 2 sources in figure 8a and 6 sources in figure 8b. The primary field is the same in each figure. As stated above, the primary pressure field was dominated by the n=3 mode with the next strongest mode being 15 dB down. Remember that the control field was determined by the optimum inputs to the control system, and for 2 sources provided little overall sound reduction. In this case, it was observed that the two sources generated strong amplitudes in both the n=1 and n=5 modes as well as the n=3. This is commonly referred to as control spillover. Since these modes were not present to a significant degree in the primary field, these modes generated by the control sources added rather than subtracted from the primary acoustic field. This was seen in the composite field mode levels, where for all modes except the n=3, the levels were higher with the controller operating. If the optimization attempted to match the n=3 mode level better in order to better attenuate this mode, the contributions from the other modes generated would have increased the integrated pressure field. When six interior control sources were used (fig. 8b), the n=3 mode was generated only 1.4 dB down from that of the primary field. Equally as important, the other modes were not strongly excited, and the overall acoustic field was effectively suppressed (fig. 7). The n=3 mode showed a 16 dB reduction in this case compared to the 4.5 dB reduction in the 2 source case. The response in the n=9 mode in figure 8b was due to its being the first odd spatial harmonic of the n=3 mode and thus represented, although to a much lesser degree, a control spillover effect.

Any criteria for source locations or numbers in the circumferential plane must consider these strong control spillover effects. For this case, six control sources were found to be the minimum for effective noise control over the cylindrical crossection. However, lesser numbers of control sources can be effective if only a part of the total crossection is considered.

CONCLUDING REMARKS

Interim results of an ongoing analytical and experimental program for the evaluation of active noise control inside cylindrical shells have been presented. A previously derived analytical model was used that accounts for the fully coupled structural-acoustical interactions of thin walled elastic structures excited by exterior noise sources. An experiment was designed that implemented this active control scheme for the minimization of the interior noise field. Results and comparisons are presented as well as discussions of the physical mechanisms that affect the system configuration and performance.

The results demonstrate an excellent correlation between theory and experiment. Especially good is the prediction of the primary interior acoustic response due to the exterior sources. The predicted suppressions are equally good, but the residual pressure fields are not as well correlated. Especially gratifying, the experimental results show that the noise suppression is attainable over most of the interior volume, at least in this preliminary experiment. Theoretical predictions of the out of plane suppressions are not well correlated due primarily to the lack of damping in the shell. In practice the shell damping causes a decay of the shell response, allowing the control sources to exert control over an extended volume. However, in cases where the forced response is stronger over a larger axial length, it is expected that axial arrays of control sources may be necessary.

The results for the out-of-phase excitation demonstrate the importance of the structural-acoustical interaction on the noise environment. The coupling between the shell response and the cavity response is an effective interface modal filter (IMF) exciting only selected modes in the interior space. The interior control sources, even if excited properly, may couple into a multitude of modes unless configured properly in number. This coupling may result in a generation of extraneous modes by the control sources, which are by definition orthogonal to the desired mode, and thus uncontrollable within the restriction of a single discrete control array. If the Nyquist criteria is applied in the spatial domain (i.e. twice the number of control sources as the highest azimuthal mode order to be controlled) effective control has been demonstrated.

These results are preliminary in nature and reflect the initial experiences of this investigation. Continuing work is ongoing to enhance both the predictions and measurements as well as extending their range of applicability.

ACKNOWLEDGMENT

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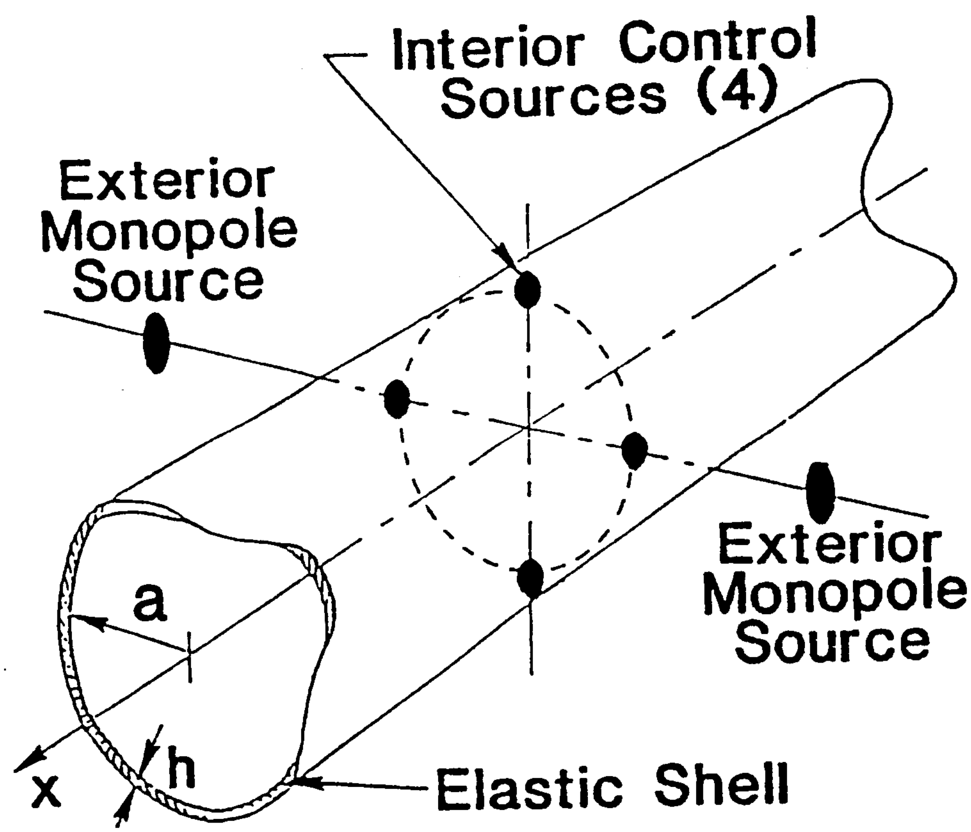

Figure 1. Schematic of infinite elastic shell and point sources of analytical model.

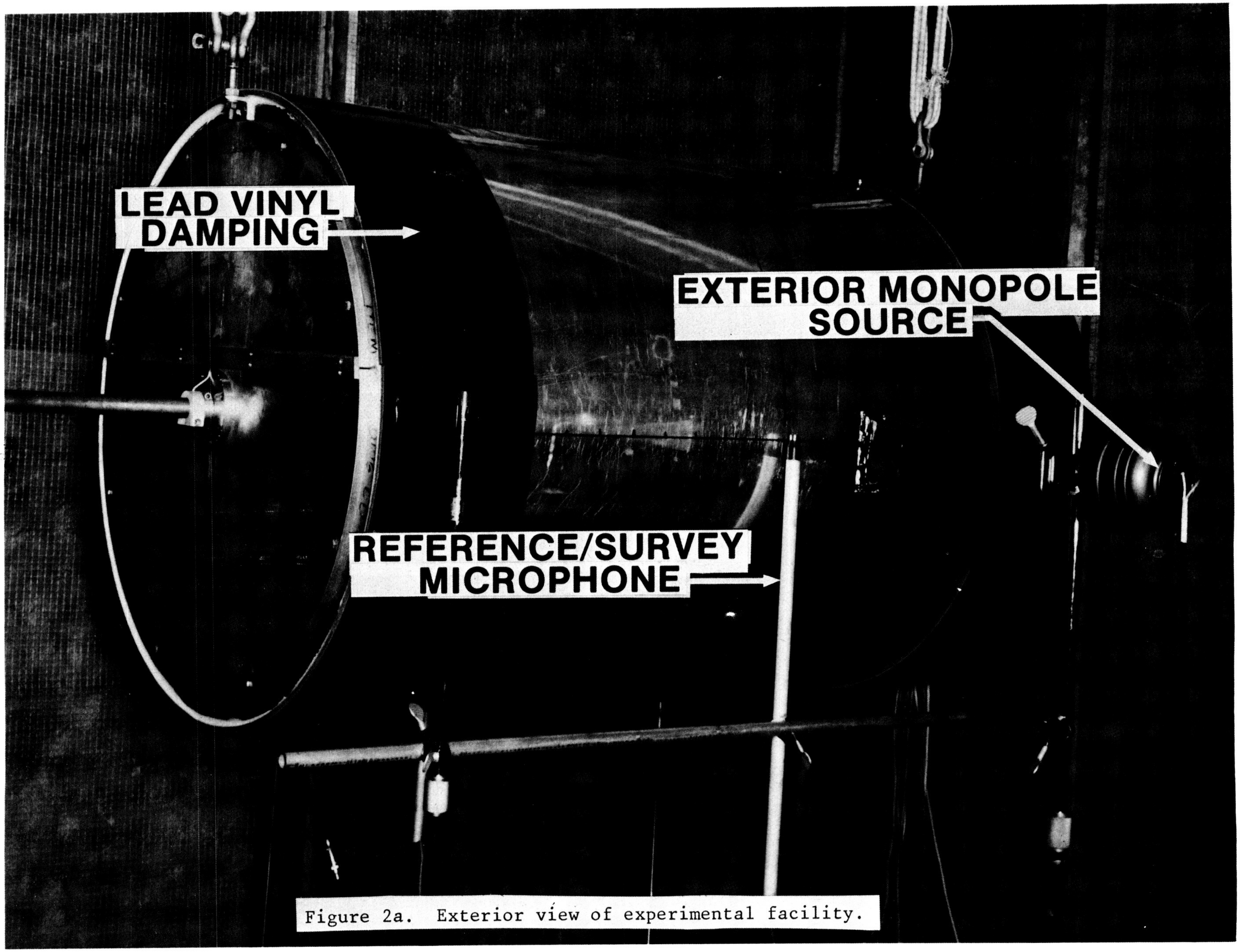

Figure 2a. Exterior view of experimental facility.

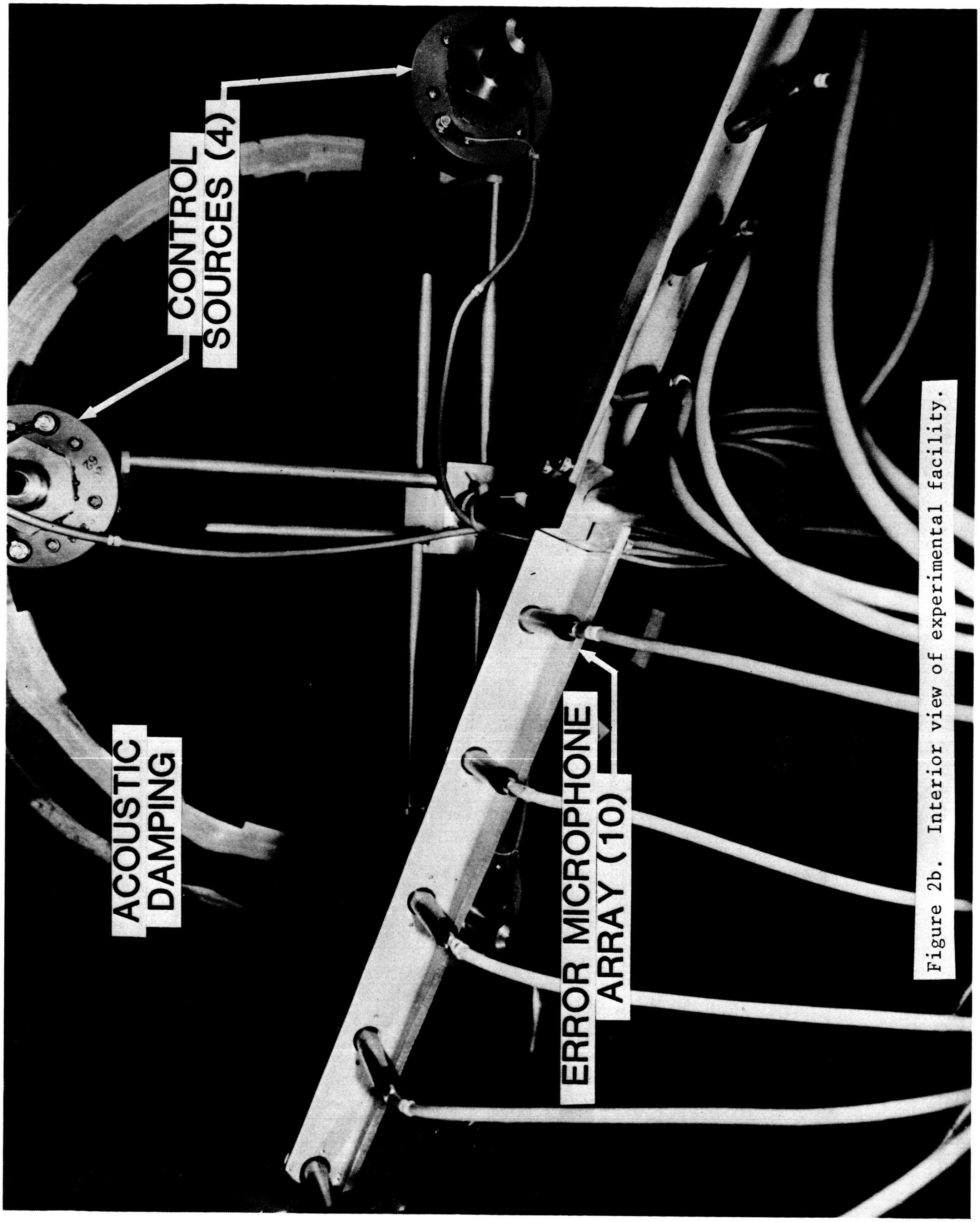

Figure 2b. Interior view of experimental facility.

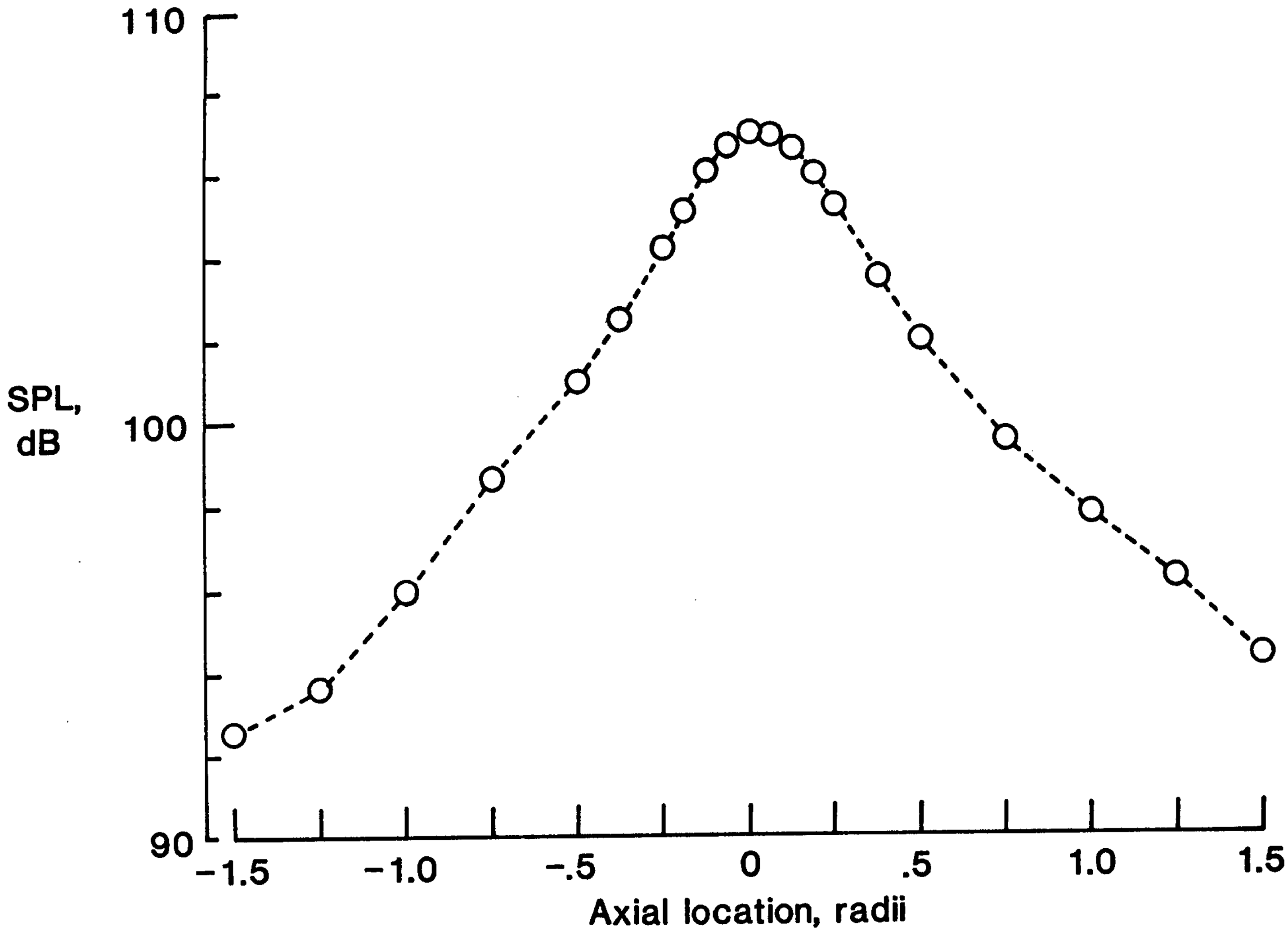

Figure 3. Exterior pressure distribution along cylinder wall in horizontal plane for 475 Hz excitation.

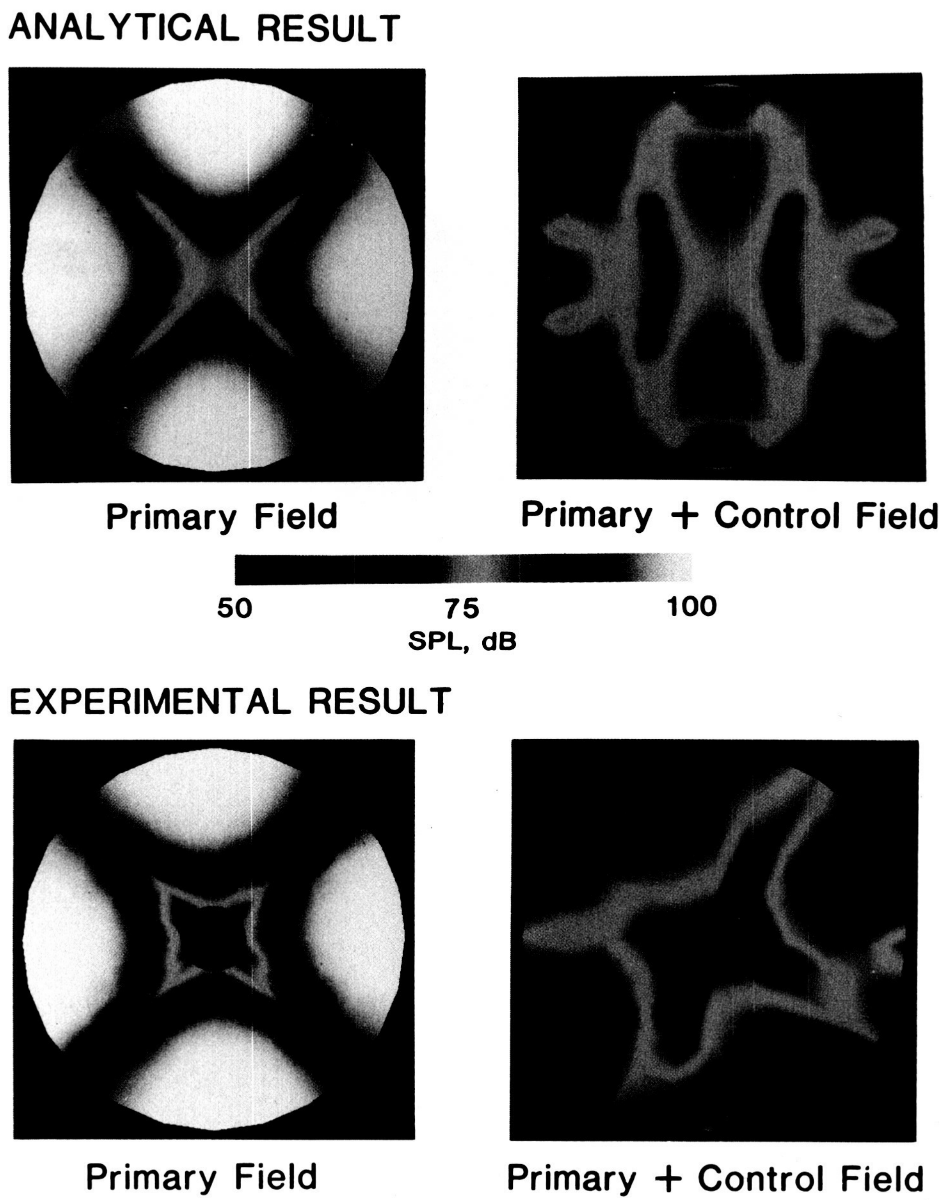

Figure 4. Comparison between predicted and measured interior pressure fields in the source plane for in-phase, external monopoles at 475 Hz.

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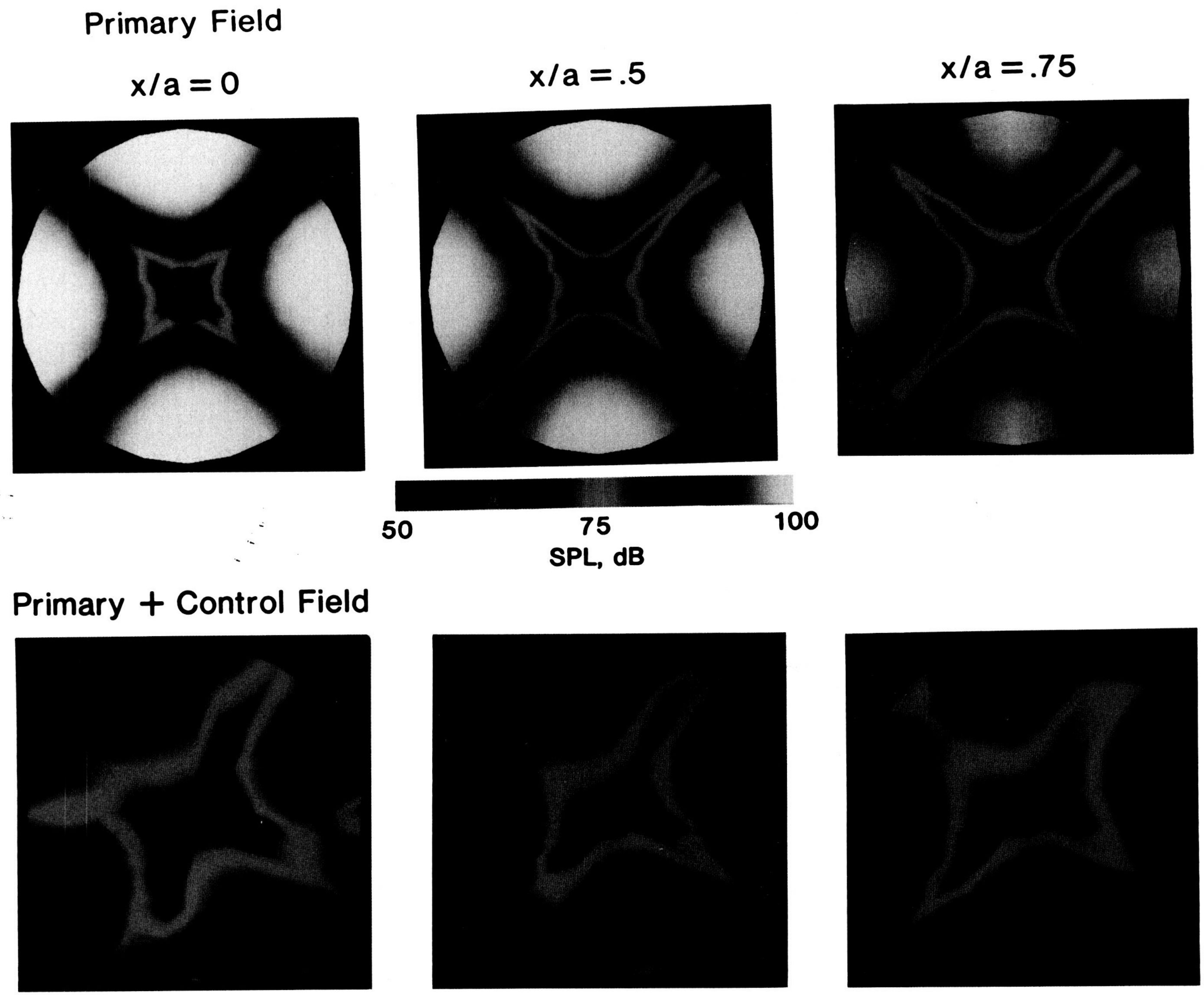

Figure 5. Evaluation of noise reductions measured inside cylinder at three axial stations.

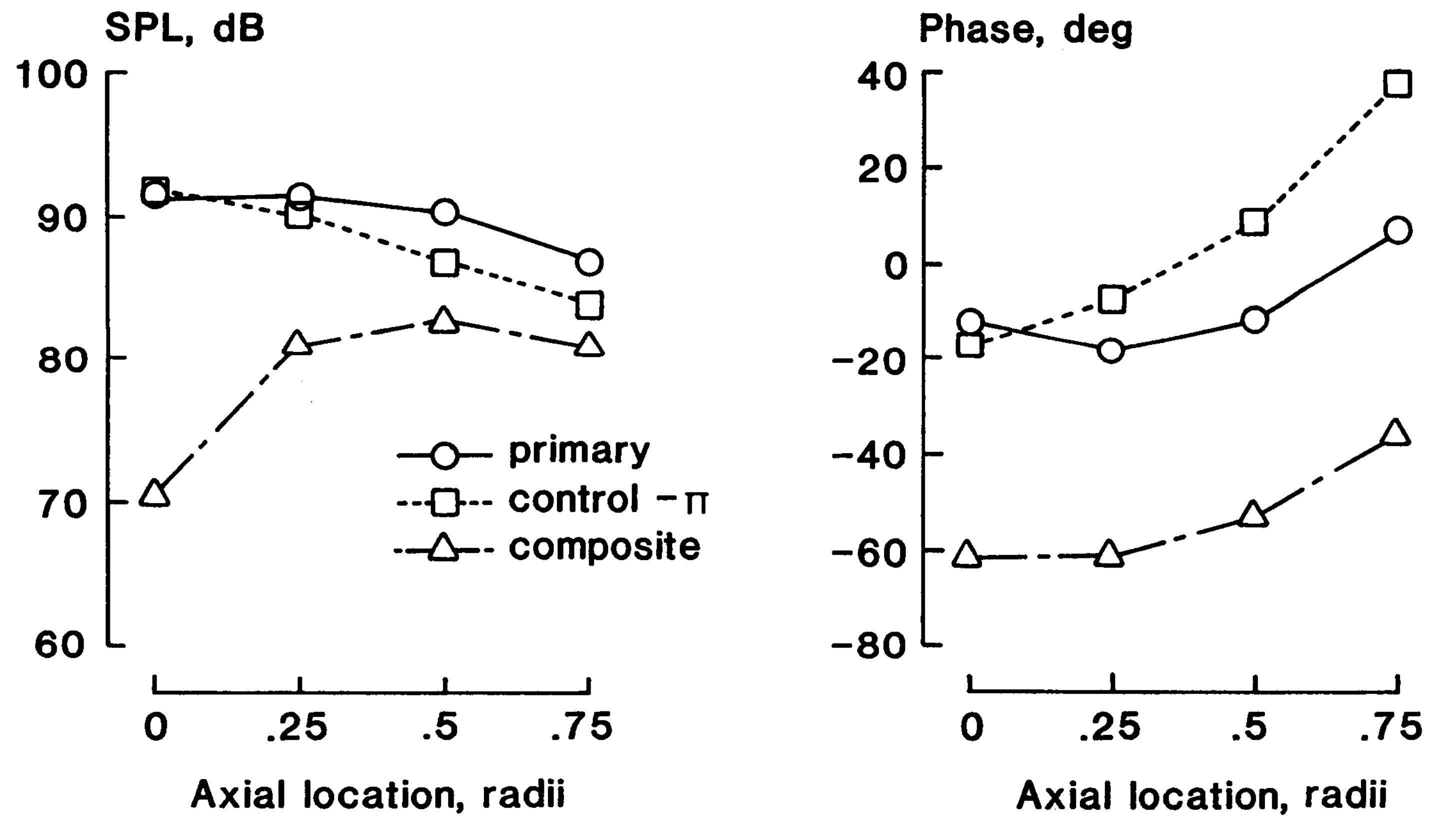

Figure 6. Measured axial distribution of 2nd order circumferential mode for three source conditions.

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COLOR PHOTOGRAPH

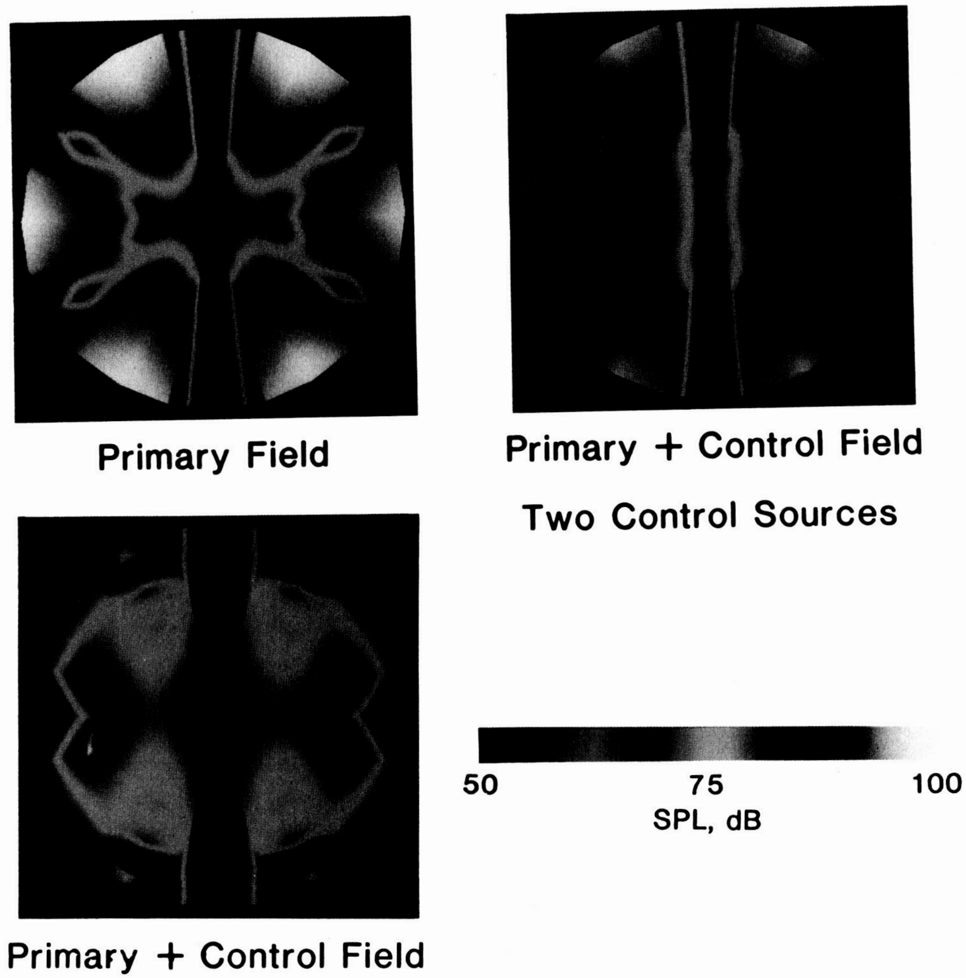

Figure 7. Analytical predictions of noise suppressions with out-of-phase exterior sources for two control source configurations.

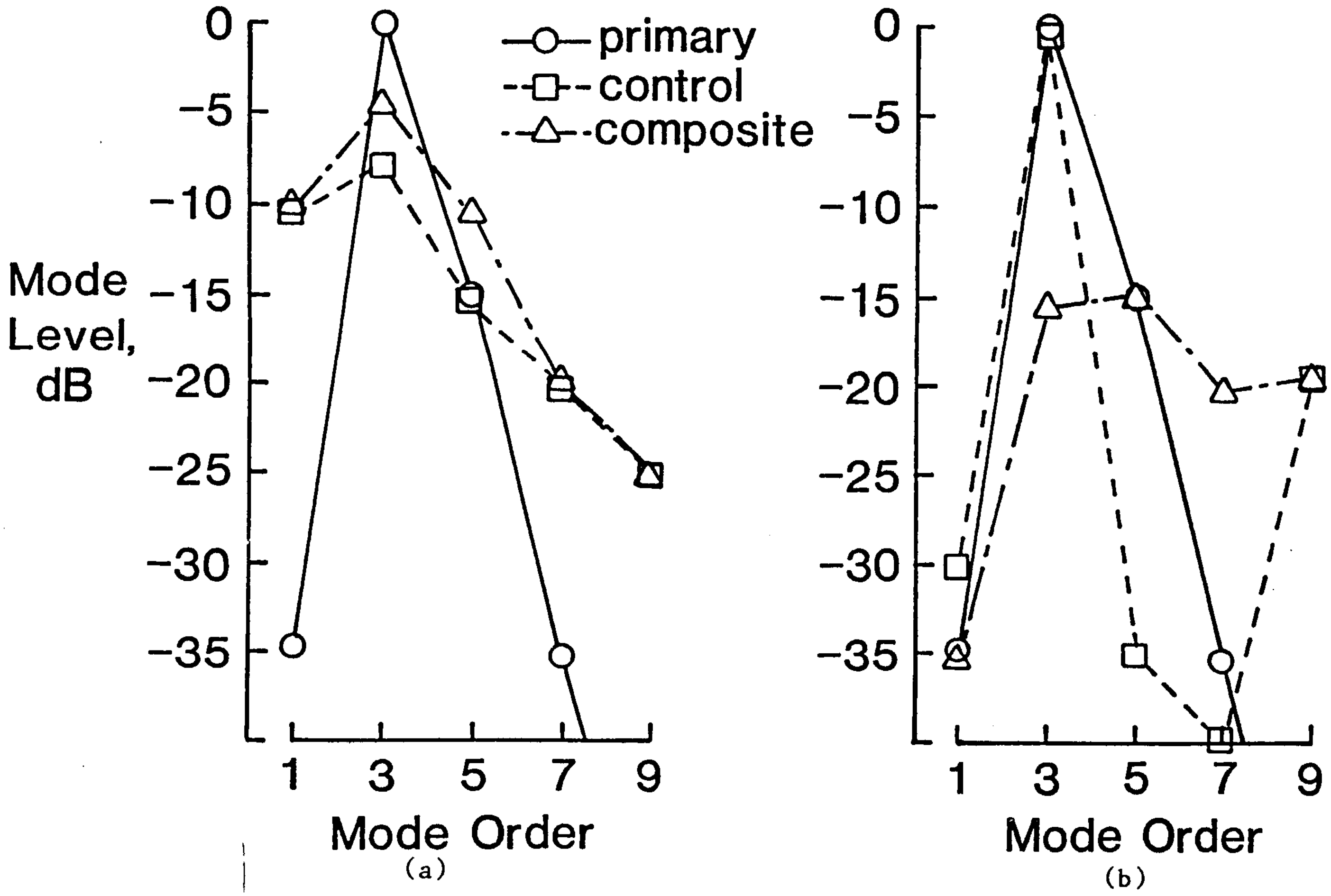

Figure 8. Modal coefficient amplitudes in source plane for out of phase exterior sources of 475 Hz, (a) two sources, (b) six sources.

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16. Abstract

This paper examines the physical mechanisms governing the use of active noise control in an extended volume of a cylindrical shell. Measured data was compared with computer results from a previously derived analytical model based on infinite shell theory. For both the analytical model and experiment, the radiation of external monopoles is coupled to the internal acoustic field through the radial displacement of the thin, elastic cylindrical shell. An active noise control system was implemented in the cylinder using a fixed array of discrete monopole sources, all of which lie in the plane of the exterior noise sources. Good agreement between measurement and prediction was obtained for both internal pressure response and overall noise reduction. Attenuations in the source plane greater than 15 dB were recorded along with a uniformly quieted noise environment over the entire length of the experimental model. Results indicate that for extended axial forcing distributions or very low shell damping, axial arrays of control sources may be required. Finally, the Nyquist criteria for the number of azimuthal control sources is shown to provide for effective control over the full cylinder crosssection.

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