ENHANCED DAMPING FOR THE SIKORSKY ACAP COMPOSITE AIRFRAME

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ABSTRACT

As part of a noise evaluation of the Sikorsky Advanced Composite Airframe Program (ACAP) helicopter, enhanced composite damping to reduce interior noise has been investigated. The present paper summarizes the effort to identify, test, and predict the potential noise reduction benefits of unconstrained woven Kevlar and off-axis unidirectional Kevlar damping laminates selectively applied to lightly damped graphite epoxy frame components to attenuate structureborne noise. Test data provided preliminary indications that woven and unidirectional damping laminates could potentially increase airframe damping levels, and Statistical Energy Analysis model predictions indicated that increased airframe damping could potentially reduce ACAP interior noise by up to 4 dB.

INTRODUCTION

Recent development efforts in helicopter technology have increasingly incorporated composite airframe construction to reduce weight and cost. One example is the Advanced Composite Airframe Program (ACAP), a joint program of the Army Aviation Applied Technology Directorate (AATD) and Sikorsky Aircraft to design, fabricate, and evaluate a predominately composite airframe. Figure 1 shows a photograph of the Sikorsky ACAP helicopter and a breakdown of the composite materials used in the external/skin components of the ACAP is shown in Figure 2.

The suppression of interior acoustic noise is always a challenge in rotorcraft and the Sikorsky ACAP helicopter is no exception. Weight limitations and requirements for large gearing reductions and rigid drivetrain to airframe attachments can exacerbate interior noise to discomforting or fatiguing levels and necessitate interior acoustic treatments with substantial cost and weight penalties. The use of composites may further increase cabin and cockpit noise levels as the bonded joints desirable for composite fabrication eliminate major loss mechanisms for structureborne noise (e.g. fretting and air pumping effects) inherent to a riveted metallic structure. As shown in Figure 3, the subassembly damping loss factors measured on the ACAP flight

flight test article during fabrication were approximately 50% lower than those measured on the Sikorsky S-76A, a comparable metallic airframe construction.

To improve the understanding of composite airframe noise characteristics, Sikorsky Aircraft investigated the ACAP helicopter [1,2] under Phase III: Internal Acoustic Noise Evaluation of the ACAP Militarization Test & Evaluation (MT & E) program, sponsored by the AATD under contract DAAJ02-85-C-0036. The major objectives of the noise evaluation effort were to: (1) develop a Statistical Energy Analysis (SEA) model of the Sikorsky ACAP airframe; (2) refine and validate the ACAP SEA model with ground and flight test data; (3) test and evaluate, using ACAP subcomponents, two noise reduction options applicable to the ACAP composite airframe; and (4) use the ACAP SEA model to predict the potential noise reduction benefits of the tested noise reduction options. The current paper summarizes the effort to identify, test, and predict the benefits of two noise reduction design options for the ACAP composite airframe.

Because composite airframe design has and will continue to trend from mechanical to bonded joints, the investigation of potential noise reduction design options was concentrated on improving structural damping through increased composite material damping. Larger damping levels would dissipate vibratory energy before it could be acoustically radiated into the cabin and cockpit. The current study evaluated unconstrained composite damping laminates suitable for bonding to the lower end caps of the longitudinal frames (beams) and cross frames in the cabin and cockpit ceiling structure. These beams and frames, fabricated of relatively lightly damped graphite-epoxy composites, were identified through modelling and testing as the primary structureborne noise transmission paths of the ACAP airframe. Although only a secondarily bonded configuration was investigated, integral hybrid designs would be potentially feasible and advantageous.

SEA MODELLING OF THE ACAP AIRFRAME

To permit analyses of the potential benefits of the noise reduction design options investigated for the ACAP, the first two tasks of the ACAP noise evaluation program included the development, refinement, and validation of a Statistical Energy Analysis (SEA) model of the Sikorsky ACAP composite airframe in conjunction with Cambridge Collaborative, Inc. The subsectioning of the ACAP ceiling structure for the SEA model is shown in Figure 4. The frame subsections were designated as, for example, Longitudinal Frame 7 Aft Left or LF7AL and Cross Frame 5 Middle or CF5M, and the outer skin panels were designated as, for example, Overhead Panel 57 Right or OP57R. The basic theory of SEA is given in Reference [3] and details of the SEA modelling effort can be found in References [1] and [2]. Comparisons of the ACAP SEA model estimates with ACAP flight test data for cabin and cockpit noise levels are shown in Figures 5 and 6, respectively. These comparisons show good agreement for a damping loss factor of 0.01 to 0.02 and indicate, in conjunction with similar comparisons of airframe vibration transfer functions, that the ACAP SEA model is sufficiently representative of the ACAP to permit evaluations of airframe design changes on interior noise levels.

ACAP INTERIOR NOISE REDUCTION

The most weight effective method to helicopter interior noise control is generally source noise control to reduce vibration excitation at the primary source, i.e. the main transmission gear meshes. However, unless incorporated during the design process, gearbox noise control often requires a costly redesign of the main transmission and thus is often an impractical solution for reducing helicopter interior noise.

Noise control in current military and commercial helicopters is primarily achieved by add-on treatments such as sound absorbing backing on the interior trim panels. The trim panels then block acoustic radiation from vibrating skin panels and frame surfaces from reaching the cabin.

In addition, sound absorbing materials are often used in the cavities between the trim and skin panels to prevent excessive noise buildup from lessening the effectiveness of the trim panels. For some noise control treatments, add-on damping treatments are also applied to the frame surfaces and, in particular, the panel skins. However, all of these conventional noise treatment designs have significant weight trade-offs which inherently limit the achievable noise reduction.

Another potentially effective method of noise control in lightweight helicopter airframes focuses on the design of the airframe structure to reduce vibratory energy transmission from the main gearbox into the frames and skin panels which subsequently radiate into the cabin and cockpit. Two methods for attenuating main gearbox noise within the airframe structure were investigated for the ACAP composite airframe. One is briefly presented for comparison and involved the beneficial effects of a structural modification which introduced an impedance mismatch at the controls enclosure or "broom closet" frame junctions in the aft cockpit ceiling structure. The primary approach, and the major concentration of the ACAP noise reduction investigation, considered increased structural damping through the application of composite materials with higher damping characteristics.

Airframe Impedance Mismatching

Comparisons of the measured ACAP vibration transfer functions along the longitudinal transmission support beams with initial SEA model predictions revealed a significant discrepancy forward of the controls enclosure or "broom closet". The initial model predictions indicated little vibration reduction throughout the transmission support beam while the measured data showed a large reduction forward of the broom closet as can be seen for frame subsection LF7W in Figure 7. As the transmission support beam is a one-piece, single lay-up construction, the measured reduction in vibration levels was unexpected. However, the reduced vibration levels were attributable to plate stiffeners originally added to the aft broom closet frame junctions to prevent fatigue cracking. The plate stiffeners, indicated by the arrows in Figure 8, effectively created a high vibration impedance which acted to reflect the vibratory energy being transmitted along the transmission support beams. This effect is partially responsible for the build-up in vibration levels between frame subsections LF45 and LF7A evident in Figure 7. In addition, the bolt-on design of the plate stiffeners may have also provided fretting and air pumping damping benefits similar to riveted joints. The coupling loss factors in the ACAP SEA model were subsequently modified to reflect the effects of the plate stiffeners and are incorporated in the SEA predictions shown in Figure 7.

Increased ACAP Airframe Damping

As a result of the SEA modelling effort, several of the overhead longitudinal beams and cross/side frames were identified as the primary transmission paths for the main gearbox noise reaching the cabin and cockpit [1]. Much of the overhead ACAP airframe structure can be seen in the photographs of the forward and aft cabin ceiling structures shown in Figures 9 and 10. These airframe components are fabricated of lightly damped [4,5], unidirectional, continuous fiber graphite-epoxies, and thus were identified as the primary candidates for increased damping. Although conventional constrained layer damping treatments could be employed to increase structural damping in the ACAP airframe, the current investigation was directed at incorporating composite materials with inherently higher damping to achieve a potentially more weight effective noise control option. Only secondarily bonded composite damping options were evaluated, but integral designs would be potentially feasible and could further enhance the weight effectiveness.

Three higher damping composite materials were considered for the investigation of increased airframe damping. The candidate materials were aligned short fiber, woven Kevlar, and unidirectional Kevlar composites. Unidirectional fiber composites under off-axis loading and woven Kevlar composites have been shown to have significantly higher damping characteristics than axially loaded, graphite reinforced composites [4,5]. Although aligned short fiber composites have demonstrated a significant potential for high damping characteristics [4,6,7,8] with acceptable strength characteristics for integral design configurations, adequate supplies of aligned short fiber composite materials were not available for the current test effort. Hence, only woven and off-axis, unidirectional Kevlar 49 composites applicable to the overhead beams and frames of the ACAP airframe were investigated.

ACAP TRANSMISSION SUPPORT BEAM DAMPING TESTS

One objective of the ACAP MT&E evaluation of increased airframe damping was to perform testing of the higher damping composites on a test beam fully representative of the ACAP airframe. The intent was to provide damping information directly applicable to the ACAP airframe. In addition, utilizing an ACAP airframe subcomponent permitted the use of existing production tooling for test specimen fabrication. However, the deep cross-section and asymmetric design characteristics of ACAP frame components presented difficulties in choosing a test beam suitable for increased airframe damping tests. The ACAP airframe subcomponent providing the highest aspect ratio while minimizing asymmetries in all three axes was found to be the 1.37 m (54 in) cabin section of the left or port transmission support beam. The cabin section of the left transmission support beam consists of subsections LF7AL and LF5FL shown in Figures 9 and 10, respectively. The transmission support beam section was chosen to maximize the test beam aspect ratio while minimizing longitudinal asymmetry. Schematics of the ACAP test beam top and cross-sectional views are shown in Figure 11. Details of the woven Kevlar and unidirectional Kevlar damping laminates are shown in Figure 12. The damping laminates were sequentially bonded to the test beam in 0.1 in thick increments to permit evaluation of treatment thickness on beam damping levels. The orientation of the unidirectional and woven Kevlar plies in the damping laminates was based on results provided in References 4 and 5, respectively.

Test Specimen Fabrication

To meet schedule and cost constraints, a single ACAP transmission support beam section was fabricated for sequential testing of the baseline and damped configurations. The 0.1 in thick woven Kevlar and off-axis unidirectional Kevlar damping laminates were fabricated in sheets sufficiently large to permit the cutting of three laminates each with the required dimensions for bonding to the lower end cap of the test beam. Fiberite HY-E17714AA Kevlar 49 tape was used to fabricate the unidirectional Kevlar damping laminates while the woven Kevlar damping laminates were fabricated of American Cyanamid 5143-285 Kevlar fabric. Dexter Hysol EA9309.3NA was used to bond the damping laminates to the test beam section. After testing of the ACAP beam with the 0.1 and 0.3 in woven Kevlar damping laminates, the damping laminates were debonded to permit reuse of the test beam with the off-axis unidirectional damping laminates. To debond the woven Kevlar laminates, the damping treatment bond was heated to 200-225^{o} F, a thin scraper was used to peel the two adherents apart, and the lower end cap surface was cleaned for rebonding. The majority of the peeling action was applied to the adhesive and damping laminates to minimize effects on the test beam section.

Test Equipment, Procedures, and Conditions

A schematic of the ACAP transmission support beam damping test setup is shown in Figure 13. The equipment necessary to acquire and reduce the damping test data included:

1. Bruel & Kjaer (B&K) 4375 accelerometers with B&K 2635 charge amplifiers.
2. a Wilcoxon F4/Z820W electromagnetic shaker and associated signal conditioning equipment.

3. a Hewlett Packard 3562 two-channel FFT analyzer.

The B&K 4375 accelerometers supplied the necessary frequency response characteristics with sufficiently low inertia to minimize effects on the damping measurements. The electromagnetic shaker provided white noise excitation and a source force/acceleration measurement internal to the impedance head.

Photographs giving side and end views of the test setup are shown in Figures 14 and 15. The test beam was supported in a free-free configuration. The freely supported electromagnetic shaker was stinger mounted to the upper end cap at locations sufficiently removed from nodes of the first few transverse bending modes of the test beam. The response accelerometer was mounted in several locations during testing to avoid modal nodes and permit characterization of the modal shapes and damping. Note that the C-channel design of the ACAP transmission support beam necessitated shaker mounting on the upper end cap offset from the web plane. To limit torsional contamination of the measured vibration transfer data, the offset from the web plane was minimized.

To acquire the frequency response data, a random vibratory signal was input by the electromagnetic shaker to the test beam. The white noise input signal was shaped and amplified to produce an acceleration spectrum approximately uniform in level within the required frequency range of 350 Hz to 5700 Hz. The input force and response acceleration signals were conditioned and input into the two-channel FFT analyzer. The ensuing frequency response functions (response acceleration/input force) were stored on disc for later analysis.

After testing in the baseline configuration, the ACAP transmission support beam was tested with 0.1 in and 0.3 in thick woven Kevlar damping laminates and 0.1 in, 0.2 in, and 0.3 in thick off-axis unidirectional Kevlar laminates. A complete modal survey of both the upper and lower end caps for one shaker attachment location was conducted for each test configuration.

Data Analysis Procedures

The measured frequency response functions for each test configuration were analyzed with Structural Measurement Systems, Inc. Modal 6.0 modal analysis software. Modal 6.0 provides global curve fitting to determine frequency and damping estimates.

ACAP TRANSMISSION SUPPORT BEAM DAMPING TEST RESULTS

Summaries of the transmission support beam damping test results for the second and third out-of-plane or transverse bending modes are shown in Figures 16 and 17, respectively. These results indicate that application of the damping laminates did effect up to an 80% damping increase for the test beam. However, the test results are inconsistent from the second to third mode, and thus do not provide adequate characterization of the increased beam damping levels for design evaluations.

The inconsistencies and limitations of the beam damping data were largely due to problems inherent to the test specimen. In particular, the data acquisition and analysis was severely complicated by the low aspect ratio, C-channel design of the test beam. The usable test section of 1.37 m (54 in) limited the beam aspect ratio to 6.75 and the C-channel design was asymmetric in all three principal axes. Hence, the test beam insufficiently approximated a slender beam with the transverse bending modal frequencies being much lower than pretest predictions, and the asymmetric design did not provide pure bending modes for analysis, i.e. the exhibited bending modes were contaminated by both torsional and local flange bending effects. The latter problem effectively prohibited analyses of the fourth and higher bending modes, while the location of the first bending mode at 350 - 375 Hz resulted in insufficient frequency resolution to generate reliable damping estimates.

SEA EVALUATION OF INCREASED AIRFRAME DAMPING

The ACAP SEA model was used to analyze the potential benefits of frame (beam) damping for reducing ACAP internal noise levels. As noted previously, the overhead longitudinal beams and cross frames constitute the primary transmission paths for the gearbox vibrations in the ACAP airframe. In addition, these airframe components are fabricated of unidirectional graphite-epoxies which previous studies have identified as relatively lightly damped [4].

Based on the results of the SEA modelling of the ACAP and previously published composite material damping values [4,5], the baseline ACAP SEA model for the increased airframe damping analysis employed damping loss factors of 0.01 for the graphite-epoxy beams and frames and 0.02 for the Kevlar outer skin panels in the overhead cabin/cockpit airframe structure. The damping loss factors for the frames given in Table 1 were then increased to 0.02 and 0.03 to simulate the effects of increased airframe damping on ACAP interior noise levels. Although ACAP test results do not yet support the increase to 0.02, the previously published results for woven and unidirectional Kevlar composites [4,5] indicate that damping loss factors of 0.02 to 0.03 are potentially achievable. Also note that the subsection selection for the increased damping evaluation is only a first cut and does not represent an acoustic benefit versus weight penalty optimization.

Longitudinal Frames (Beams)	Cross and Side Frames
LF45L	CF4L
LF45R	CF4M
LF5FL	CF4R
LF5FR	CF5L
LF7AL	CF5M
LF7AR	CF5R
OLF45L	CF7L
OLF45R	CF7M
OLF57L	CF7R
OLF57R	CF45L
	CF45R
	SF4L
	SF4R

Table 1. ACAP Subsections Selected for Application of Increased Damping

The results of the SEA evaluation of increased airframe damping on ACAP interior noise levels are summarized in Figure 18 and indicate that 1 to 4 dB noise reductions may be achievable. The frequency dependency of the noise reductions shown in Figure 18 reflect the increasing importance with frequency of the damping loss factors relative to the coupling loss factors employed in the ACAP model [1,2]. Although the estimated noise reductions are relatively small, the SEA results indicate that the addition of woven or unidirectional Kevlar damping laminates to the ACAP frame components may represent a partial but weight effective noise control option.

CONCLUSIONS AND RECOMMENDATIONS

The execution of the ACAP transmission support beam damping test was determined by contractual, schedule, and budgetary constraints Because of the difficulties encountered in the acquisition and analysis of the beam damping data, the results do not represent a definitive characterization of the damping potential of woven and unidirectional Kevlar in the tested applications. To achieve more reliable results, testing with a high aspect ratio, symmetrical beam design would be required. In addition, more extensive testing of the effects of laminate orientation, thickness, and composition (i.e. fabric type, epoxy/resin type, etc.) would be needed to provide quantitative guidelines for using the woven or unidirectional Kevlar laminates to increase airframe damping and decrease interior noise levels in composite rotorcraft. However, the damping data did give preliminary indications that increased damping would be feasible for the ACAP or comparable composite helicopter airframes.

The SEA model of the ACAP indicated that interior noise reductions of 1 to 4 dB are achievable with full realization of the woven and unidirectional damping characteristics demonstrated in previously published results. Although these noise reductions would only be barely significant acoustically, the application of woven or unidirectional Kevlar damping laminates to the lightly damped graphite epoxy airframe components could represent a weight effective noise control option relative to interior trim panel acoustic treatments and warrants further investigation to better characterize potential damping benefits.

ACKNOWLEDGMENT

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Figure 1. Photogragh of the Sikorsky ACAP Helicopter

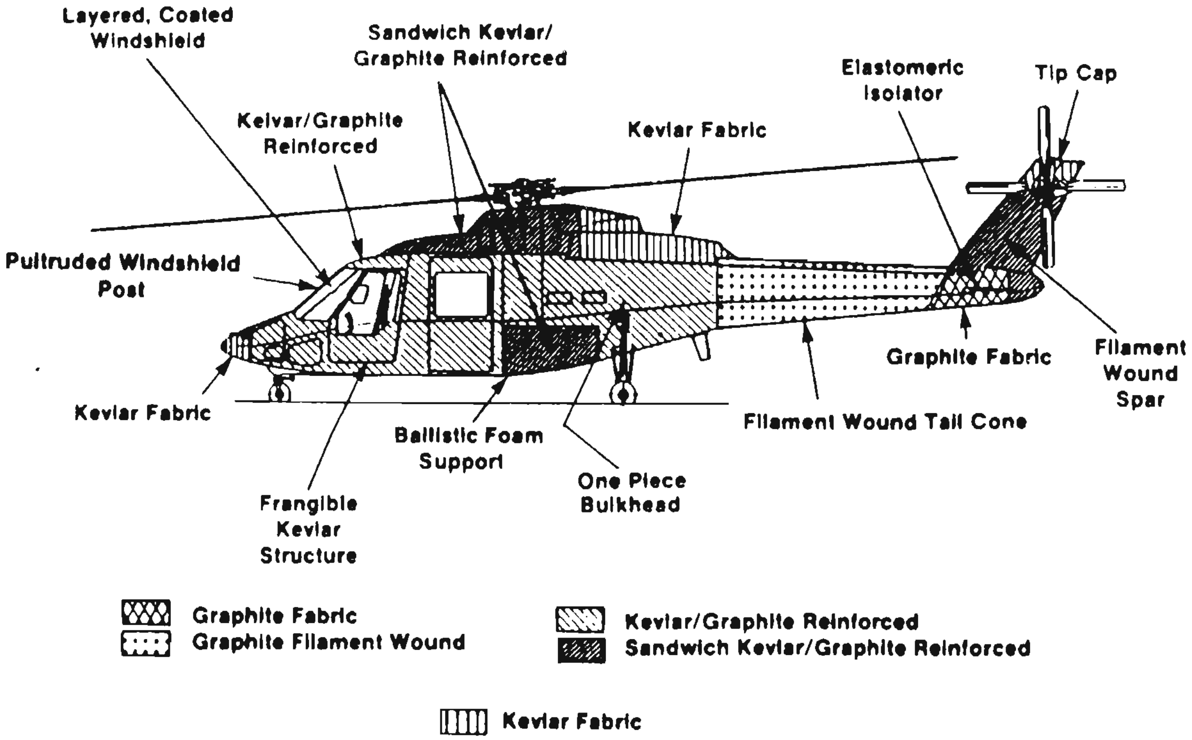


Figure 2. ACAP Airframe Materials

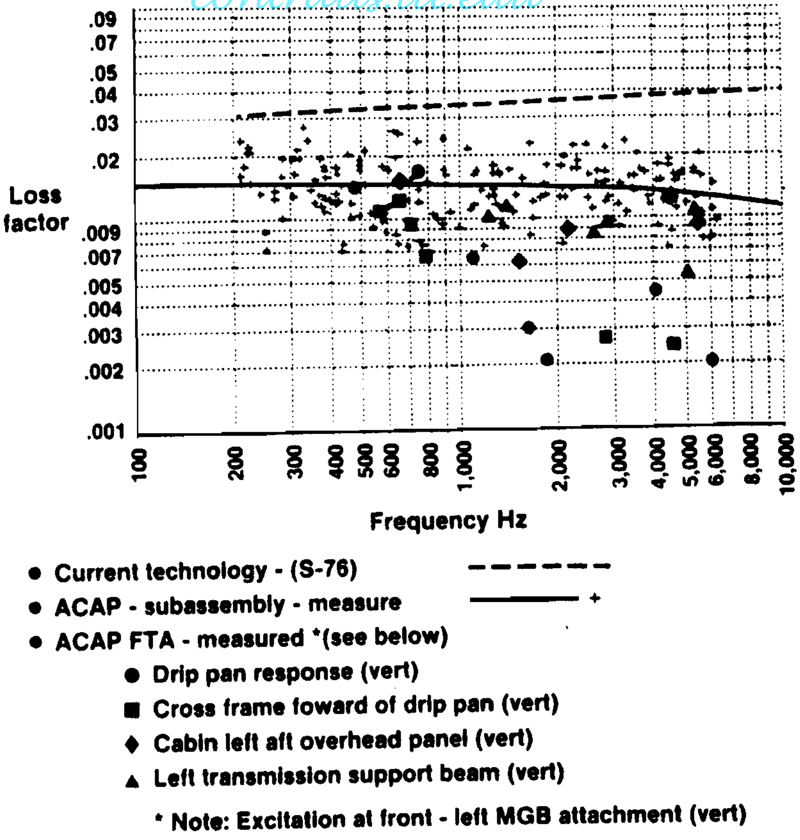


Figure 3. ACAP Subassembly Damping Survey

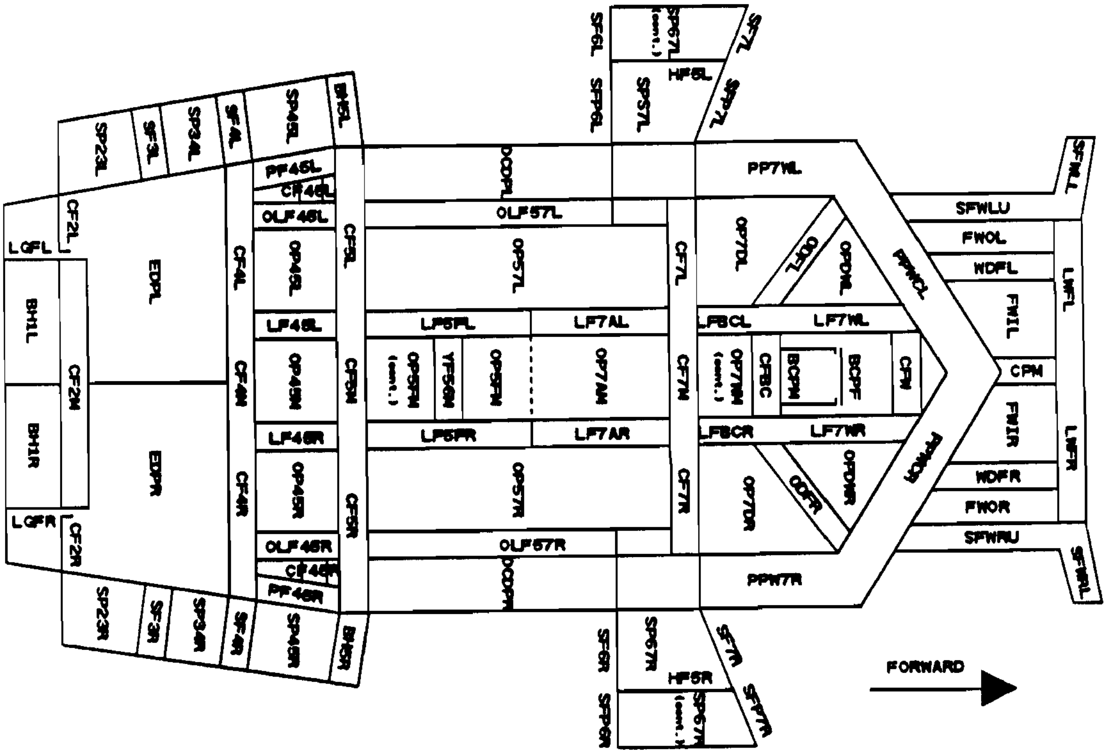


Figure 4. SEA Subsectioning of the ACAP Overhead Structure - Top View of Airframe Foldout

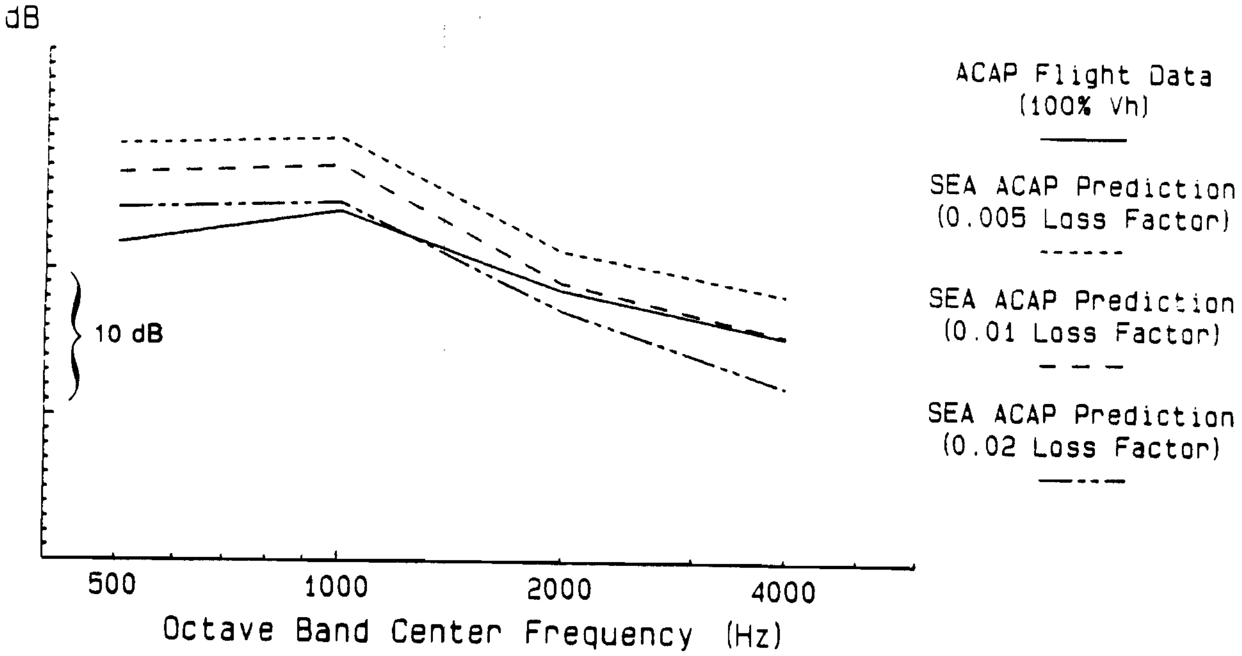


Figure 5. Measured Acoustic Levels vs. SEA Model Estimates - ACAP Cabin

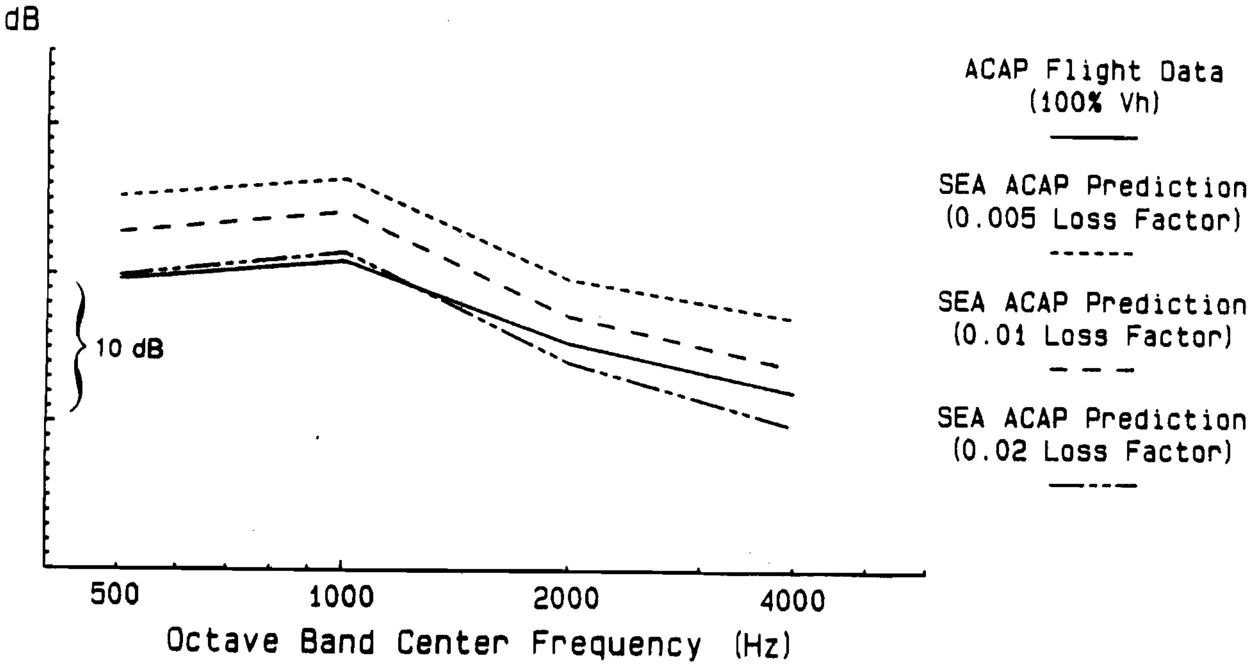


Figure 6. Measured Acoustic Levels vs. Sea Model Estimates - ACAP Cockpit

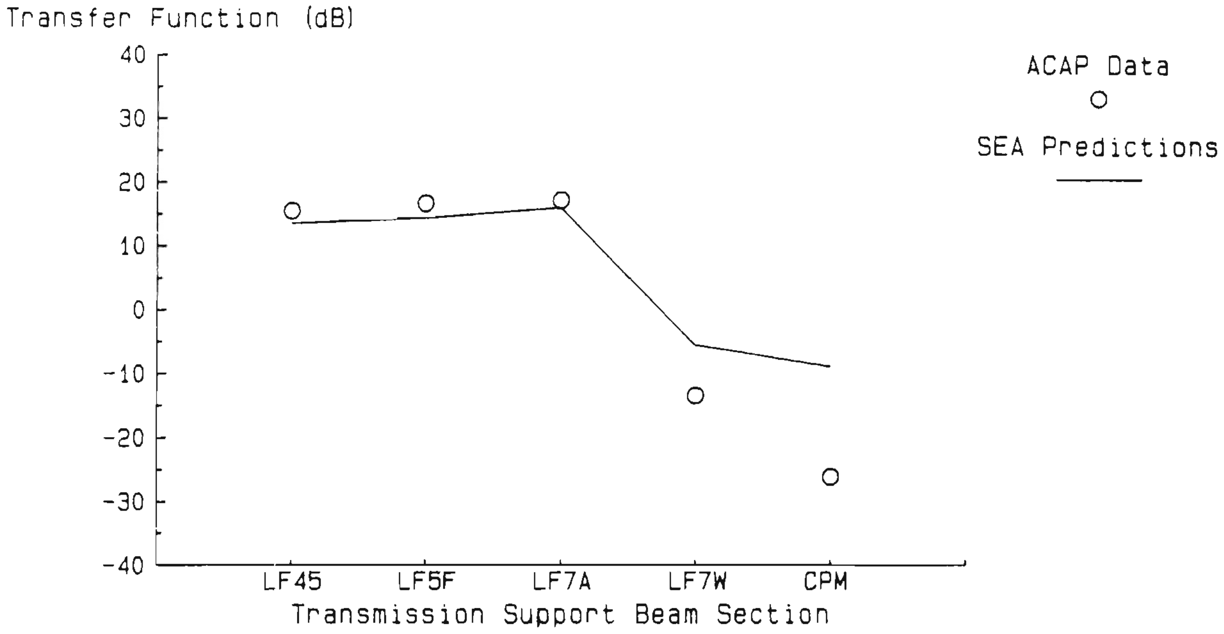


Figure 7. Measured and Predicted Vibration Transfer Functions - ACAP Transmission Support Beam (1000 Hz Octave Band)

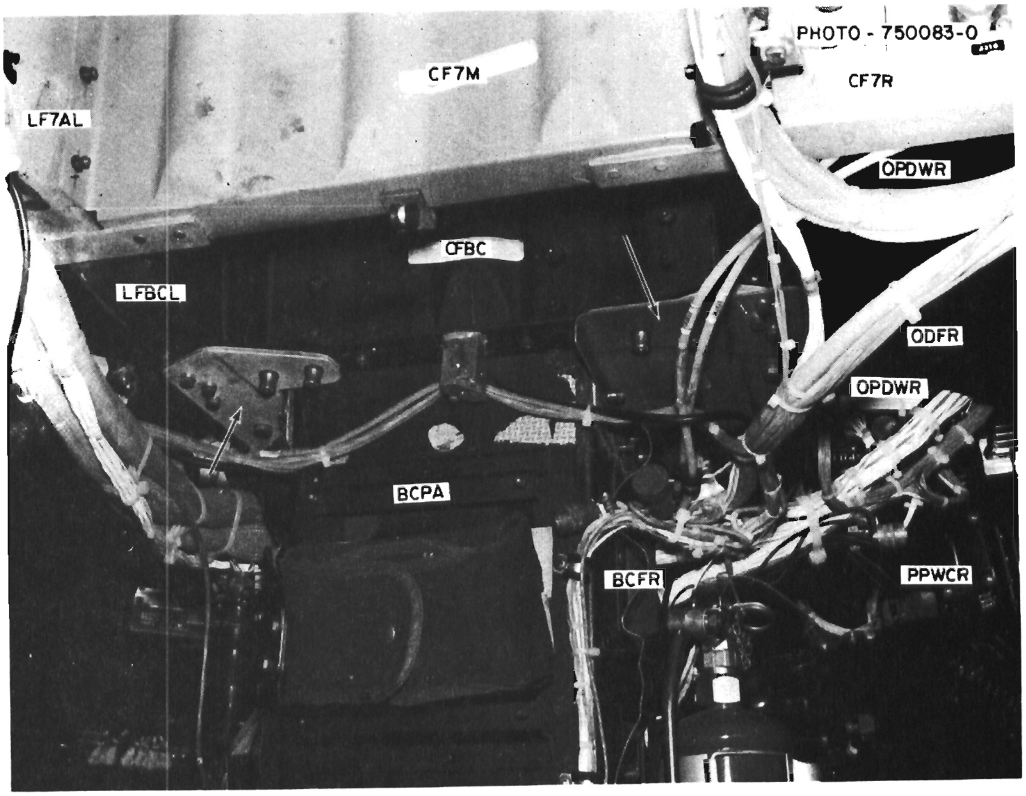


Figure 8. Photograph of ACAP Broom Closet Structure with Plate Stiffeners

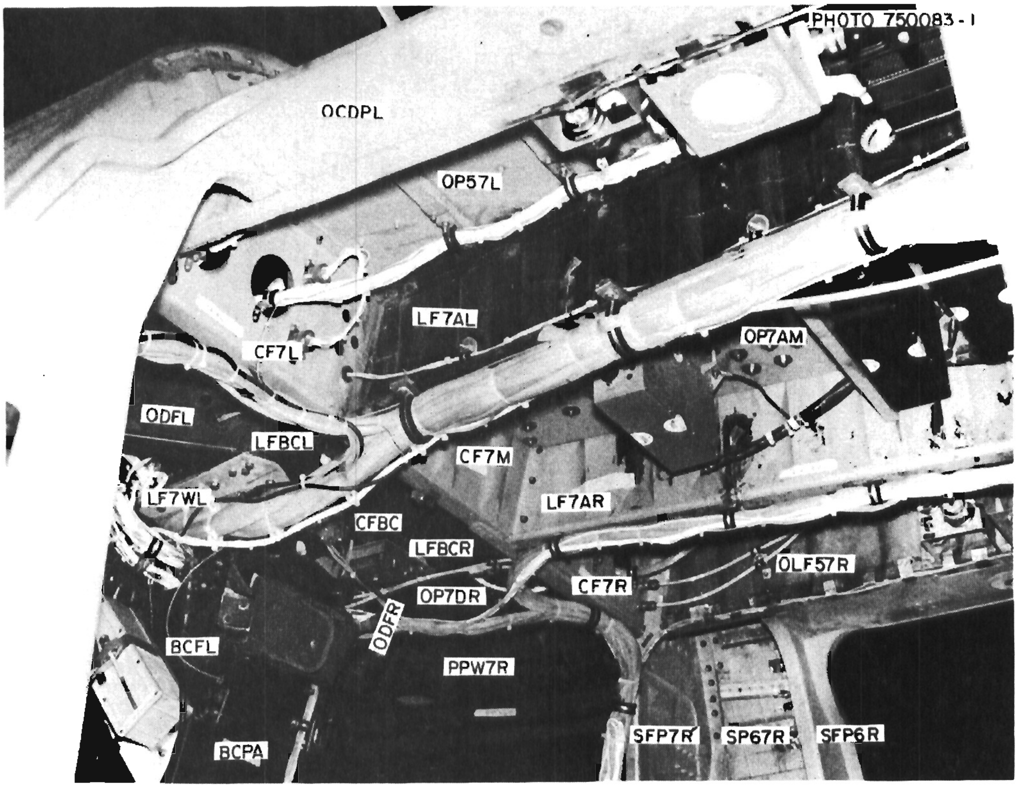


Figure 9. Photograph of ACAP Ceiling Structure - Forward Cabin

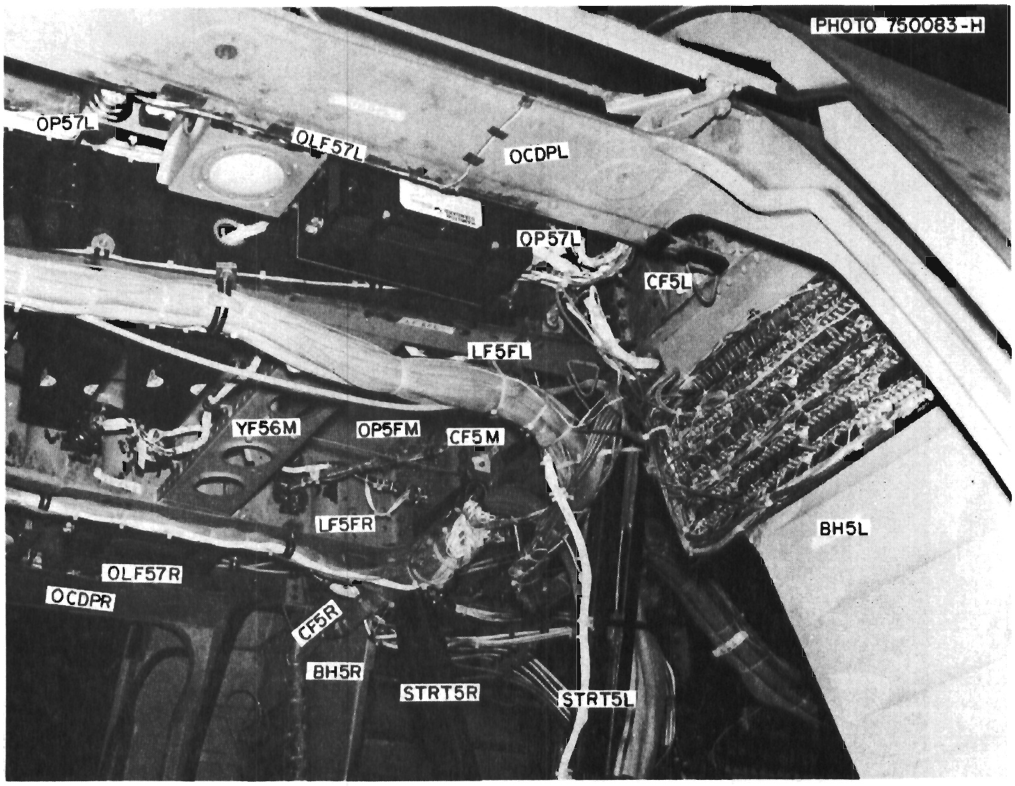
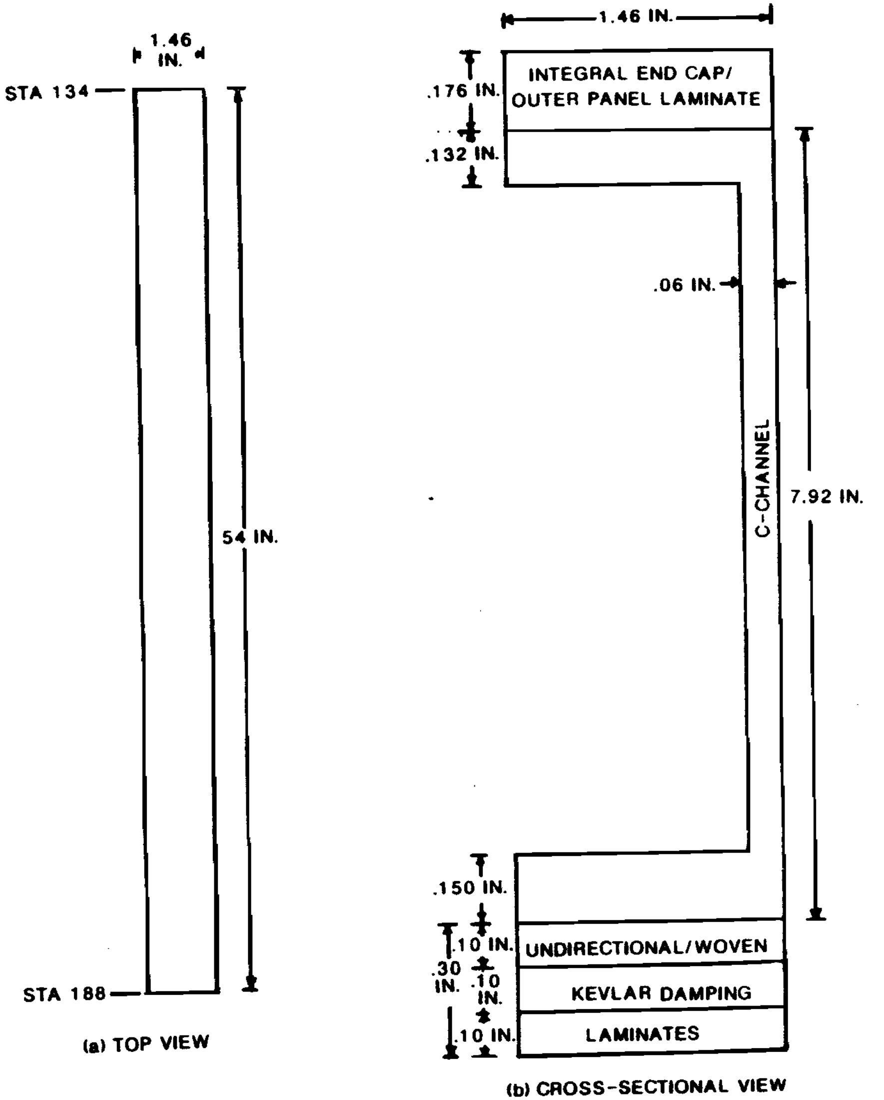


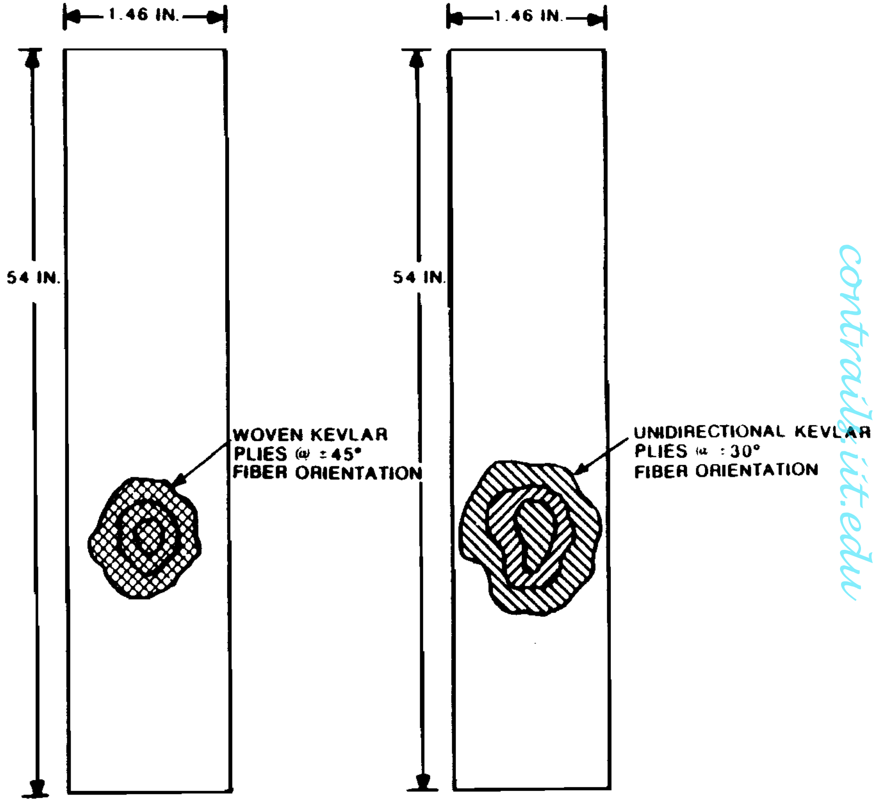
Figure 10. Photograph of ACAP Ceiling Structure - Aft Cabin



(a) TOP VIEW

(b) CROSS-SECTIONAL VIEW

Figure 11. Top and Cross-Sectional Schematics of ACAP Test Beam



(a) WOVEN KEVLAR DAMPING LAMINATE

(b) UNIDIRECTIONAL KEVLAR DAMPING LAMINATE

Figure 12. Details of the Woven and Unidirectional Kevlar Damping Laminates

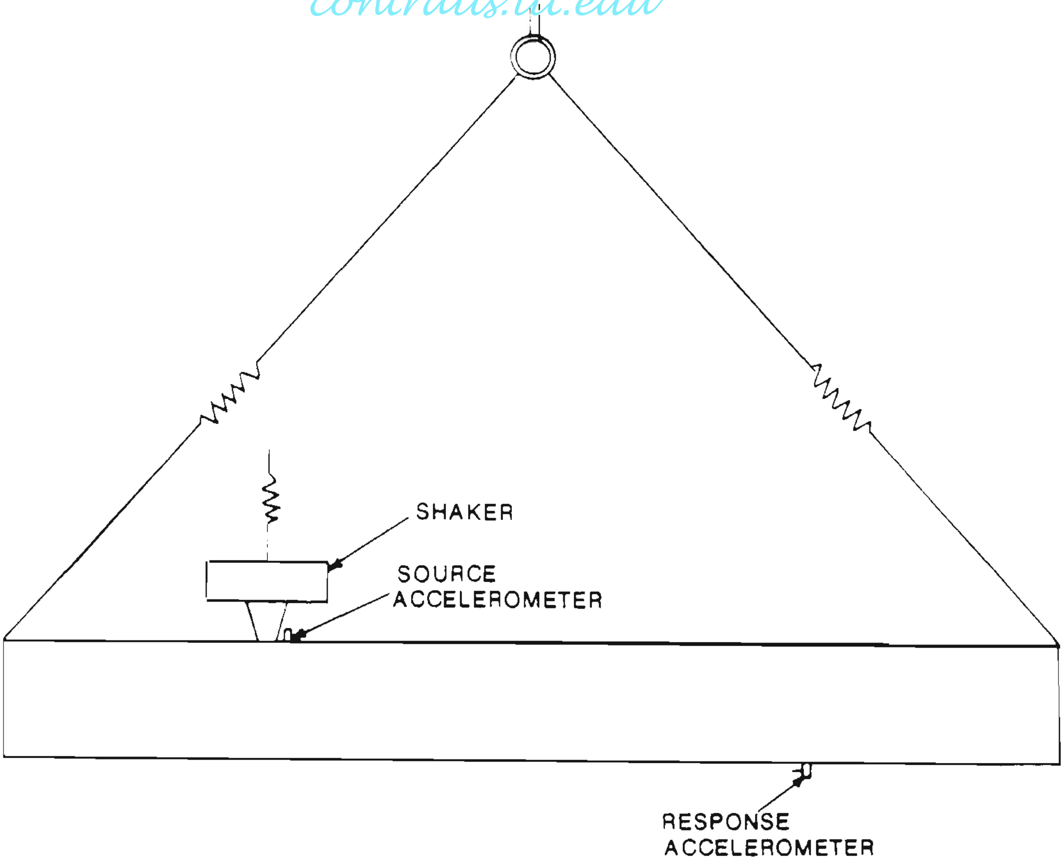


Figure 13. Schematic of Free-Free Test Configuration for the ACAP Beam Damping Test

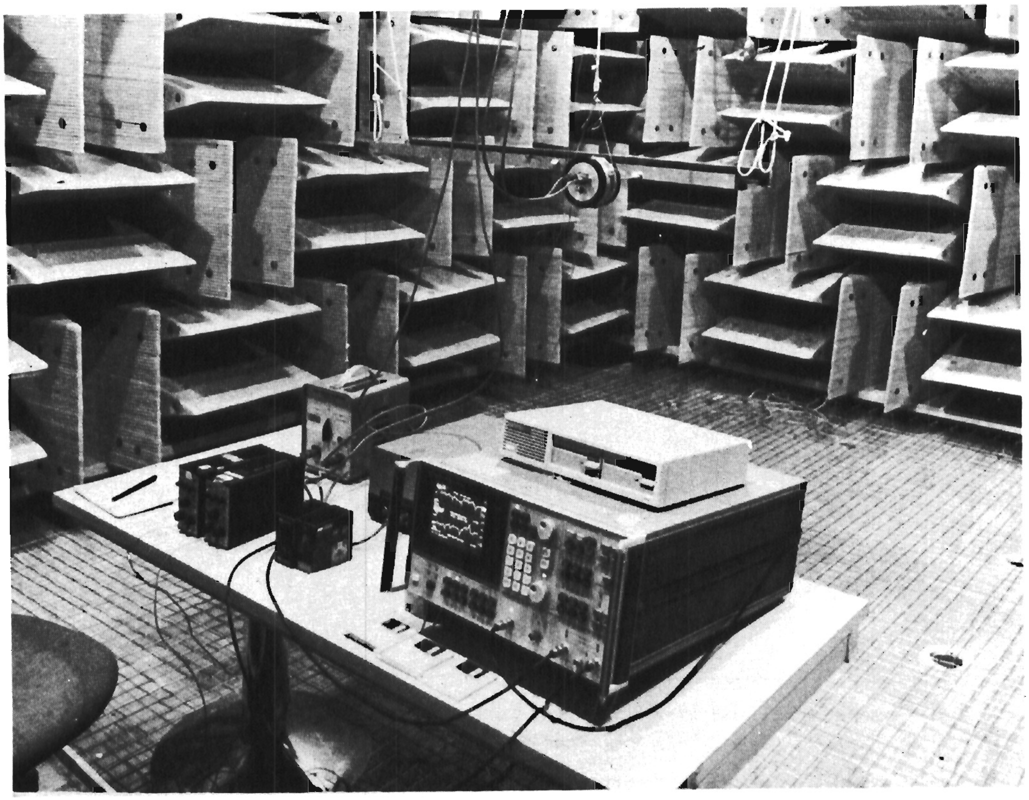


Figure 14. Photograph Showing Side View of the ACAP Beam Damping Test Setup

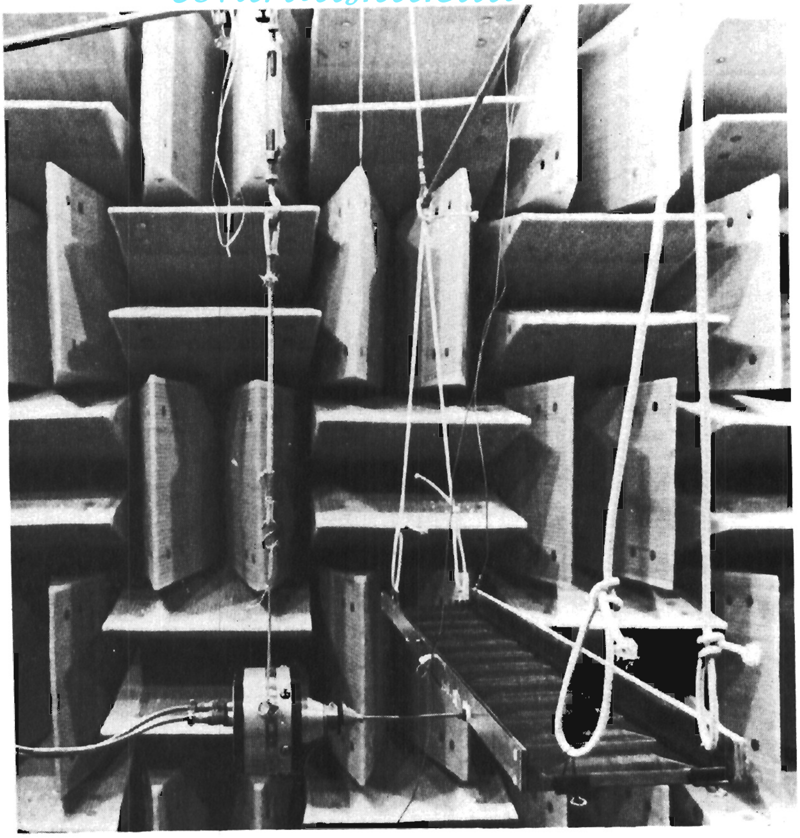


Figure 15. Photograph Showing End View of the ACAP Beam Damping Test Setup

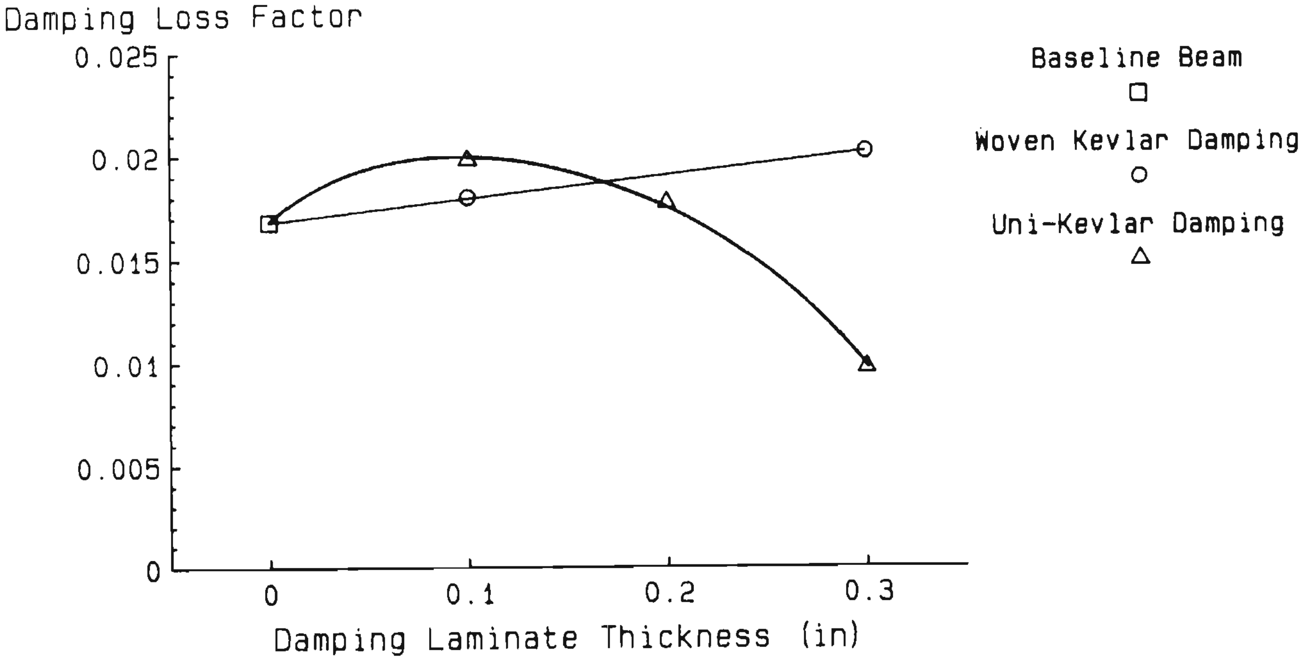


Figure 16. ACAP Transmission Support Beam Damping - 2nd Bending Mode (580 - 600 Hz)

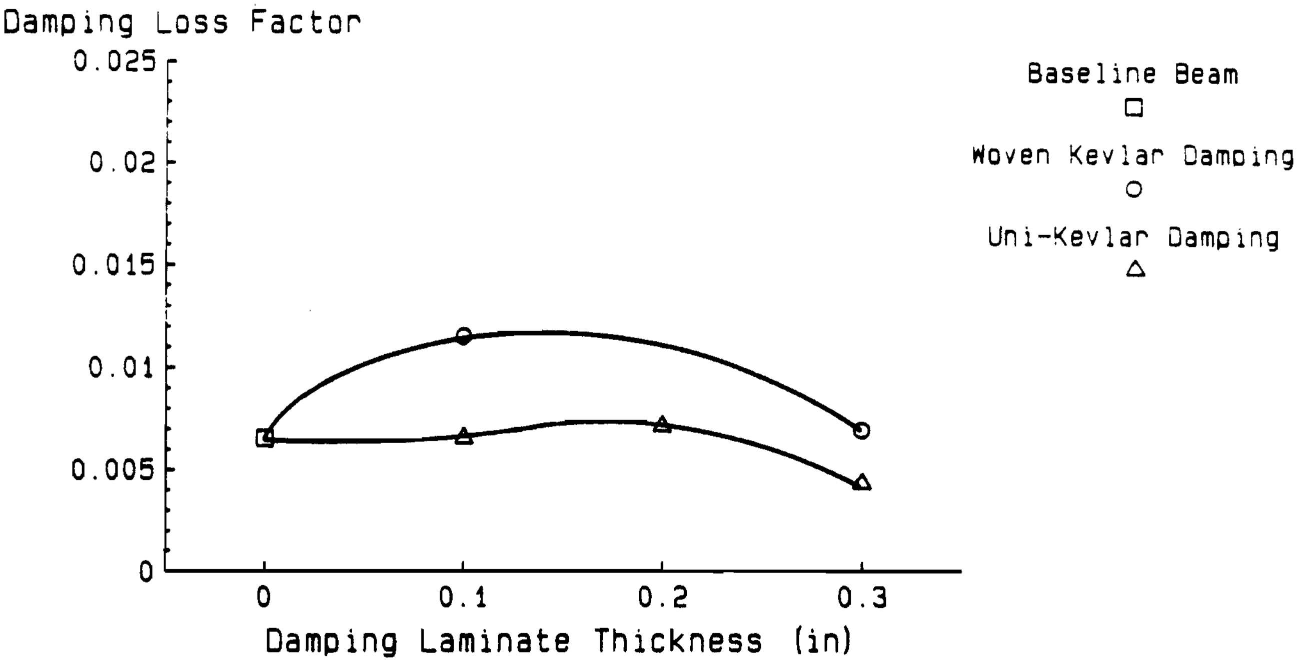


Figure 17. ACAP Transmission Support Beam Damping - 3rd Bending Mode (750 -790 Hz)

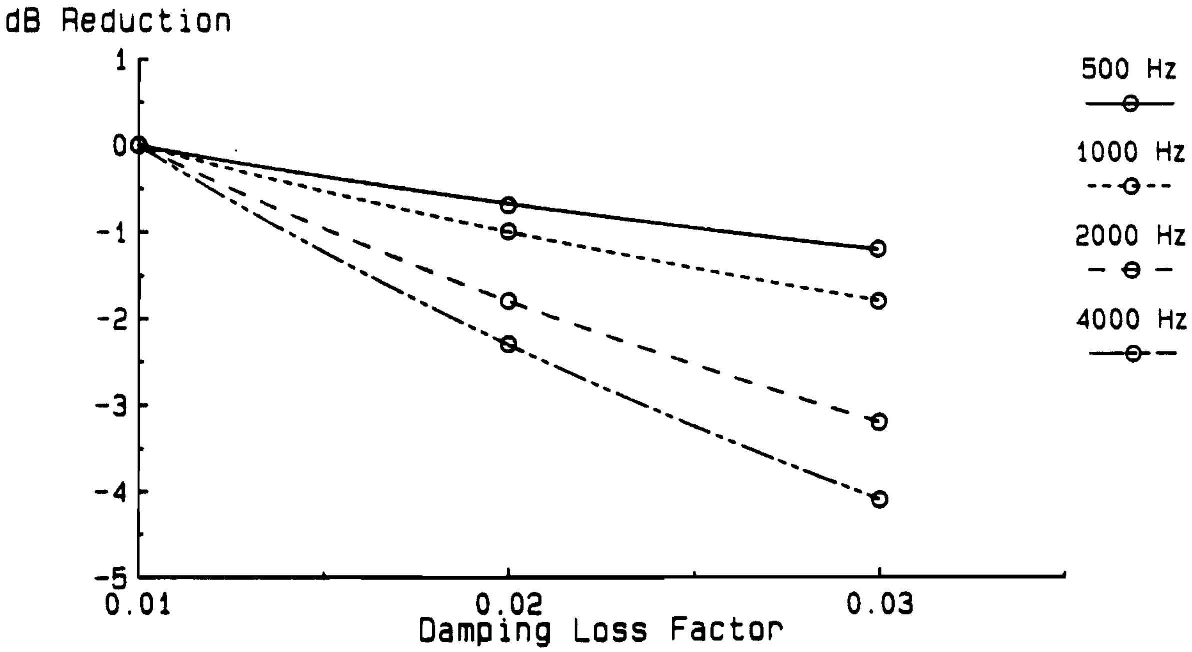


Figure 18. Estimated Effects of Increased Airframe Damping on ACAP Cabin and Cockpit Acoustic Levels