Full-Scale Demonstration Tests of Cabin Noise Reduction Using Active Vibration Control

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This paper reports the results of tests conducted to demonstrate the effectiveness of active vibration control techniques in reducing structureborne noise in aircraft cabins. A prototype active vibration control system was tested in the Douglas Aircraft Company Fuselage Acoustic Research Facility, using the aft section of a DC-9 aircraft as the test article. Shakers attached to the engine pylon were used to simulate engine structureborne vibrations, which caused noise in the cabin. Active control forces were applied with shakers located in the aircraft interior, connected to the fuselage structure. The level and phase of the control forces were set by a PC-based control system, which was designed to minimize the average acoustic energy measured at selected locations in the aircraft cabin. These tests showed good global reduction of interior noise levels and represent the first demonstration of the benefits of active vibration control in a full-size aircraft.

Introduction

THE control of low-frequency noise in aircraft passenger cabins by passive means often carries with it unacceptably high weight penalty. The use of active control techniques is, therefore, an attractive option. One application of particular interest is in the control of low-frequency tones in aircraft powered by advanced turboprop engines, called Ultra-High Bypass (UHB) engines at Douglas Aircraft Company. UHB engines utilize a jet turbine to drive two rows of counterrotating propellers. At high-speed cruise conditions, the tips of the propellers are moving at supersonic speed, resulting in high acoustic loads impinging on the pylon and fuselage at the blade passage frequency (BPF) and harmonics of the BPF.

Noise in the aircraft cabin can arise from two distinct paths. First, there is the airborne path in which propeller noise transmits directly through the fuselage sidewall. Second, structureborne noise arises from pylon-transmitted engine vibrations that excite the fuselage and subsequently radiate acoustic energy into the cabin interior. The tests reported here investigated the use of active vibration control techniques to reduce cabin noise due to the structureborne path.

Previous experiments have demonstrated the potential of using active vibration control techniques to reduce sound in aircraft,[1,2,3] but have all been performed in simplified aircraft models typically using a small-scale unstiffened cylinder. In the tests reported here, the aft section of a fully furnished DC-9 aircraft was used to demonstrate the effectiveness of these control techniques in a real fuselage, with its inherent complex structure and inhomogeneous interior space.

The next section reviews the basic concepts underlying active vibration control. Subsequent sections cover test procedures and the configurations and measurement results of each test. Conclusions are presented in the final section.

Active Vibration Control Concepts

An active vibration control system to reduce aircraft interior noise attempts to minimize the average acoustic energy in a defined volume by introducing control signals whose level and phase are set by a dedicated computer (the "controller") to cancel the source signals and thereby minimize cabin noise levels. The control signals are generated by internally mounted shakers, and conceptually are most successful in reducing interior noise levels when these noise levels are also generated by fuselage vibration excitation (such as from engine forces or acoustic loads on the pylon that propagate structurally) and when the control and source vibrations originate at or near the same point. This approach can be contrasted with the more conventional method of using arrays of acoustic sources to control interior noise. In essence, the technique described in this paper attacks the problem at the source—the vibrating fuselage—and thus appears very efficient.

During the control process, sound levels are sampled within the cabin at specified microphone locations (termed "error sensors"). A spatial average of the squared acoustic pressure, called a "cost function," is computed by the controller from the measurements at these error sensors. The cost function is proportional to the average acoustic energy in the control volume and, as shown in Fig. 1, includes contributions from both the input source (or noise) signals and the control signals. Although the source signals are fixed, the control signals are variable and depend on the level and phase settings of the control shakers. The task of the controller is to adjust these parameters to minimize the cost function and thus find the optimal solution, as depicted in Fig. 1. As the cost function is quadratic,[3] there is one optimal solution for the control settings. Also, the controller is constantly "adapting" to changes in noise inputs and requires no system identification, as in classical control approaches, except a reasonable spectral estimate of the noise input. This can easily be obtained in aircraft from an exterior microphone or the shaft pipper signal, for example.

Test Procedures

All tests were performed in the Douglas Aircraft Company Fuselage Acoustics Research Facility in Long Beach, California. The facility consists of the 50-ft aft section of a DC-9

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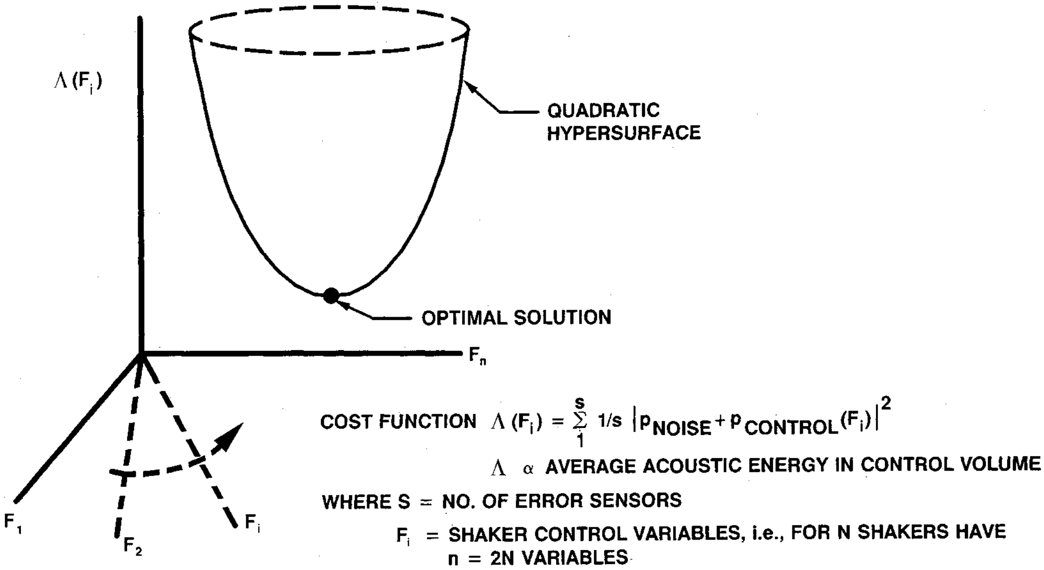

Fig. 1 Control cost function definition.

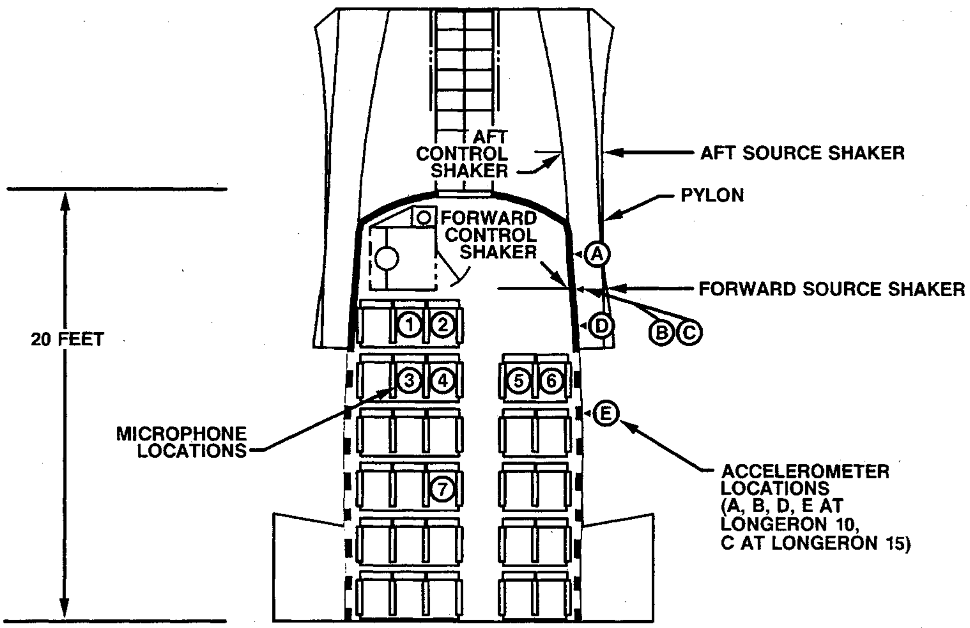

Fig. 2a Shaker, microphone, and accelerometer locations in the test fuselage.

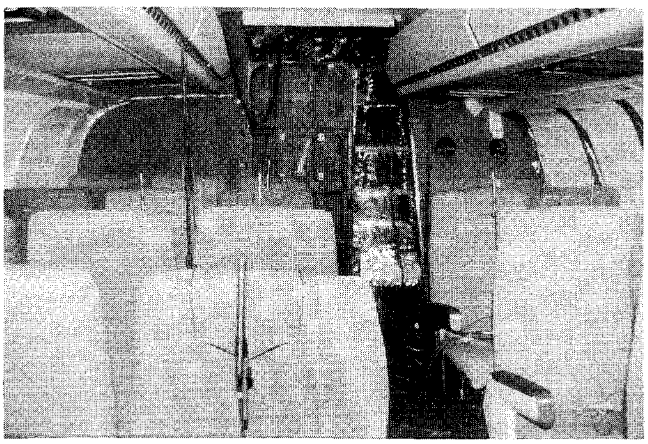

Fig. 2b Cabin interior, facing aft, showing placement of microphones.

Series 10 aircraft, located in an anechoic chamber. The fuselage section is isolation-mounted on a test stand and includes a bulkhead plug at the forward end of the passenger cabin to provide an enclosed acoustic environment for interior noise test purposes. The cabin is 34 ft long and fully furnished.

The physical arrangement of the fuselage, source and control shakers, and measurement microphones and accelerometers in the rear portion of the cabin is shown in Fig. 2a; the cabin interior is pictured in Fig. 2b. Vibration inputs were horizontally applied at the forward and aft engine mount points on the left pylon with 50-lb shakers to simulate engine vibration excitation of the structureborne path into the cabin. The vibration signals were single frequency sine tones generated by a reference oscillator. The resulting structureborne vibrations were transmitted to the aircraft interior space as structureborne noise at the excitation frequency.

Active control was provided by two 25-lb control shakers located in the interior and connected directly to the fuselage. The shakers were suspended from the fuselage by bungee cord in a pendulum configuration, and thus worked purely by inertial back reaction. Due to the presence of structural elements in the fuselage, it was not possible to align the control shakers so that they acted normal to the fuselage surface. Thus, the shakers were aligned at a slight angle to the normal, as shown in Figs. 3a and 3b, using a flexible joint to restrict the input to the structure to a normal vector in the horizontal plane.

The forward control shaker was placed near the front pylon attachment point and attached to a longeron at the same axial location as the source shaker, near the lavatory wall of the fuselage. The aft control shaker was opposite the rear engine mount, behind the pressure bulkhead. The two control shakers were thus located as close as possible to the two source shakers.

Sound levels were measured by seven microphones located at selected points in the aircraft interior, as shown in Fig. 2. The microphones were positioned 4 in. above seat-back height (approximately 46 in. above the floor). Also, five accelerometers were mounted on the fuselage to measure vibration levels during selected tests. Four of the accelerometers were positioned on longeron 10, just above the window belt; the fifth accelerometer was positioned at longeron 15, just below the window belt and immediately adjacent to the forward control shaker attachment point.

A schematic diagram of the experimental setup is shown in Fig. 4. The controller consists of a "host" IBM PC portable with a remotely-controlled phase/gain device and a high-speed data acquisition board. The controller was designed as a multi-input/multioutput device for controlling pure tones. For convenience, a frequency oscillator was used to generate a sinusoidal reference signal for both the primary source(s) and the phase/gain control device. Thus, the controller was not designed to model the control feedback path. (In actual flight operation, this reference control signal could easily be synthesized with engine speed or vibration transducers.) Secondary signals to the control shaker(s) were specified by the phase/gain device under the direction of the minimization algorithm on the host PC. The minimization algorithm was an interactive frequency-based code that exploited the quadratic nature of the cost function (see Fig. 1). The control algorithm was not cast in the more conventional time-based digital filter form such as least-mean-square (LMS) and recursive-least-mean-square (RLMS) digital filters, and thus was not a quick adapting controller. Rather, the controller simply evaluated a finite-difference approximation of the gradient of the cost function and used it to define the direction of optimization. Because the controller was interactive, the convergence rate could easily be varied to assure stability and proper convergence. Because of the interactive frequency-based nature of the controller, it would generally require a few minutes to optimize. However, because the primary focus of the investigation was to demonstrate the proof-of-concept of using vibrational actuators for actively controlling interior cabin noise rather than developing a high-speed controller, this was not seen as a significant problem.

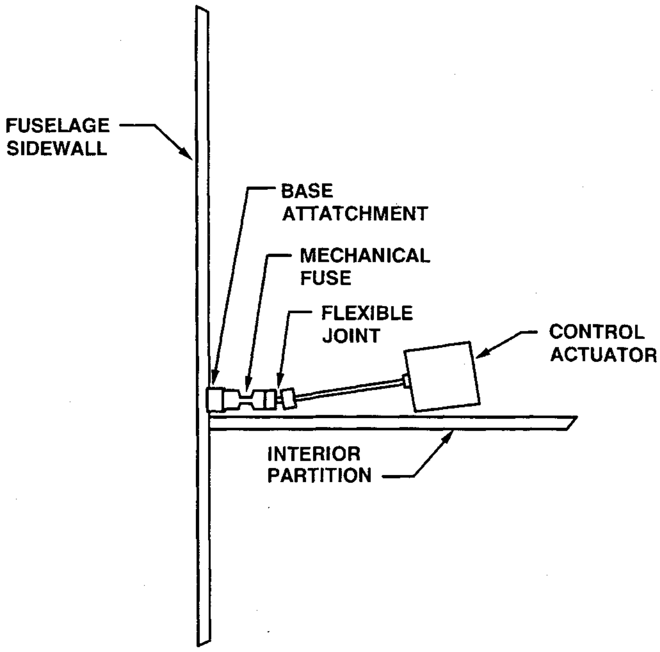

Fig. 3a Configuration of control shaker attachment.

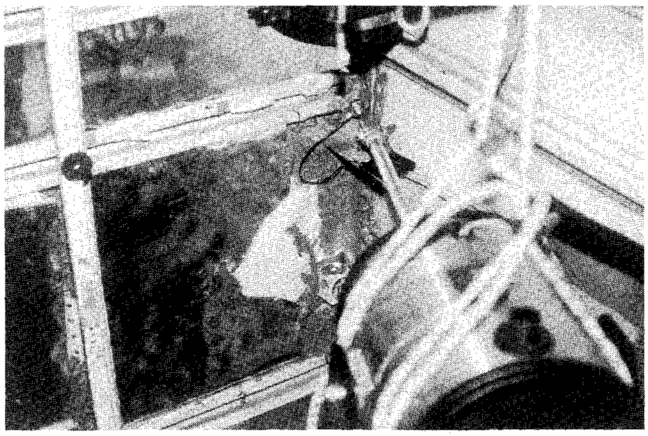

Fig. 3b Control shaker in place.

Error sensors during most of the tests consisted of from one to four microphones. For two tests, however, a fuselage accelerometer was used as an error sensor, thereby minimizing vibration levels instead of average acoustic energy levels.

For each test, the source and control configurations were selected first. The levels at the various microphone and/or accelerometer locations were measured with the input vibration source alone. The controller was then turned on and allowed to minimize the acoustic (or vibrational) energy at selected microphone (or accelerometer) error sensors. These "minimized" levels were then measured. From these two sets of measurements, the decibel reduction for sound pressure level or acceleration level at each sensor was calculated. These values gave an estimate of the reduction near each sensor.

By assuming that the sensors occupy a "control volume" in the aircraft interior, the measured levels at the individual sensor locations were used to calculate the spatially averaged energy reduction in the control volume due to active control. This spatially averaged value gives a better indication of the control system's global performance than the noise reductions at each sensor.

Test Configurations and Results

Ten tests were conducted. The test configurations are summarized in Table 1. As shown, the tests were organized in four sets in order to evaluate various test parameters that affect the performance of the active vibration control system. Specifically, the tests were designed to provide data on the effectiveness of multiple error sensors relative to a single sensor, the sensitivity of the system to source frequency, the use of accelerometers instead of microphones as error sensors, and the effectiveness of an input source at an alternate location with both single and multiple control shakers.

For each test, Table 1 lists the signal frequency, the location of the source shaker, the location of the control shaker, the number and type of error sensors, and the number and type of measurement sensors (used to determine the localized and spatially averaged noise reduction).

Each test is discussed in detail below, grouped by test set.

Test Set I

The first set of tests examined the effects of the number of error sensors on cabin noise reduction.

In test 1, the source was the forward shaker and the excitation frequency was 170 Hz. The control signal was applied at the forward control shaker. One error microphone sensor was used, located at position 2.

Test results are presented in Fig. 5. In this figure, as well as in subsequent figures that apply to the remaining tests, source levels (without control) and minimized levels (with control) are shown for each measurement sensor. The reduction in level at each sensor is also shown (an increase is denoted by a negative value), as is the spatial averaged energy reduction over the control volume. The figure also depicts the location of the source and control shakers and the measurement sensors and identifies the error sensors.

Figure 5 shows a significant reduction of 20 dB at the error sensor, as expected, along with large reductions at positions 5 and 6, but an increase in levels at positions 3, 4, and 7. The overall energy reduction is 9.5 dB, indicating good global control. This is mainly because the source noise levels at positions 3, 4, and 7 are significantly lower than at the other positions. Thus, the effect of the control system with one error sensor is to "fill in" these positions with "spillover" of control energy while minimizing the louder positions.

Test 2 utilized the same configuration as test 1 except the number of error sensors was increased to two, at positions 2 and 3. (Position 3 was added because it showed the greatest sound-level increase in the previous test.)

The test results (Fig. 6) indicate that the spillover (or increase in levels) at positions 3, 4, and 7 is significantly reduced. However, the energy reduction of the control volume remains around 9 dB. This behavior is caused by a reduction in attenuation at other positions (except position 2), as the controller is now responding to information from two sensors and attempts to find the optimal averaged solution.

For test 3 the configuration was the same as the earlier ones, except the number of error microphones was increased to four at positions 2, 3, 5, and 7. Figure 7 shows that control spillover has been completely eliminated with attenuation occurring at six of the seven microphone positions. However, as previously observed, this is at the expense of large reductions in the attenuations at individual microphones. The energy reduction of the control volume remains about the same at 9 dB; hence, the controller with increased measuring points tends to produce a reasonably smooth distribution of

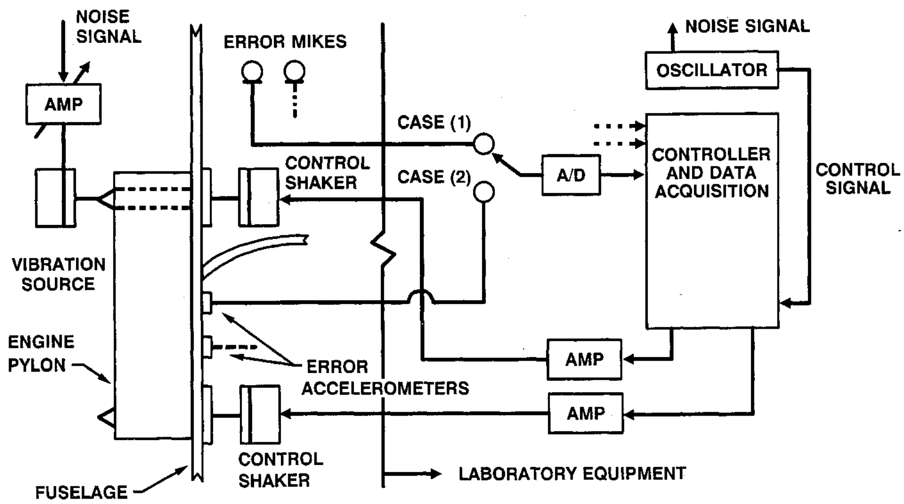

Fig. 4 Experimental test arrangement.

Table 1 Active vibration control test configurations

Test set	Test no.	Source frequency, Hz	Source location	Control location	Error sensors	Measurement sensors	Test parameters evaluated
I	1	170	Forward	Forward	1 mic	7 mics	Number of error
	2	170	Forward	Forward	2 mics	7 mics	sensors
	3	170	Forward	Forward	4 mics	7 mics	
II	4	185	Forward	Forward	4 mics	7 mics	Source frequency
	5	120	Forward	Forward	4 mics	7 mics	
III	6	170	Forward	Forward	1 accel	5 accels	Accelerometer
	7	170	Forward	Forward	1 accel	7 mics	error sensor
IV	8	170	Aft	Aft	1 mic	7 mics	Source of location/
	9	170	Aft	Aft	4 mics	7 mics	number of control
	10	170	Aft	Forward and aft	4 mics	7 mics	shakers

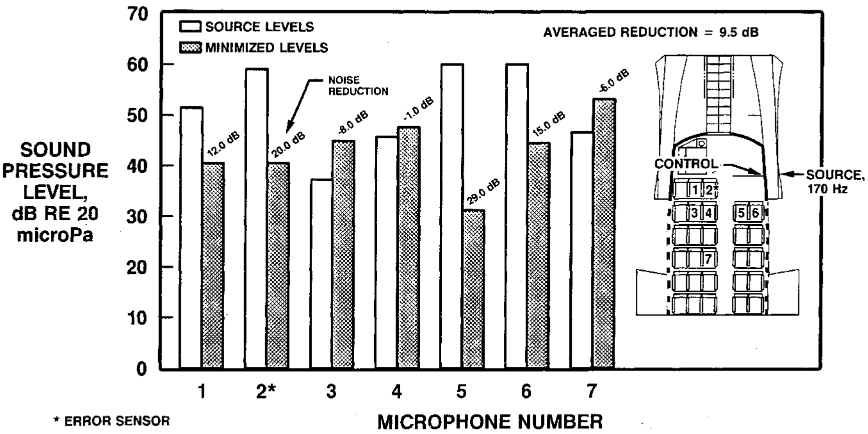

Fig. 5 Measured noise levels, one error sensor (Test 1).

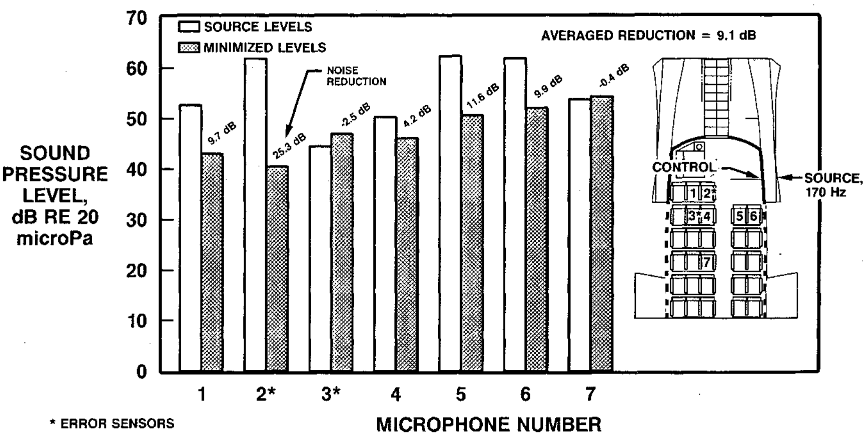

Fig. 6 Measured noise levels, two error sensors (Test 2).

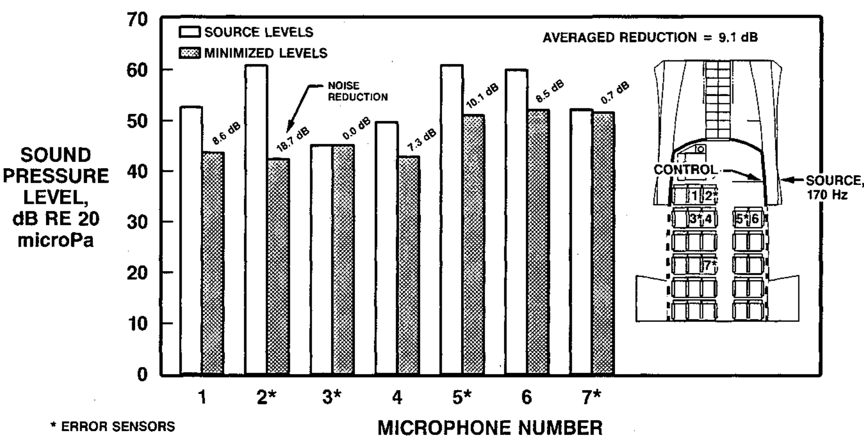

Fig. 7 Measured noise levels, four error sensors (Test 3).

minimized levels throughout the control volume. From a passenger perspective, reducing large changes in noise level throughout the cabin would be desirable.

The minimization algorithms in the controller are designed in such a way that levels at the error sensors in the minimized condition would be essentially identical. The differences observed here are due to the finite resolution of the digital nature of the controller, as well as small differences in the spatial distributions of the acoustic energy generated by the source and control shakers. However, the controller can be observed from the results to try to produce an even distribution of sound levels across the error sensors.

Test Set II

The purpose of these tests was to determine whether the high noise reductions obtained throughout the cabin at 170 Hz would occur at other frequencies.

For test 4, the excitation frequency was changed to 185 Hz; all other conditions were the same as in test 3. As can be seen in Fig. 8, the measured levels show very good attenuation at all measured microphones throughout the control volume. The reduction is calculated to be 9.2 dB, indicating excellent global control.

The same test configuration was used in test 5, except that the excitation frequency was lowered to 120 Hz. The test results (Fig. 9) show excellent reduction in sound pressure levels at all positions except 1 and 3. However, an examination of the noise field shows that noise levels are very low at these two positions, thus leading to some control spillover. This is also reflected in an acoustic energy reduction in the control volume of more than 13 dB, indicating that reduction of acoustic energy is achieved throughout the interior space, not just locally.

As a result of these two tests, the active control technique is seen to work well at three different frequencies, verifying that it is robust to varying load conditions due to changes in engine speed, etc.

Test Set III

For these tests, the configuration was changed markedly. The source and control shakers were still connected at the forward location and the excitation frequency was reset to 170 Hz. However, the error sensor chosen was the accelerometer mounted on the fuselage near the forward engine pylon attachment (accelerometer position C in Fig. 10). The purpose of these tests, then, was to explore the consequences of using an accelerometer, rather than a microphone, as an error sensor.

Test 6 measured vibration levels at five accelerometer points for this configuration. The results shown in Fig. 10 indicate that the control force provides very good global control of vibration transmitted along the engine pylon. As expected, the largest attenuation is at the error sensor point. However, a spatial-average reduction in out-of-plane vibrational energy of 13.3 dB was measured. Using more error sensors is likely to improve the global attenuation somewhat, as has been seen in previous test results.

Test 7 was a continuation of test 6, with the controller still operating to minimize vibration levels at the accelerometer position-C error sensor. To assess system performance, however, sound levels were measured instead of acceleration levels.

The test results in Fig. 11 show that suppressing the fuselage vibration near the front pylon spar attachment measur-

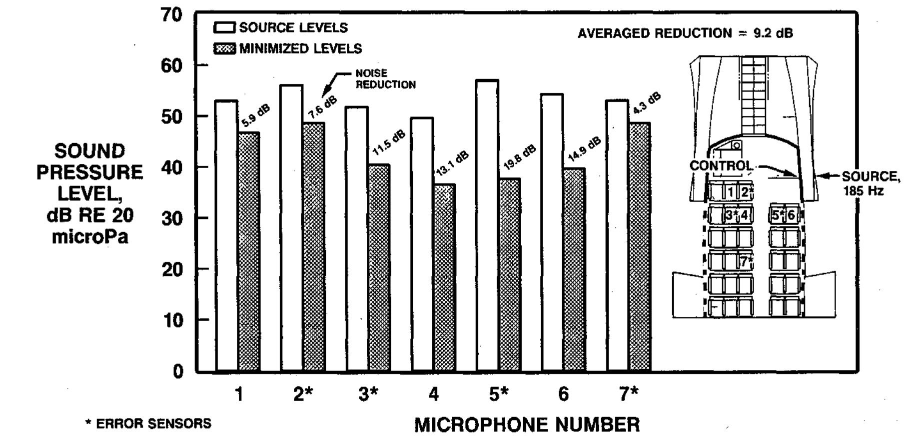

Fig. 8 Measured noise levels, 185 Hz (Test 4).

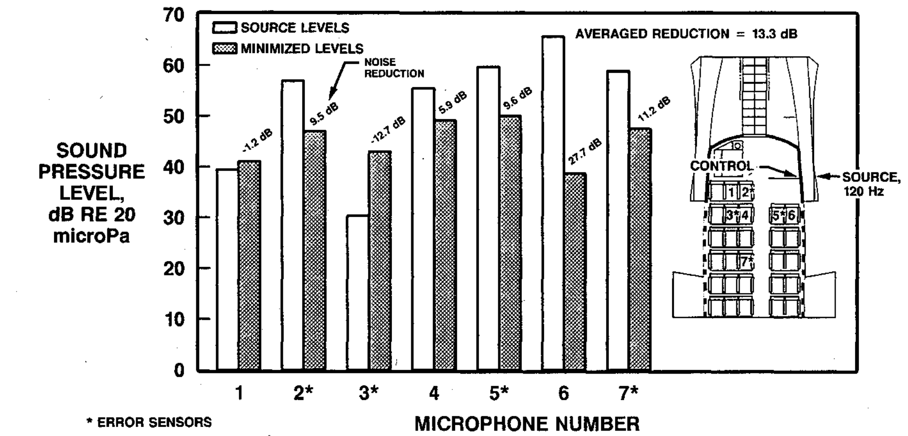

Fig. 9 Measured noise levels, 120 Hz (Test 5).

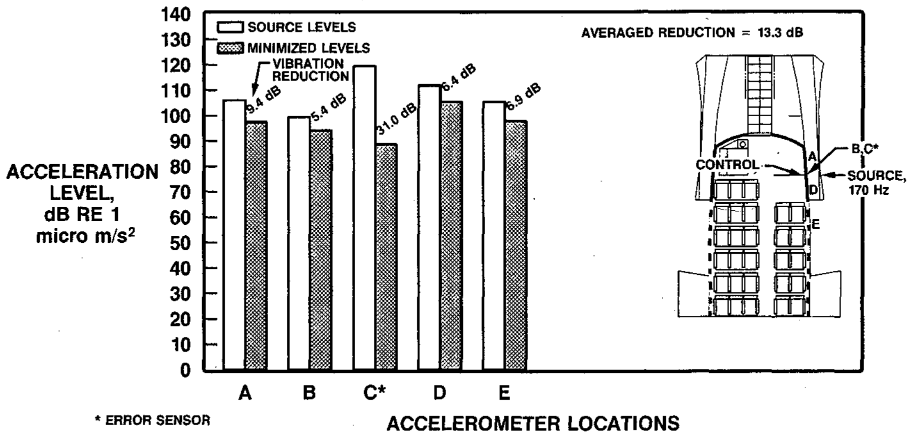

Fig. 10 Measured vibration levels, one accelerometer error sensor (Test 6).

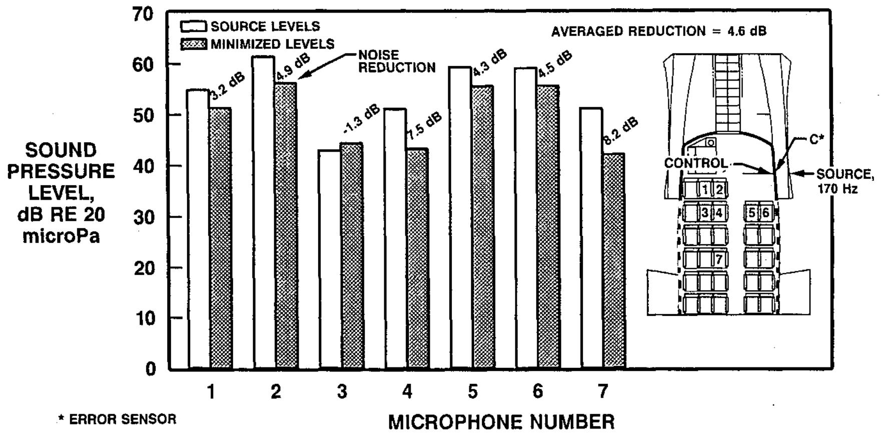

Fig. 11 Measured noise levels, one accelerometer error sensor (Test 7).

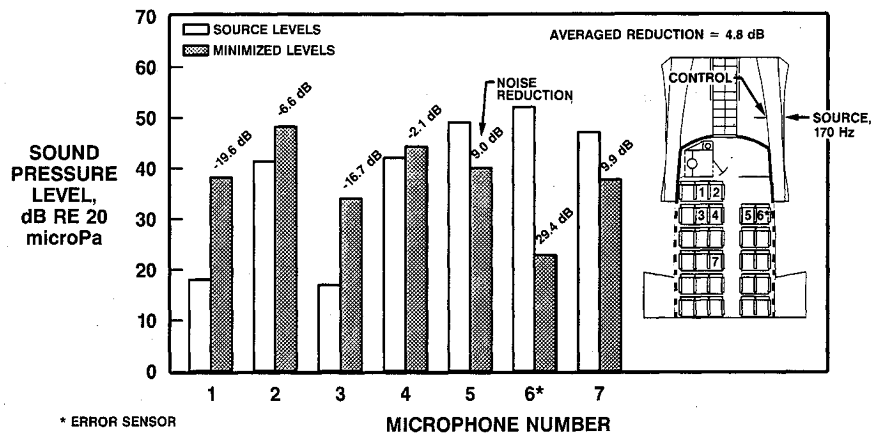

Fig. 12 Measured noise levels, aft source and control shakers, one error sensor (Test 8).

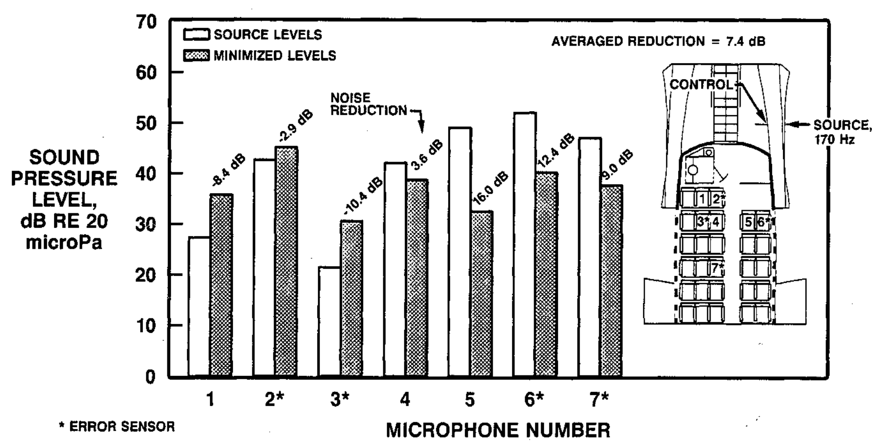

Fig. 13 Measured noise levels, aft source and control shakers, four error sensors (Test 9).

ably reduces interior noise levels. Nevertheless, the global reduction is far less in this case than when the error sensors are acoustic transducers: an average reduction of less than 5 dB here compared to more than 9 dB in tests 1–3.

This result highlights the importance of carefully selecting the location, type, and number of transducers in designing an optimal active control system. If the goal is to minimize fuselage vibration, then the error sensors should be accelerometers located on the fuselage. For interior noise reduction, the error sensors should be interior microphones, even though the noise is caused by structureborne vibration that results from structural-acoustic coupling.[2] However, if it is not possible to use microphones, then diminished fuselage vibration will still lead to some reduction at interior noise levels, and it may be possible to improve this by including, for example, radiation efficiency factors.

Test Set IV

For the preceding tests the source shaker was applied at the forward engine mount, which has a direct structural connection with the forward pylon spar where the forward control shaker was applied. Thus, interior noise levels were reduced by a single shaker generating control forces at essentially the same point as the source input forces.

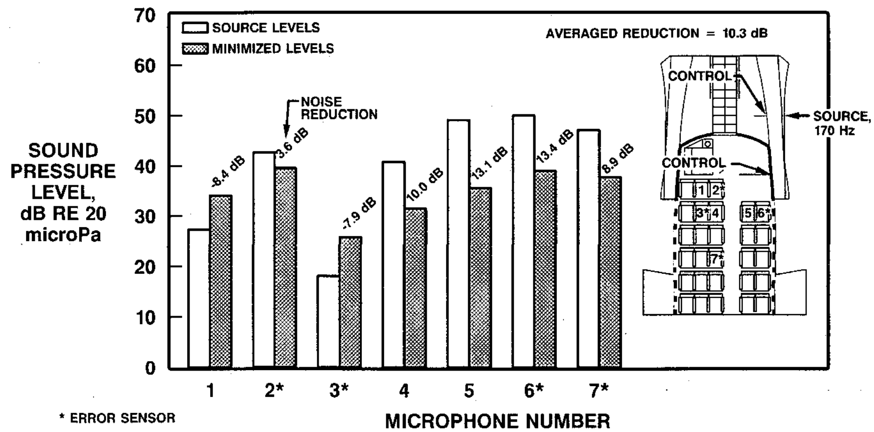

Fig. 14 Measured noise levels, forward and aft control shakers (Test 10).

In test set IV, the source shaker was relocated to the aft engine mount. At this location, no structural member directly connects the attachment point with the aft pylon spar. Vibrational energy is transmitted to the fuselage through the entire pylon, as though it were generated by a distributed rather than a point source. The next three tests investigated active control of this source, as compared with the source at the forward location. In addition, the use of multiple control shakers was examined.

First, in test 8, active control was applied with a single shaker at the aft location. The excitation frequency was 170 Hz. The error sensor was a single microphone at position 6. The measured levels for this test, shown in Fig. 12, indicate an impressive reduction at position 6 but significant control spillover at other positions; consequently, the average attenuation is only 4.8 dB.

Test 9 was identical to test 8 except that the number of error sensors was increased to four, located at positions 2, 3, 6, and 7. The test results in Fig. 13 show that the average attenuation is significantly improved to 7.4 dB, the tradeoff being a reduction in attenuation at position 6. It is also still apparent that significant control spillover is occurring at position 3, even though this is the location of an error sensor. It appears in this case that the interior acoustic field is due to two separate modal components or two different structure-borne paths. Thus, it appears to be infeasible to achieve complete global control with just one control shaker.

In test 10, a forward control shaker was added to the configuration used in test 9, that is, both forward and aft control shakers are optimized simultaneously. As shown in Fig. 14, a significant reduction in control spillover occurs, with average attenuation on the order of 10 dB. The two shakers appear to be acting independently to control the two different modes or paths. (Note that independent modal control has previously been demonstrated in simplified fuselage tests.[2])

This result is very significant, given the distributed nature of the input vibration. The active control system provides good global control in this case with just two point actuators and again highlights the importance of controlling fuselage vibration to reduce interior noise.

Conclusions

These experiments have shown that active vibration control techniques give good global reduction of interior sound levels for vibrations transmitted along the engine pylons with only two point control forces, located near the pylon attachment. Likewise, the active system gives excellent reduction of fuselage vibration levels when the error sensors are fuselage accelerometers. Thus, the active vibration technique shows much potential for reducing both interior sound and fuselage vibration caused by engine excitation transmitted through the pylons to the fuselage, whether the vibrations are localized or distributed forcing functions.

In addition to providing good global control, an operating system would be able to provide adaptive control of a number of frequencies simultaneously; that is, it could control the levels at multiple frequencies and respond to changes in both level and frequency as source conditions change. Further, such a system could be designed to provide a desirable distribution of interior noise levels by careful selection of type, number, and location of error sensors. These features and benefits of an active vibration control system would be available without the significant weight penalty normally associated with passive noise control techniques.

Future work will address the technical challenges that still remain to convert the prototype active vibration control system into a system suitable for use during actual flight. The primary challenge is to develop small lightweight actuators that could easily be installed where needed in the cabin interior. Other areas of development include increasing the controller speed and providing the capabilities to handle multiple frequencies and multiple source locations.

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