Cabin Noise Control Ground Tests for Ultra High Bypass Aircraft

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Measurement and analysis procedures for cabin noise control ground tests conducted on a DC-9 aircraft test section are presented along with a summary of test results. These tests were designed to analyze the effectiveness of selected noise control treatments in reducing passenger cabin noise on aircraft with aft-mounted, advanced turboprop engines. The performance of various structural and cabin sidewall treatments is assessed, based on measurements of the resulting interior noise levels and fuselage acceleration levels under simulated advanced turboprop excitation.

Introduction

OVER the past 15 years, there has been renewed interest in the use of fuel-efficient turboprop engines for aircraft power plants because of concern over rising fuel costs and the accompanying desire for energy conservation. Advanced turboprop engines, which make use of recent developments in blade design and fabrication, have the potential for providing thrust that is comparable to today's turbofan engines with a significant reduction in fuel use.

McDonnell Douglas Corporation (MDC) is studying the feasibility of developing commercial transport aircraft powered by such advanced turboprop engines, known as ultra high bypass (UHB) engines. A major technology issue associated with UHB aircraft is the noise environment that may be experienced by passengers. The longest portion of a typical flight is spent at high-altitude, high-speed cruise. Under these conditions, the UHB engine is expected to produce its highest noise levels since the tips of the propeller blades are moving at supersonic speeds.

The resulting acoustic energy is generated in discrete tones, at frequencies corresponding to the blade passage frequency and its multiples for each propeller rotor. These frequencies typically lie between 100 and 250 Hz, where the transmission loss characteristics of standard aircraft sidewalls are not sufficient to reduce exterior levels to acceptably low interior levels and where traditional methods of noise control may adversely affect aircraft performance (e.g., add-on treatments that are bulky and massive). Since today's airline passenger expects a pleasant cabin environment, noise control treatments are required that result in satisfactory interior noise levels and meet space and weight constraints.

In 1985, a UHB technology readiness program was started in which a Fuselage Acoustic Research Facility (FARF) was developed to study the control of UHB interior noise. FARF utilizes the aft section of a DC-9 aircraft as a full-scale test article. Testing began in October 1986 in FARF to evaluate noise control treatments.

One major purpose of these tests was to support the design of a noise control treatment package for the UHB demonstrator aircraft, an MD-80 aircraft modified by replacing one of its turbofan engines with a prototype UHB engine. The treatment package was designed to achieve noise levels in the aft cabin of 82 dBA or lower. In June 1987, flight testing of the demonstrator began. The demonstrator was powered by one JT8D engine and one UHB engine with eight blades on both the forward and aft rotors (an 8 × 8 configuration), with a minimal noise control treatment package. Further treatments were subsequently added, guided by the FARF test results. In July, the installation of the full treatment package was completed, and the 82 dBA interior noise goal was attained. In August, the 8 × 8 engine was replaced by a 10 × 8 engine (10 blades on the forward rotor and 8 blades on the aft rotor), and the noise goal was again achieved.

As one element of NASA's advanced turboprop (ATP) technology program, the NASA/Industry Flight Demonstration program was started in 1987 to work with the aircraft industry in the study of passenger cabin noise in advanced turboprop aircraft. Under this program, NASA issued a contract to MDC to analyze in detail the interior noise measurement data acquired during the ground and flight tests. This paper documents the major results of the fuselage ground tests.

Test Description

All tests were conducted in the FARF, which is equipped with the aft section of a DC-9 aircraft fuselage, noise and vibration sources to simulate advanced turboprop excitation, a multichannel digital data acquisition and processing system, and an anechoic chamber to house the fuselage section. The experimental setup is shown in Fig. 1, while Fig. 2 shows the test article being rolled into the anechoic chamber.

The DC-9 fuselage section was selected as a realistic, modally responding structure that was representative of aft-engine mount configurations and that could be subjected to full-scale testing. During all tests, the fuselage was pressurized to a pressure differential of 5 psi.

Two banks of loudspeakers were utilized to simulate UHB acoustic excitation. In each bank, 25 speakers were mounted in a specially fabricated rack in a 5 × 5 array. During testing, each bank was positioned near the aft portion of the aircraft, one on each side, centered in the plane of the forward UHB propeller and rotated toward the fuselage (see Fig. 3).

The acoustic signal is created by inputting sine tones from a signal generator through a series of amplifiers to different combinations of speakers so that the noise level distribution on the exterior surface of the fuselage could be adjusted, within limits, to simulate the expected noise level distribution. For a UHB 10 × 8 engine operating in the 1260–1280-rpm range, the blade passage frequency (BPF) and first two harmonics for the rear eight-bladed rotor are nominally 169, 338, and 507 Hz, respectively, and for the forward 10-bladed rotor,

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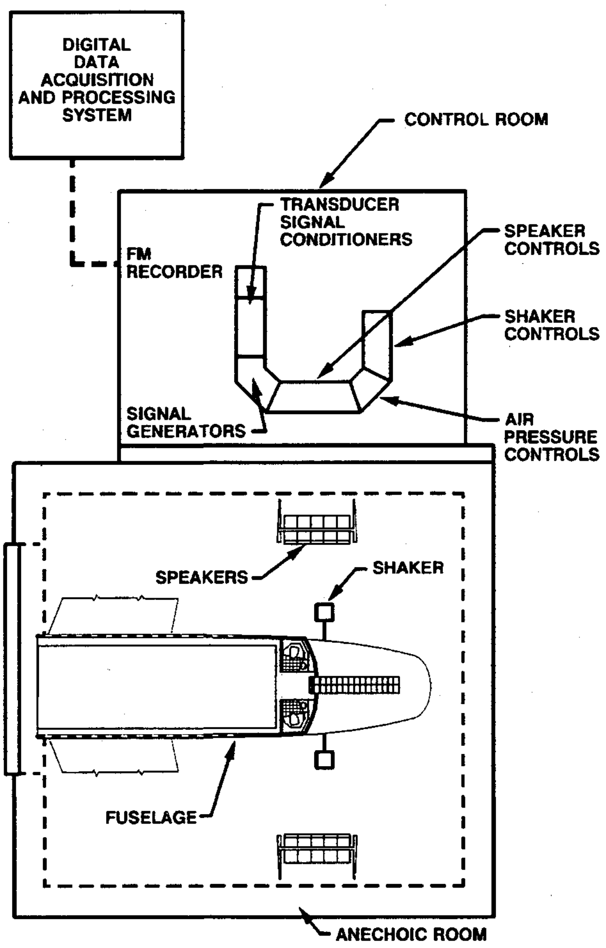

Fig. 1 Schematic of the Fuselage Acoustic Research Facility (FARF).

nominally 213, 426, and 639 Hz, respectively. These six frequencies were used for the acoustic excitation tests.

Vibration excitation was generated by electrodynamic shakers attached to the engine pylon to simulate the propagation of vibrational energy from the engine into the fuselage structure. As shown in Fig. 4, the shaker was external to the fuselage; vibration was imparted through a stinger connected to the pylon at a 45-deg angle at the engine attachment point. Since the absolute vibration levels generated by a UHB engine were unknown, the approach used was to apply sine tones of arbitrary levels at 169 and 213 Hz. Differences in fuselage response to the same arbitrary input were used to measure the effects of different treatments.

Exterior microphones were located on the aft fuselage and in an array outside of the passenger cabin (see Fig. 5). Interior microphones were located at typical passenger positions. As shown in Fig. 5, six interior microphones were utilized at each of four fuselage stations. The microphones at positions A, B, C, E, and F correspond to seated passenger head height (40 in. above the floor), and the microphone at position D corresponds to a standing head height (65 in. above the floor) in the aisle on the cabin centerline.

Accelerometers were located on a frame in the midcabin area (at station 718) and along longeron 10 from station 859 forward to station 718 (see Fig. 6). In addition, accelerometers were mounted on the pylon at the shaker attachment point to measure the lateral, longitudinal, and horizontal components of the input acceleration.

A digital data acquisition and processing system (DDAPS) was used for all tests. DDAPS consists of a special digitizer coupled to a DEC MICROVAX II computer and is designed to rapidly calculate and display a variety of time-series functions from which frequency domain data can subsequently be obtained. The system is capable of simultaneous sampling of up to 32 channels of analog data at a rate of 12,600 samples/s/channel for up to 2 min covering a frequency range of up to 4 kHz. The sampling duration for each measurement was 30 s, sufficient to provide the frequency resolution (3.125 Hz) used in the analysis.

Data were recorded on an FM tape recorder, 26 channels at a time. Annotation information and a time code were recorded on the remaining two channels. The data tapes were then processed on DDAPS. Software operating on a DEC VAX 8300 coupled with an array processor was used to convert the digitized time-series data into the frequency domain and to produce tabular and graphic output for subsequent analysis and data presentation.

All measured data were normalized to either the exterior microphone level at station 908 (for noise measurements) or to the vertical accelerometer level at the pylon (for vibration measurements).

Test Configurations

The tests were divided into three phases: a baseline phase and two modification phases in which the effectiveness of various noise control treatments were evaluated. The physical condition of the test fuselage is described in terms of various configurations. The untreated fuselage used in the baseline phase is described as follows.

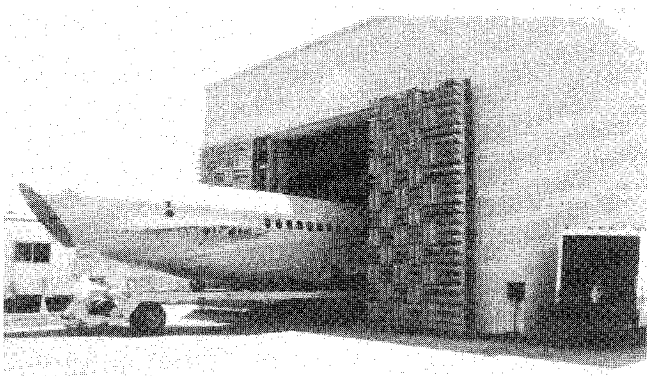

Fig. 2 The test section entering the anechoic chamber on its transporter.

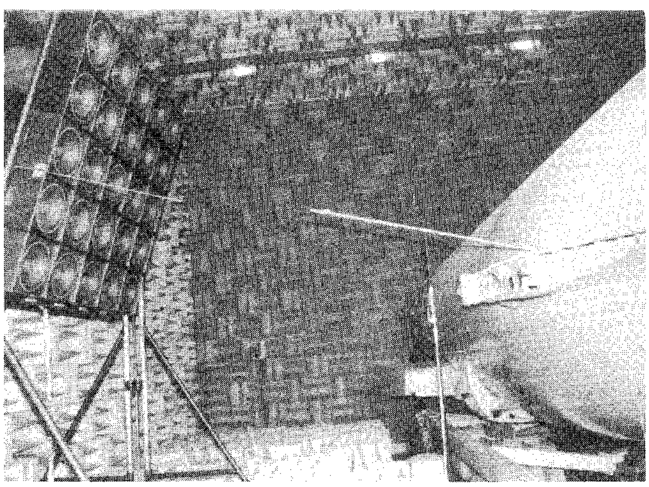

Fig. 3 The loudspeaker array, positioned at the UHB prop plane.

Configuration 1. This is the "bare" or "green" fuselage configuration, with no interior furnishings or treatments. In both the pressurized cabin and the unpressurized aft fuselage sections, the various skin and floor surfaces and frames and longerons were completely uncovered. The lavatories were removed, so that the engine mount bulkheads (which separate the lavatories from the passenger seating area) and the complete aft pressure bulkhead were also uncovered. The only exposed surface that was not bare metal was the bulkhead plug at the forward end of the fuselage section, to which fiberglass wedges were attached. In the aft unpressurized section, all systems, ductwork, and equipment were removed. The cargo compartment below the floor was also bare and empty (see Fig. 7).

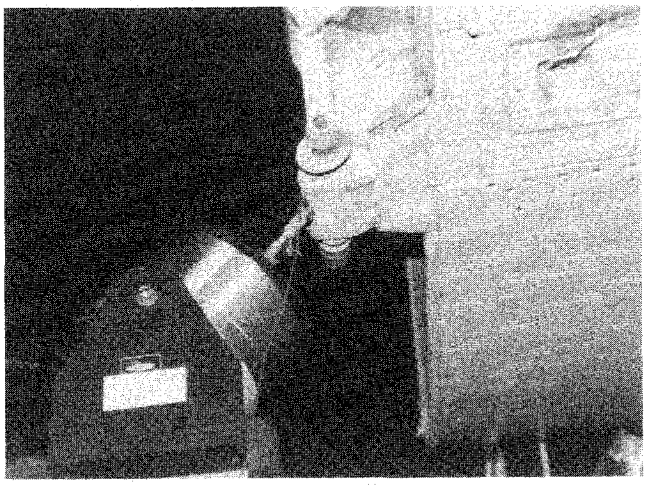

Fig. 4 The shaker mounted to the left pylon at the engine attachment point.

Treatments were designed to control propagation along three potential paths on a UHB aircraft: 1) an airborne path through the cabin sidewall, 2) an airborne path into the aft unpressurized section and then through the pressure bulkhead, and 3) a structural path through the engine pylon and into the fuselage structure.

In the structural modification phase, selected structural treatments related to increasing the mass, stiffness, damping, or isolation characteristics of the fuselage were applied and studied. In the furnished fuselage phase, additional treatments related to increasing mass, damping, and isolation in the furnished cabin were evaluated. The configurations used in the structural modification phase, in sequence, are as follows.

Configuration 2. A "torque box" was installed in the aft cabin area. This is a patented device designed to greatly increase the stiffness of an existing frame, particularly to torsional motion. The torque box consists of a new frame installed approximately 4 in. from an existing frame (located at station 766), with a cover plate over both frames.

Configuration 3. Two additional frames were installed in the aft cabin area, slightly forward of the engine mount at stations 748 and 776, to stiffen the sidewalls. These frames, identical to current production frames, were added midway between existing frames. Figure 8 shows the general arrangement of the new and existing frames in this section of the aircraft.

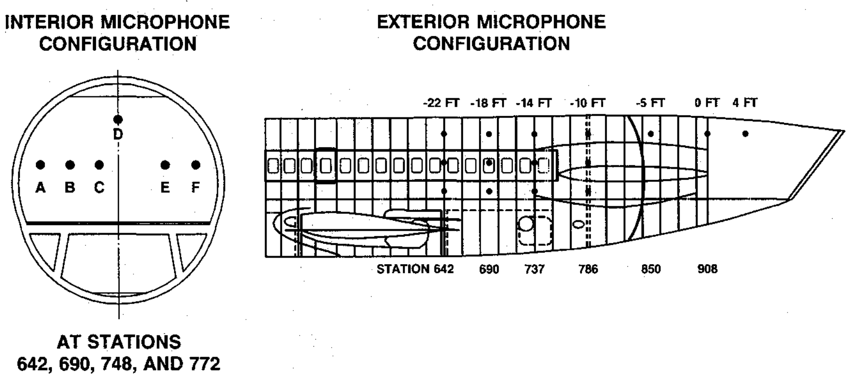

Fig. 5 Microphone locations.

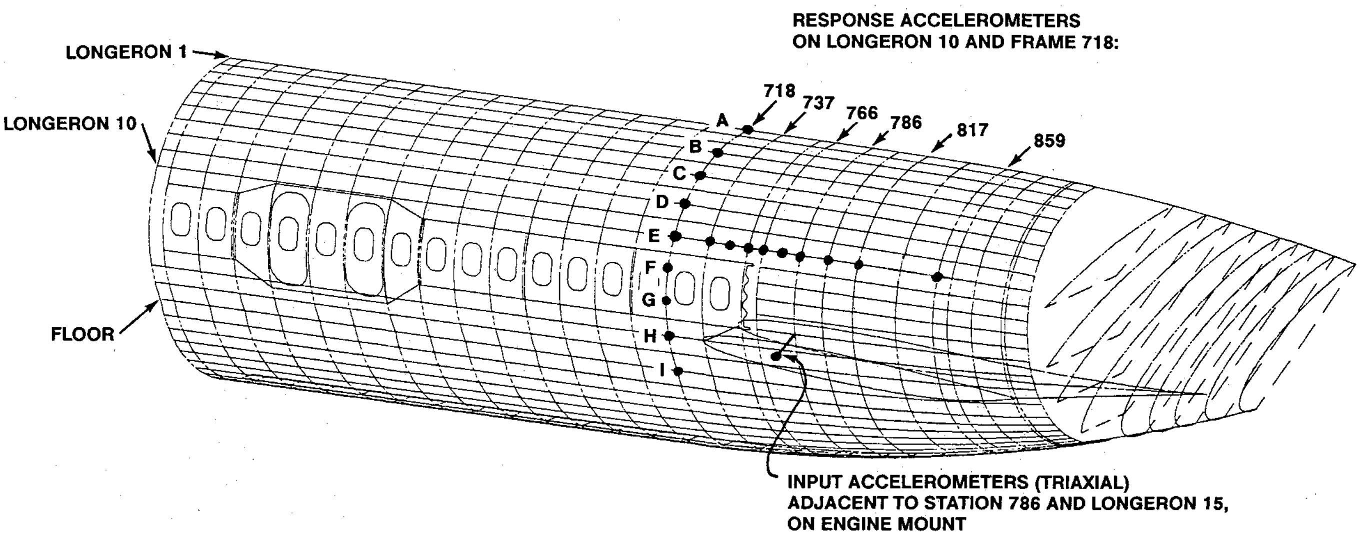

Fig. 6 Accelerometer locations.

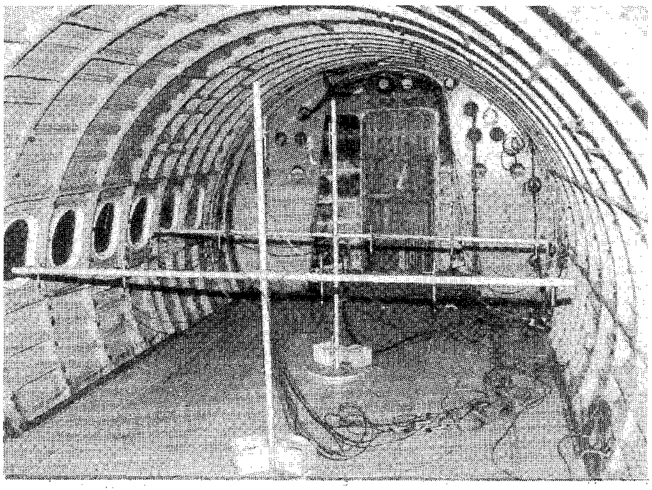

Fig. 7 The bare cabin with interior microphones on test stands.

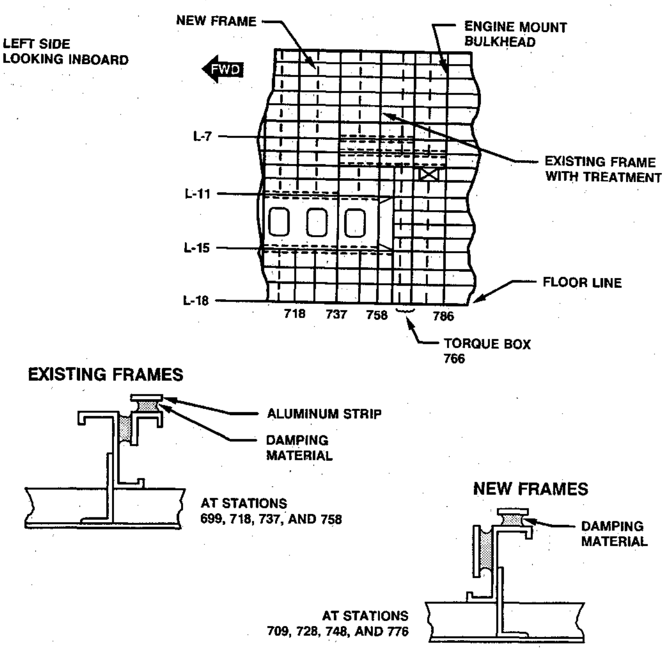

Fig. 8 Frame modification details for selected treatments.

Configuration 4. A second set of two additional frames was installed, at stations 709 and 728 (see Fig. 8 for details).

Configuration 5. Damping material was applied to the four new frames and to several existing frames in the aft cabin area. This material (EAR type C-1002-12) was used to reduce structural vibration, particularly at the frame modal frequencies (see Fig. 10).

Configuration 6. Damping material was applied to the cover plate of the torque box to reduce structural vibration from this device. The damping material and the method of applying the material on the top of the frames were the same as in configuration 5.

Configuration 7. The torque box was "disabled" by drilling out the rivets connecting the cover plate to frame 762 and inserting damping material (the same material as in configurations 5 and 6) between the cover plate and the frame to prevent rattling. (This configuration was prompted by test results, which indicated that the torque box was increasing rather than decreasing cabin noise levels.)

Configuration 8. A double wall was installed approximately 3-in. forward of the pressure bulkhead to reduce sound transmission from the aft unpressurized section into the cabin. The double wall was constructed of 0.063-in. aluminum in three sections, one over the bulkhead door and the other two over the side sections of the bulkhead, where the lavatories are located. This configuration also included damping material (EAR type SD-40AL/3203-50PSA) applied only to the side sections of the pressure bulkhead and isolator mounts to attach the double wall to the fuselage structure.

Configuration 9. Dynamic tuned absorbers were mounted on nine frames between stations 672 and 801. Tuned to 169 Hz, these absorbers were used to reduce frame vibration at the blade passage excitation frequency. The absorbers were installed at three locations per frame, near longerons L6, L10, and L14.

Configuration 10. Absorption blankets were installed in the aft unpressurized section to absorb acoustic energy in this area and thereby decrease transmission through the pressure bulkhead. The blankets, made of 2-in.-thick fiberglass insulation with a quilted facing, were installed over the pressure bulkhead and over portions of the ventral stairs.

Configuration 11. Damping material was applied to the fuselage skin throughout the passenger cabin area and the aft unpressurized section. The material, soundcoat type 10MS/10LT12, is being considered to reduce sonic fatigue of the fuselage skin in the vicinity of the UHB propeller planes, where high acoustic loads are expected. Since this treatment will also affect noise transmission into the aft section and structure-borne propagation through the fuselage, it was tested in FARF and included here as a separate configuration.

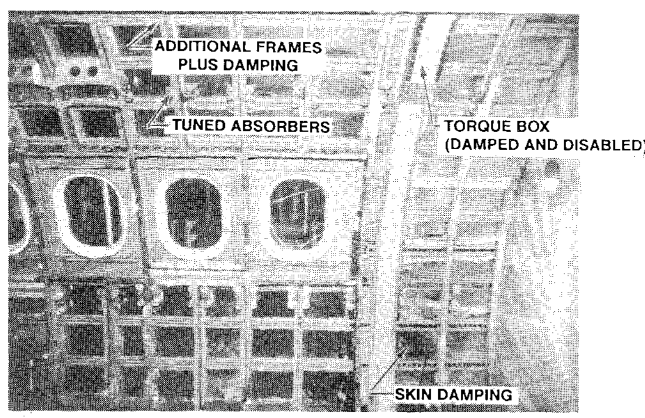

Fig. 9 Treatment of the fuselage sidewall.

Fig. 10 The fully furnished cabin.

Table 1 Treatment evaluation test configurations

Configuration	Phase	Description	Path[a]	Noise data	Vibration data
1	Baseline	Bare cabin	—	×	×
2	Struct mod	Torque box	1,3	×	×
3	Struct mod	Two frames	1,3	×	
4	Struct mod	Four frames	1,3	×	×
5	Struct mod	Frame damping	1,3	×	×
6	Struct mod	Damped torque box	1,3	×	
7	Struct mod	Disabled torque box	1,3	×	×
8	Struct mod	Disabled wall bulkhead	2	×	
9	Struct mod	Tuned absorbers	1,3	×	×
10	Struct mod	Absorption blanket	2	×	
11	Struct mod	Sonic fatigue damping	1,3	×	×
12	Struct mod	Skin acoustic damping	1,3	×	×
13	Furnished	Furnished, no lav, no double wall bulkhead	1,3	×	×
14	Furnished	Double wall bulkhead added	2	×	×
15	Furnished	Trim damping, lav added, no double wall bulkhead	1,3	×	×
16	Furnished	Fully furnished	1,2,3	×	

[a]Path: 1 = Airborne through sidewall; 2 = Airborne through aft section and pressure bulkhead; 3 = Structure-borne.

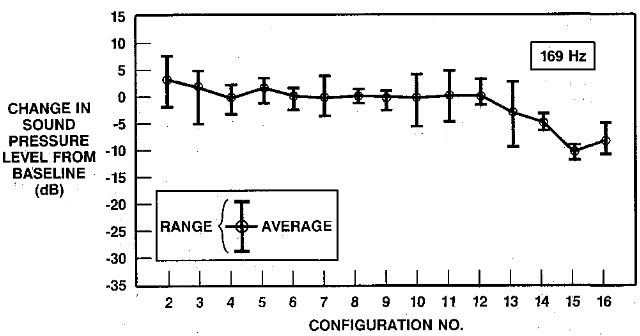

Fig. 11 Treatment sound pressure levels, 169 Hz.

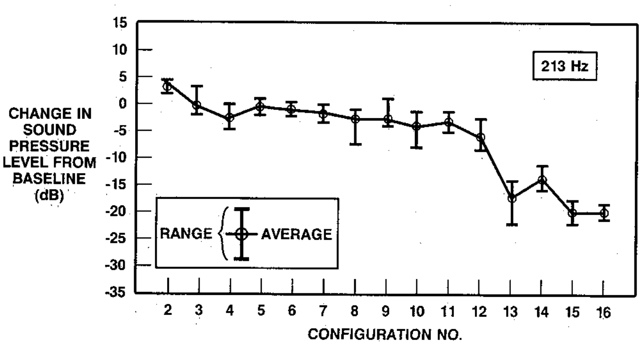

Fig. 12 Treatment sound pressure levels, 213 Hz.

The damping material was installed on the skin in the rectangular areas formed by the frames and longerons.

Configuration 12. A second damping treatment was applied to the fuselage skin, specifically for acoustic purposes. The damping material, EAR type SD-40AL/3202-50PSA, was installed directly over the sonic fatigue damping material on all skin panels throughout the passenger cabin.

Selected treatments from the structural modification phase are pictured in Fig. 9. Four additional configurations were studied in the furnished fuselage phase:

Configuration 13. The basic cabin furnishings were installed in this configuration, including carpeting on the floor, the sidewall kick panels, the engine mount bulkhead walls, trim panels, two thermal insulation blankets in the sidewall, baggage racks, ceiling panels, and seats. Prior to installing these furnishings, the pressure bulkhead double wall, the aft absorption blankets, and the dynamic tuned absorbers were removed. Also, lavatories were not installed for this configuration.

Configuration 14. This was the same as configuration 13 except that the pressure bulkhead double wall was reinstalled.

Configuration 15. The double wall bulkhead was again removed and the lavatories were installed. Also, damping material (EAR type SD-40ALPSA) was added to all the trim panels throughout the cabin on the side facing the sidewall cavity.

Configuration 16. The double wall bulkhead was again installed. This configuration represents the fully treated cabin, as shown in Fig. 10.

All the configurations studied in these tests are summarized in Table 1.

Measurement Results

Acoustic Excitation Data

In order to evaluate the effectiveness of the various treatments in reducing interior noise levels resulting from acoustic excitation at simulated UHB frequencies, sound pressure levels for each treatment were subtracted from the baseline sound pressure levels. Results are shown in Figs. 11–16. Each figure applies to a single tone frequency. The relative noise levels are shown as a function of configuration and are presented as the range and average value of the levels at the four cabin measurement stations. A 1- or 2-dB difference in average levels from one configuration to the next is not significant given the relatively large ranges on the various figures.

Several gross trends can be observed. First, noise levels increased above baseline levels at all frequencies after the first few treatments were added. Second, configuration 2 (the torque box) generally caused the highest levels; levels decreased after successive treatments were added. Third, the furnished fuselage configurations (13–16) substantially reduced the levels from the structural modification configurations.

Specific trends for each excitation frequency amplify these gross trends. For 169 Hz, Fig. 11 shows that the torque box results in interior levels that are higher than baseline levels. Adding two and then four frames (configurations 3 and 4) reduces the level to the baseline level, but subsequent configurations in the structural modification phase have a negligible effect. Installing the fuselage interior (configuration 13) reduces levels, and a further reduction of 5–6 dB occurs when the trim panels are damped (configuration 15).

Figure 12 shows nearly identical trends for 213 Hz. Addition of the fuselage interior yields a greater benefit at this frequency than at 169 Hz.

For 338 Hz, it is apparent in Fig. 13 that the torque box further increases levels relative to the baseline, and again two additional frames counteract this effect. The double wall pressure bulkhead (configuration 8) provides significant benefit at this frequency but is compromised somewhat by the next configuration (tuned absorbers). The furnished fuselage configurations (13–16) provide increasingly greater reductions.

The data in Fig. 14 for 426 Hz differ from the data for the prior frequencies in that levels decrease by some 15 dB after the two frames are installed, and then remain nominally 5 dB below baseline levels, rather than at baseline levels, for the next few configurations. The double wall bulkhead reduces levels, but not to the extent observed at 338 Hz. The tuned absorbers (configuration 9) appear to provide a benefit, which is surprising since the absorbers are tuned to 169 Hz. Levels further decrease by 4 dB after the sonic fatigue damping is added (configuration 11). The first furnished configuration again provides a significant reduction, which increases with subsequent configurations.

For 507 Hz (Fig. 15), the torque box increases levels above the baseline by 3 dB, and four added frames are required to reduce this effect. The double wall pressure bulkhead again yields some benefit. For this frequency, the skin acoustic damping (configuration 12) shows an 8-dB improvement in levels, followed by another large decrease in levels when the furnishings are added. Here, additional configurations do not greatly reduce levels as they did for the prior frequencies, although the net effect is a 5-dB reduction from configuration 13 to configuration 16.

The data for 639 Hz are presented in Fig. 16. Again, the torque box causes levels to increase above the baseline, but

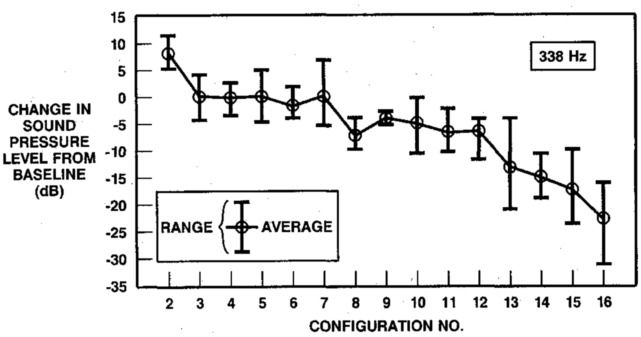

Fig. 13 Treatment sound pressure levels, 338 Hz.

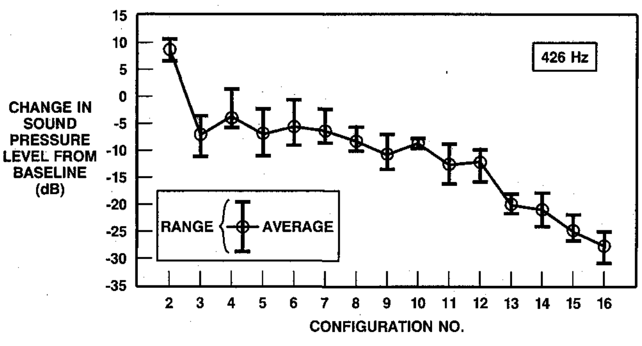

Fig. 14 Treatment sound pressure levels, 426 Hz.

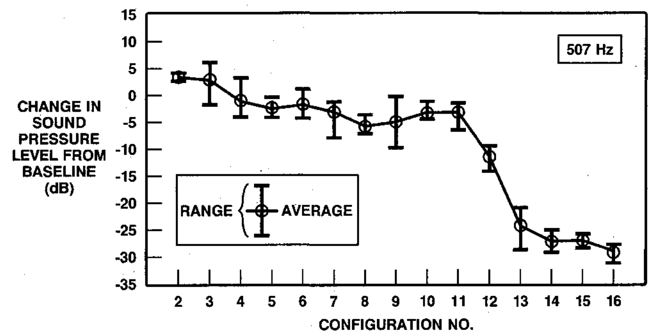

Fig. 15 Treatment sound pressure levels, 507 Hz.

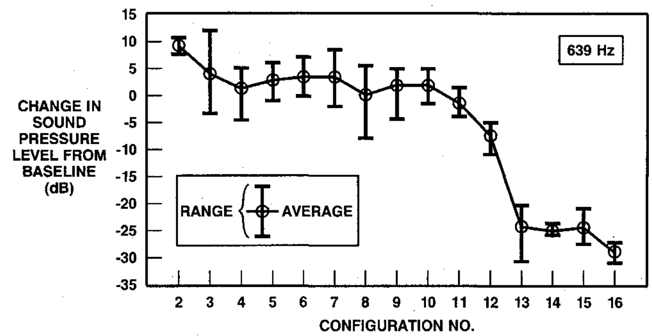

Fig. 16 Treatment sound pressure levels, 639 Hz.

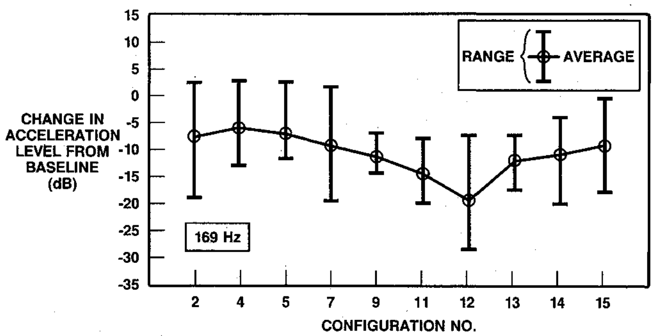

Fig. 17 Treatment acceleration levels at station 718, 169 Hz.

two and then four frames reduce levels to near baseline. The double wall bulkhead yields a 4-dB improvement in levels. The sonic fatigue damping (configuration 11) also results in 4-dB lower levels, and the skin acoustic damping (configuration 12) drops levels 5 dB further. The first furnished fuselage configuration then decreases levels by 15–20 dB, with an additional 5 dB occurring for the final configuration.

Vibration Excitation Data

The approach taken for analysis of the vibration excitation data is similar to that for the acoustic excitation data. For the vibration tests, however, only two frequencies were studied (169 and 213 Hz) and not all of the configurations were evaluated. Treatment effectiveness is evaluated on the basis of changes in fuselage acceleration levels relative to baseline levels. (It is assumed that reductions in acceleration of the structure translate into reductions in cabin noise levels; future research will be oriented toward studying this structural/acoustic interaction.)

Figures 17–20 show the average acceleration levels relative to baseline levels for each configuration. Figures 17 and 18 present data measured on station 718 and longeron 10, respectively, at 169 Hz. Similarly, Figs. 19 and 20 present 213-Hz data measured on station 718 and longeron 10, re-

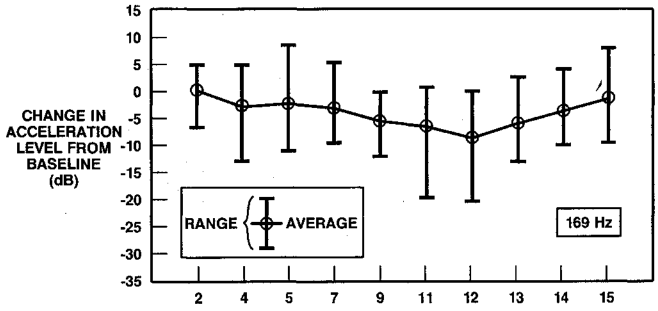

Fig. 18 Treatment acceleration levels on longeron 10, 169 Hz.

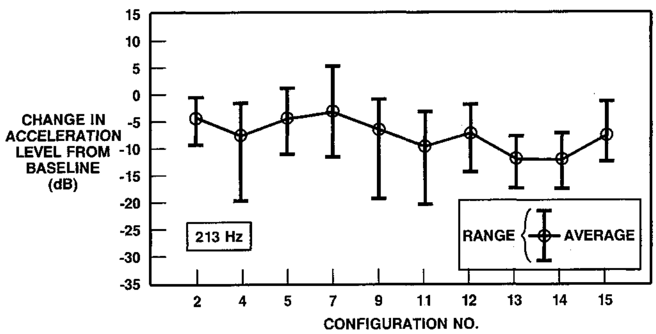

Fig. 19 Treatment acceleration levels at station 718, 213 Hz.

spectively. The station 718 data are based on the acceleration levels measured at locations A, C, D, E, and H, and the longeron 10 data are based on the acceleration levels measured at locations 718, 737, 747, 757, 766, and 776.

One immediately striking trend that can be observed in these four figures is that for both frequencies, the station 718 relative levels are consistently 5 dB lower than longeron 10 relative levels for nearly every configuration. One possible explanation is that each treatment yields benefits (in terms of reducing acceleration levels) that increase with distance along the fuselage from the vibration source. This explanation is supported by review of the normalized acceleration data measured along longeron 10, which shows relatively constant levels for the baseline configuration but with levels that generally decrease with distance from the vibration input point for the various treatments. This is not surprising for extensive damping treatments. However, for localized treatments, such as the torque box, this increasing benefit with distance was not anticipated.

Figures 17 and 18 both show that for 169 Hz, the torque box does not increase (average) vibration levels. Figure 17 shows a relatively steady decrease in vibration levels on station 718 with successive treatments. (This trend is less pronounced in the longeron 10 data.) In particular, the station 718 data show that the tuned absorbers (configuration 9), sonic fatigue damping (configuration 11), and skin acoustic damping (configuration 12) each reduce acceleration levels significantly (3–5 dB). For the furnished fuselage configurations, acceleration levels rise; this may be due to structural energy propagating through the frames into the trim panels and then radiating as acoustic energy through the sidewall air gap back to the fuselage skin and structural members, where increased vibration levels result.

For 213 Hz, Figs. 19 and 20 show that the torque box and four added frames both reduce levels, but there is an increase in levels with frame damping (configuration 5). Disabling the torque box (configuration 7) appears to increase the levels on station 718 but decrease levels on longeron 10. For station 718, the tuned absorbers (configuration 9) and the sonic fatigue damping (configuration 11) again show good reductions in the acceleration levels, but the skin acoustic damping (configuration 12) does not have the same benefit at this frequency as it did for 169 Hz. There is a reduction in level of 4 dB when the fuselage furnishings are added, but this benefit disappears for configuration 15.

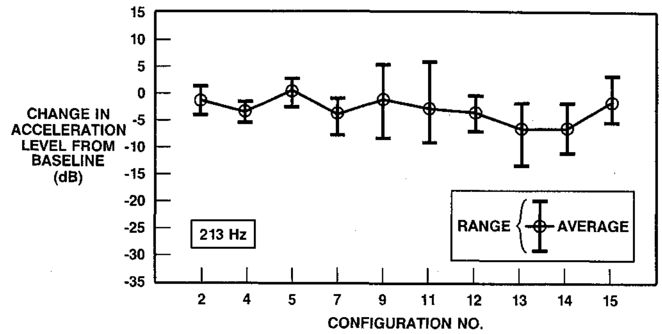

Fig. 20 Treatment acceleration levels on longeron 10, 213 Hz.

Summary and Conclusions

The measurements and results described in this paper have demonstrated the usefulness of the FARF for evaluating the effectiveness of different types of noise control treatments. For an aft-engine mounted configuration using advanced turboprop engines, the performance of individual treatments in reducing acoustic and vibration excitation has been tested, with the various treatments installed in the fuselage as they would be on a real aircraft.

The test data showed that treatment effectiveness is frequency-dependent as well as dependent on type of excitation. The major results of these tests are as follows:

1) The torque box increases noise levels in the cabin at all frequencies for acoustic excitation, but substantially reduces acceleration levels for vibration excitation.

2) The two extra frames decrease noise levels, and the levels generally decrease further with the installation of a second set of two extra frames. The four frames also reduce acceleration levels for vibration excitation.

3) The frame damping treatment has no effect on interior noise levels and a relatively minor reduction in acceleration levels. The same conclusions apply to application of damping to the torque box and to disabling the torque box.

4) The double wall pressure bulkhead reduces interior noise levels for the higher excitation frequencies.

5) The tuned absorbers have no significant effect on interior noise levels, but reduce acceleration levels at 169 Hz and to a lesser extent at 213 Hz, for vibration excitation.

6) The absorption blanket has no significant effect on noise levels for acoustic excitation.

7) The sonic fatigue damping and the skin acoustic damping treatments both provide reductions in noise levels and acceleration levels, depending on frequency. For acoustic excitation, the benefits of the sonic fatigue damping begin above 213 Hz, while additional noise level reductions due to the skin acoustic damping begin above 426 Hz. For vibration excitation, both treatments reduce acceleration levels at 169 Hz, but only the sonic fatigue damping reduces the levels at 213 Hz.

8) The cabin furnishings significantly reduce interior noise levels at all frequencies for acoustic excitation. The individual furnished fuselage configurations generally provide increasing benefits at the higher excitation frequencies; at the lower frequencies, trim panel damping reduces the interior levels. In contrast, for vibration excitation, acceleration levels do not decrease significantly and in fact increase at 169 Hz.

For vibration excitation, treatments effective in decreasing fuselage acceleration levels included the fuselage stiffening treatments (the torque box and the additional frames), the tuned absorbers, and the damping treatments applied to the fuselage skin. For acoustic excitation, however, none of the treatments was particularly effective in reducing cabin noise levels at the lower UHB frequencies (169 and 213 Hz). For the higher UHB frequencies, the additional frames, double wall bulkhead, and various damping treatments reduced noise levels transmitted into the cabin.

The need still exists to identify and test lightweight and compact treatments that effectively reduce cabin noise levels resulting from acoustic excitation at frequencies below 250 Hz. There is also a need to better understand the structural and cabin cavity modal characteristics and their effects on interior noise levels.

Acknowledgments

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