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STATUS OF AIRCRAFT INTEGRAL DAMPING DEMONSTRATION

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Abstract

The sound pressure levels generated by aircraft jet engines can result in sonic fatigue of structure and damage to sensitive, on-board electronic gear. The program objective is to develop the passive damping technology required to achieve sonic fatigue resistance at reduced weight and to suppress structural vibration within aircraft equipment bays. The approach is to incorporate constrained layer damping into the fuselage and equipment racks as an integral part of their design, rather than to use less effective add-on damping treatment after the structure has been manufactured. The aft equipment bay of the B-1B aircraft was selected as the baseline component with which to compare and demonstrate the technology developed in this program. The analyses and experimental testing accomplished during the preliminary design phase of this program are discussed. It is shown that integral damping can reduce vibration transmitted into equipment racks by 90 percent, and that the fuselage structure can be made sonic fatigue resistant at reduced weight.

Introduction

The skins and substructure of military aircraft are often exposed to intense vibroacoustic environments that can reduce structural fatigue life and cause equipment malfunction.

The usual design approach to reducing resonant response is to stiffen the structure, by increasing skin thickness for example, which results in a weight penalty. A need exists to develop lightweight aircraft structures that can withstand the severe environment while transmitting less vibration into equipment racks.

The use of add-on damping treatment is a common method of dealing with sonic fatigue and resonant vibration in aircraft skins and substructure. Previous exploratory development studies have shown that the most cost-effective way to apply passive damping is to incorporate the viscoelastic material as an integral part of the structure during the design/fabrication process. This is a more efficient approach to reducing structural vibration than the addition of constrained layers of damping material, a method that characteristically requires more mass in order to be effective.

The purpose of the program described in this paper is to demonstrate that the use of advanced metallics can significantly reduce the weight and life-cycle cost of aircraft structures and equipment operating in a high vibroacoustic environment. This will be achieved by developing lightweight sonic fatigue-resistant aircraft structures incorporating passive damping. The validated technology that evolves from this program will provide generic guidance for the incorporation of new damping concepts and materials into the design of future aircraft. In addition, the technology will apply to the redesign of structural components on operational aircraft that have high maintenance costs. The program approach will be to redesign an existing aircraft structure that, because of its severe operational vibroacoustic environment, is especially vulnerable to damage from sonic fatigue, and whose interior equipment bays are subject to high vibration levels that adversely affect sensitive electronic gear. This baseline structure will be identified as the demonstration component.

Demonstration Component

The aft equipment bay (AEB) of the B-1B strategic bomber was selected as the baseline component for this program. It is considered the best of the candidate structures for several reasons. It is a major structural component, a 360 degree self-contained, retrofittable compartment that comprises part of the B-1B aft fuselage. The location of the AEB makes it an excellent baseline to demonstrate the objectives of this program (Fig. 1). It is located immediately aft and adjacent to the jet engine exhaust nozzles; as a result, the external surfaces of the AEB and the sensitive electronic gear within the bay are susceptible to damage from extended periods of exposure to the intense sound pressure levels (SPL) generated by the engines.

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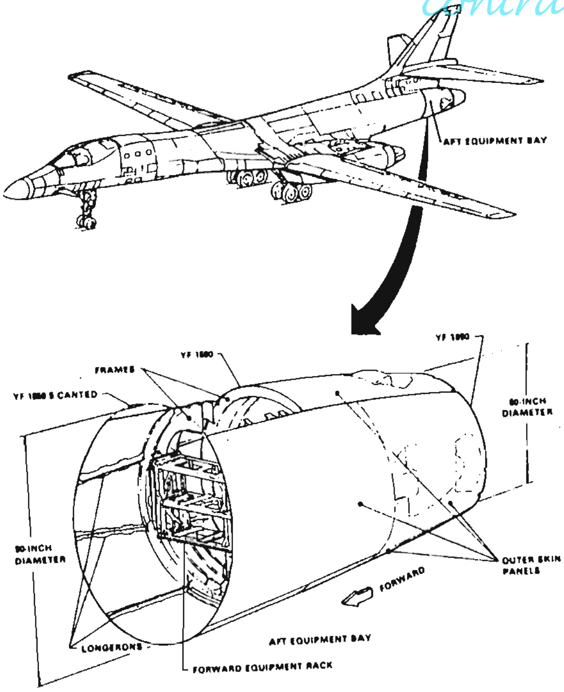

Fig. 1 Location of the Aft Equipment Bay on the B-1B Aircraft.

The AEB basic construction is conventional aluminum, stepped chem-milled skins riveted to a frame/longeron substructure. It contains two equipment rack assemblies, one forward and one aft, that are anchored to frame webs through cup-type vibration isolators. The AEB is 130 inches (3.30 m) long, with a 90 inch (2.29 m) forward diameter at station YF-1559, tapering down to 60 inches (1.52 m) at station YF1690. It weighs approximately 1350 lbs (612.9 kg) without avionics equipment installed. The AEB structure is sealed for pressurization above 8,000 ft (2440 m) altitude (Fig. 2 and 3).

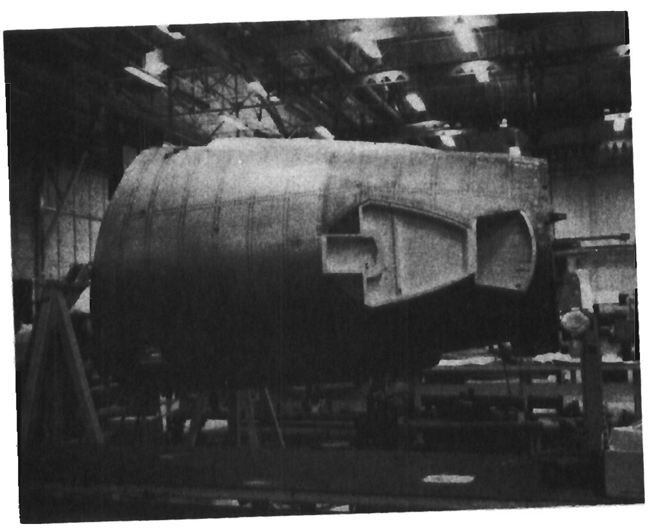

Fig. 2 Aft Equipment Bay (AEB).

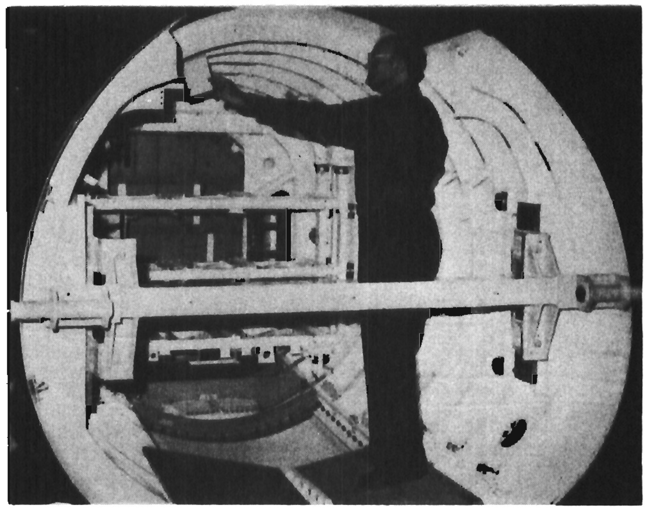

Fig. 3 View of the AEB Looking Aft.

Program Structure

The work described in this paper will be accomplished in three phases:

Phase I (Preliminary Analysis)

Baseline design criteria will be assembled and trade-off studies conducted of various viscoelastic materials and damping concepts. Coupon samples will be tested to evaluate candidate materials. Advanced design test panels will be fabricated for sonic fatigue and noise reduction tests. Advanced design features will be identified for the replacement AEB fuselage structure and equipment racks.

Phase II (Advanced Development Segment)

A full-scale structural segment of the replacement component will be fabricated using an advanced design based upon the results of Phase I. The segment will include internal structure that is integral to the segment, such as equipment racks, shelving, and shelving support structure. The instrumented segment will be used for modal response and acoustic fatigue tests and for noise reduction measurements. An assessment of the advanced segment performance will be made regarding its potential application in the design and construction of a complete full-scale component for future flight test demonstrations.

Phase III (Advanced Development Component)

The end product of this program will be a full-size, form-fit-and-function replacement structure that will be retrofittable in its entirety with the production baseline component. It will be designated as the advanced development component, designed on the basis of Phase I results and incorporating any modifications identified during the

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advanced segment tests in Phase II. The advanced development component will be instrumented for static, dynamic and noise reduction tests. These tests will be performed in order to qualify the advanced development component for flight certification. Flight demonstrations of the advanced development component are planned for a future program.

Structural Analysis

Finite Element Model

The geometry of the baseline equipment racks, both fore and aft, is composed of a rigid system of shelving, braces and vertical rack supports interfacing the fuselage frames through an array of conventional cup-type vibration isolators. The forward equipment rack assembly is shown in Figures 4 and 5. At best, this arrangement presents a "stiff ride" for sensitive shelf-mounted equipment units in a severe vibroacoustic environment. Although most of the vibration is structurally transmitted into the racks, airborne noise within the AEB is a secondary source of excitation (Fig. 6).

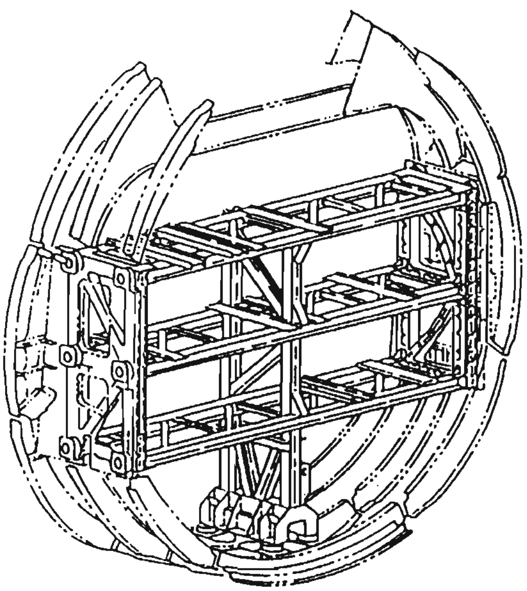

Fig. 4 Sketch of Forward Equipment Rack Assembley.

To improve the vibroacoustic environment, a study was conducted to determine the best means of incorporating integral damping into the equipment rack structure. The approach taken was to conduct a modal analysis of the equipment rack structure using finite element modeling (FEM). Key rack components and structural joints, designated as Principal Design Features (PDFs), were selected for FEM analysis, both individually and as an assembly. The PDFs were: skin section, skin-to-frame joint, frame-to-rack interface, rack-to-shelf interface, and shelf section. A finite element model of the baseline rack assembly is shown in Figure 7.

The rear access door of the AEB is constructed of graphite/epoxy skins bonded to a honeycomb core. In addition to the rack-related PDFs, the door also was modeled by FEM to investigate damping a composite component.

Analytical Results

The results from the equipment rack analysis are impressive. It was demonstrated by FEM that by using damped honeycomb shelves, each supported in a "floating beam" frame, the vertical end support posts and the vibration

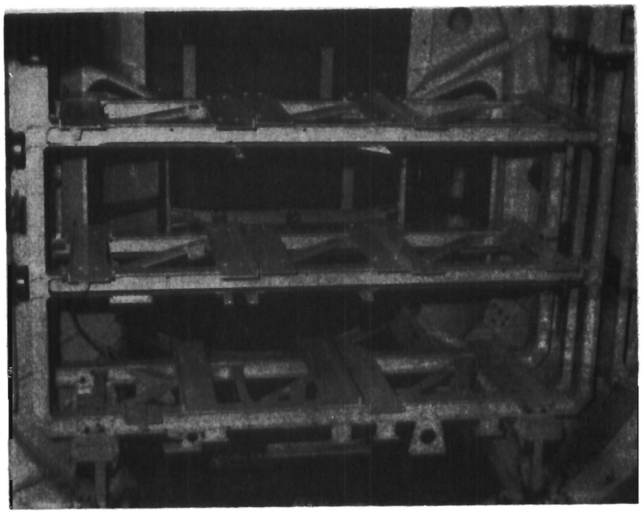

Fig. 5 Forward Equipment Rack Mounted on Vibration Isolators (Without Center Post).

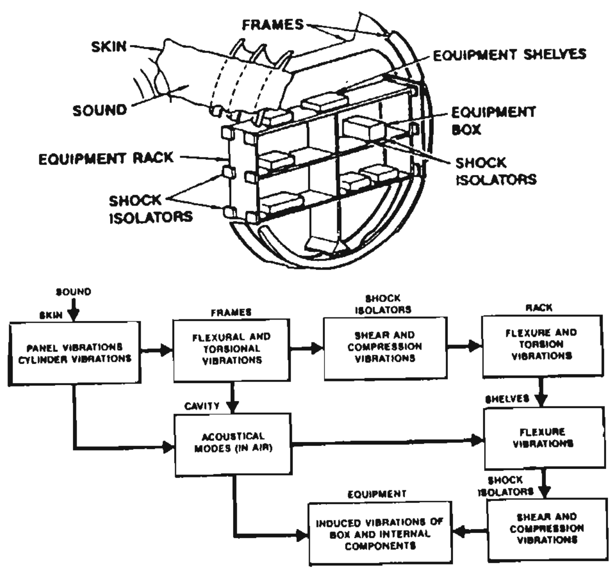

Fig. 6 Paths of Structural Vibration and Airborne Noise into the Equipment Rack.

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isolators can be eliminated (Fig. 8 and 9). In their place, polymer "tension pads" will be used as an interface to independently anchor each shelf directly to the fuselage frames (Fig. 10). The tension pads also function as expansion joints during fuselage pressurization. The center support post of the rack structure will be retained. It is estimated that this "soft ride avionics" concept will reduce the total rack weight by over 50 percent and decrease vibration transmitted into equipment shelving by 90 percent.

Similarly, FEM analyses show that by using laminated skins/frames, sonic fatigue resistance of the fuselage structure can be achieved at a weight reduction of 20 to 25 percent.

Two concepts of damping the AEB composite access doors were examined by FEM. These are described in Acoustic Test Panels. It was shown that damping loss factors should be high enough to reduce the door weight by 5 percent.

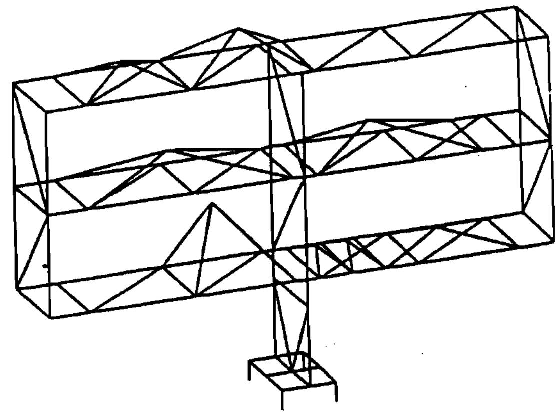

Fig. 7 Finite Element Model of the Baseline Forward Equipment Rack.

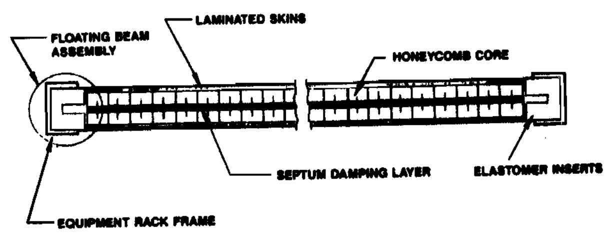

Fig. 8 Honeycomb Shelf with Laminated Skins and Damping Septum.

Selection of Damping Adhesives

Different types of damping adhesives are required, each for a particular application, to incorporate damping into the various elements that comprise the advance design AEB skins and equipment racks. The expected resonant frequency responses and operational temperature ranges are the most important design parameters in adhesive selection. From previous screening, candidate adhesives were evaluated according to type for three particular applications; for use in laminated skins, rivet-bonding and graphite/epoxy structure.

Standard ASTM test specimens were used to characterize the strength and damping properties of the candidate adhesives. These included lap shear and creep coupons and vibrating reeds. From these tests nomographs were constructed showing how the loss factor and shear modulus of a particular adhesive vary for a given combination of temperature and frequency. An example is shown in Figure 11. The nomograph is entered horizontally from the right at the selected resonant frequency. Where that horizontal line intersects the temperature of interest, a vertical line is drawn. It, in turn will intersect the two plotted curves, giving the respective values of shear modulus and loss factor. The most promising of the candidate adhesives were identified for further evaluation.

Effective damping can be extended over a wider range of temperatures by using a "duplex system" of adhesives. This entails the use of two different adhesives, each with its own effective temperature range, in a back-to-back layup and single cure cycle.

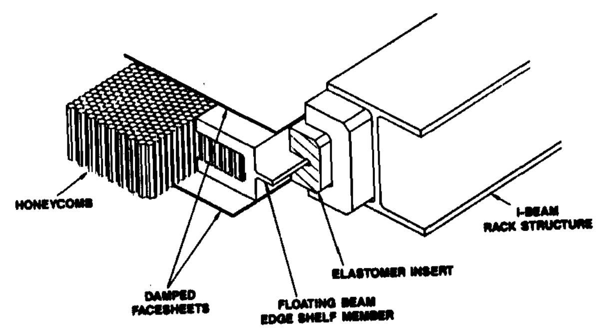

Fig. 9 Floating Beam Support for Equipment Rack Shelves.

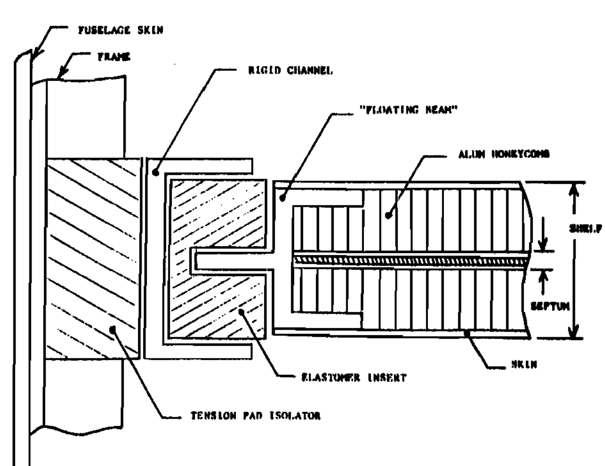

Fig. 10 Shelf Interface with Fuselage Frame.

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Two duplex systems were selected for both metallic and Graphite/Epoxy laminates. They were AF-32/PM-2160 (film-film) and AF-32/EC-1838 (film-paste) (Fig. 12). AF-32 performed best at lower temperatures. Both the PM-2160 and the EC-1838 were selected for their high temperature properties and because their processing and cure characteristics were compatible with AF-32. Although paste adhesives are generally more difficult to work with, EC-1838 was included for comparison.

EC-3594 is the preferred adhesive for rivet bonding. It meets the room temperature cure requirement and has a pot life long enough to enable completion of assembly before it sets-up.

Acoustic Test Panels

Configurations

Nine curved acoustic test panels were fabricated to evaluate different skin laminates, using the damping adhesives previously identified. Each panel is curved to a 48 inch (1.22 m) radius, with a 50 inch (1.27 m) arc length and 30 inch (0.76 m) width. The features of each of the nine panels are listed in Table I.

Six of the panels are metallic, 9-bay configurations that represent the frame/longeron construction at Station YF 1610 on the B-1B AEB (Fig. 13). The six metallic panels are divided into two groups of three each; the first group (Concept 1.0) all have riveted skins; the second group (Concept 2.0) all have rivet-bonded skins. Concept 1.1 is the undamped baseline metallic with chem-milled lands. The remaining five metallic panels have laminated skins with bonded doublers. They vary within their own group only by the type of damping adhesive used in the laminates; the exception is Concept 2.3, which has damped frames in addition to laminated skins.

Table 1 Acoustic Test Panel Configurations

BASIC GROUP	CONCEPT	CONSTRUCTION	ADHESIVES
1.0 METALLIC	1.1	BASELINE	
	1.2	LAMINATED SKIN	DUPLEX (A) AF-32/EC-1838
RIVETED SKIN AND FRAMES	1.3	" "	DUPLEX (B) AF-32/PM-2160
2.0 METALLIC	2.1	" "	(A)
	2.2	" "	(B)
RIVET BONDED SKIN AND FRAMES (EC-3594)	2.3	LAMINATED SKIN AND FRAMES	(B)
3.0 COMPOSITE	3.1	BASELINE	
	3.2	LAMINATED SKINS OR DAMPING SEPTUM	(B)
GR/EP SKINS HONEYCOMB CORE (FM-300)	3.3	TUNED DAMPERS	PRC-1750 SILICONE

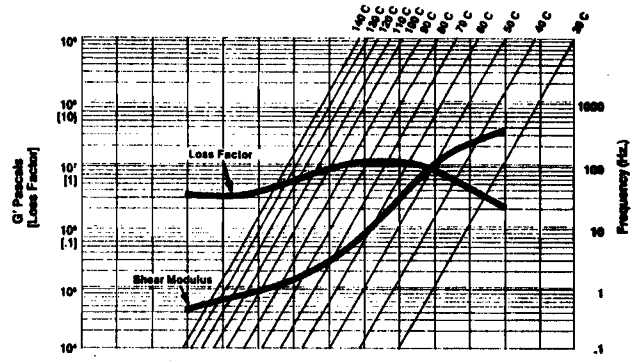

Fig. 11 Loss Factor and Shear Modulus of a Viscoelastic Material Related to Frequency and Temperature.

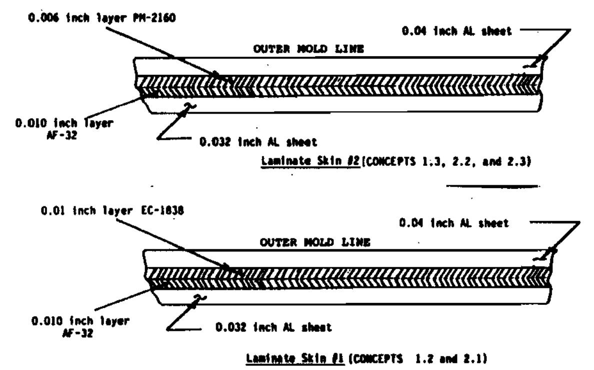

Fig. 12 Duplex Viscoelastic Damping Adhesives.

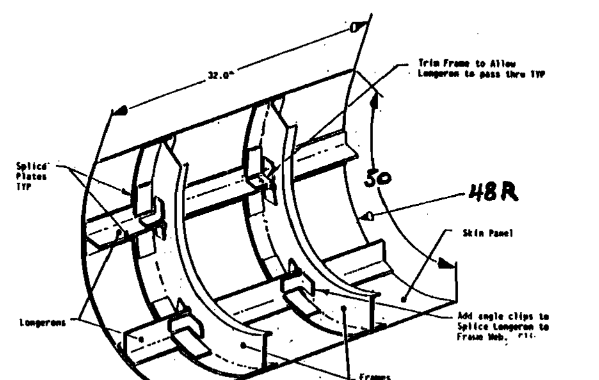

Fig. 13 Construction of Metallic 9-Bay Acoustic Test Panels.

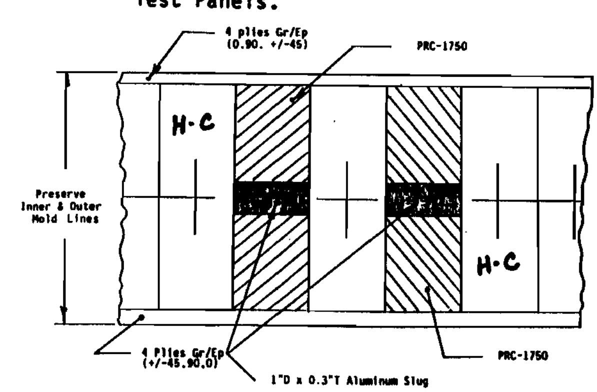

Fig. 14 Cross Section of Composite Panel Using Tuned Dampers.

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The remaining three panels (Concept 3.0) are constructed with graphite/epoxy skins bonded to an aluminumin honeycomb core. Concept 3.1 is the baseline configuration with no damping.

Concept 3.2 will have either damped skins or a damping septum within the structure that divides the honeycomb core near the neutral axis. This configuration is similar to the damped honeycomb shelf shown in Figure 8.

Concept 3.3 uses a damping system composed of an array of "tuned-damper" aluminum slugs. As shown in Figure 14, each slug is suspended within the honeycomb core between two silicone inserts. This allows each slug to oscillate freely on an axis normal to the skins. The slugs are designed to oscillate at maximum amplitude when the panel is at its fundamental resonant frequency. In principle, this is the mechanism by which the vibration energy is dissipated.

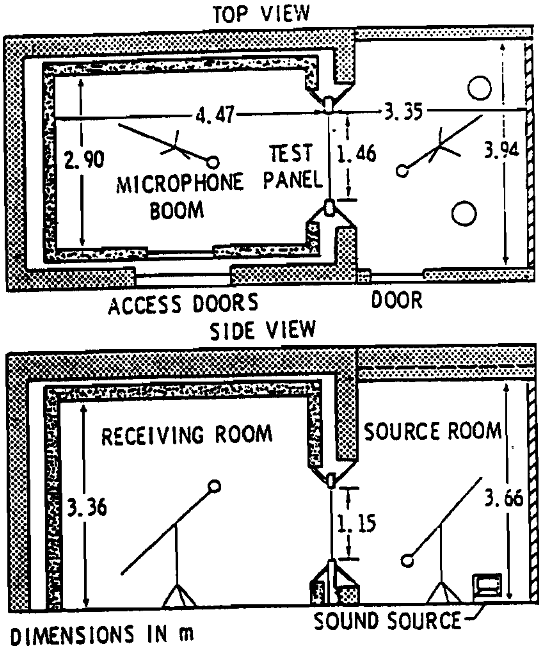

Fig. 15 NASA LaRC Noise Reduction Test Facility.

Test Conditions

A test plan was developed to evaluate the performance of the candidate damping adhesives and the damping concepts that are represented by the nine acoustic test panels. Experimental data will be obtained to determine the modal response, sound transmission loss and sonic fatigue resistance of each panel.

Response Tests

Modal response data will be recorded using two test methods, during which each panel is shaker-driven while mounted in a high-mass test fixture. The roving accelerometer method will be used first, followed by a holographic technique that enables mode shapes to be recorded on video tape or by still photography.

Additional modal response data will be recorded during frequency sweeps made with the panels mounted in a progressive wave test section and using electropneumatic noise generators as a source of acoustic excitation. All modal tests will be accomplished at the Flight Dynamics Laboratory's sonic fatigue test facility at Wright-Patterson AFB, OH.

Noise Reduction Tests

A sound transmission survey will be made to determine the noise loss through each of the nine panels. These tests will be conducted at the NASA Langley Research Center, Hampton VA. Their noise reduction test facility is composed of a "source" room and a "receiving" room (Fig. 15). Each of the panels will be installed in a rubber-mounted steel fixture that is built into the wall dividing the source and receiving rooms.

A random sound field is generated in the source room by two floor-standing centrifugal fans, reinforced by loudspeakers to obtain the required broadband spectrum over a frequency range of 100 Hz to 10 kHz.

Space- and time-average recordings of the SPL are made during a 32 second sampling in both rooms for each test condition. Panel temperatures are monitored using thermocouples, and accelerometer data are recorded from the center bay of each panel.

It is planned to test each panel at ambient temperature and at 180°F, first without and then with an acoustic/thermal material applied to the "receiving side" of the panel. A Fiberglas thermal blanket will be used on the two baseline panels. A sound absorbent polyurethane foam will be applied to each of the remaining seven advanced design panels. The test procedure for each panel in turn will be:

a) Install panel without treatment.

b) Conduct noise reduction test at ambient room temperature.

c) Heat panel until its "source side" temperature stabilizes at 190°F ± 10 degrees, then conduct noise reduction test.

d) Install appropriate material on the receiving side of the panel.

e) Conduct noise reduction test at ambient room temperature.

f) Repeat (c).

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Fatigue Tests

Acoustic tests will be conducted on each of the nine panels to evaluate their sonic fatigue resistance. Each panel will be installed in a 2 ft (0.61 m) wide x 6 ft (1.83 m) high x 8 ft (2.44 m) long progressive wave test section at the Flight Dynamics Laboratory's sonic fatigue test facility located at WPAFB OH. A sketch of the facility is shown in Figure 16. Three Wyle 30 kilowatt electropneumatic noise generators provide the noise source. They are controllable from 50 Hz to 500 Hz. The upper regions of the spectrum are filled in by the harmonics.

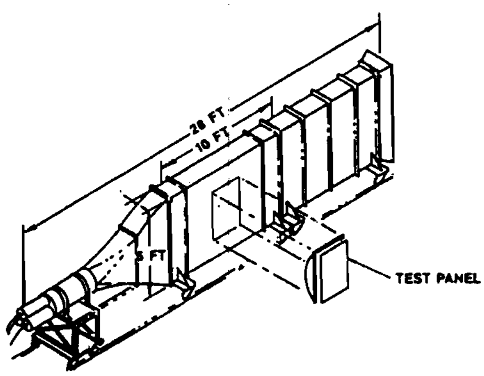

Fig. 16 Progressive Wave Test Section.

The qualification test conditions will be based upon measured flight data that show the AEB experiences 168-169 dB overall SPL at Station YF-1610 represented by the test panels (Fig. 17). Spectrum shaping will be accomplished by concentrating much of the acoustic power output into the 1/3 octave bands that contain the predominant response peaks that were identified during preliminary sine wave sweeps. The required test duration for each panel has been established at 21 hours. This figure is based on the predicted number of full-afterburner takeoffs that the B-1B aircraft will make during its projected 25 year life.

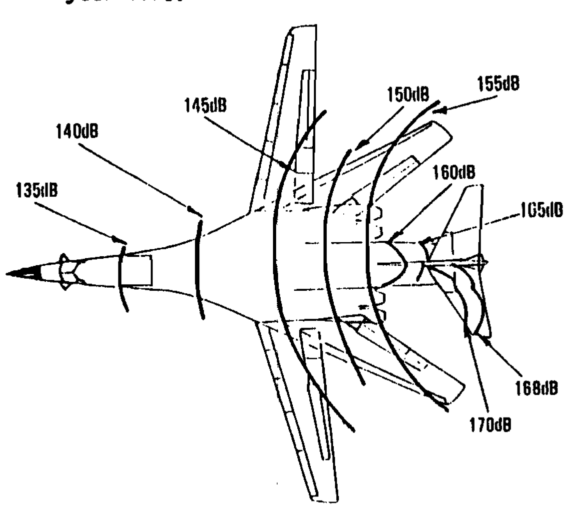

Fig. 17 SPL Contours on the B-1B Aircraft.

Summary

The results of the FEM study show that a less complex design of the equipment racks can be achieved by incorporating integral damping into the structure. This can be accomplished primarily by using damped honeycomb shelves with "floating beam" corner supports. These innovations would eliminate the need for the heavy vertical end posts and bulky vibration isolators, resulting in a weight reduction of over 50 percent.

The results also show that the sonic fatigue resistance of the fuselage structure can be attained by using laminated skins rivet-bonded to the substructure while reducing weight by 20 to 25 percent.

In addition, it is estimated that the overall redesign of the aft equipment bay will result in a 90 percent reduction in the vibroacoustic environment currently experienced by shelf-mounted line equipment items in the baseline AEB.

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