Approach to Interior Noise Control Part I: Damped Trim Panels

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The attenuation mechanisms for interior trim panel systems are reviewed, emphasizing the significance of structure-borne transmission through the trim attachments. The significant factors for high-frequency performance include number of attachments per unit area, panel critical frequency, and panel damping. The need for sufficient damping below and maximal damping above the trim panel critical frequency is described. Described are two experimental flight demonstrations that emphasize the role of trim panel damping. One program involves the new interior system design for a large business jet. Utilization of portions of the weight budget in the form of structural damping treatments permitted a +40% weight savings in acoustical materials with no significant increase in cabin noise levels. Significant reductions in noise levels were achieved in the cockpit, galley, and lavatory. A second program involved a commercial twin-engine jet, with a design objective of significant reduction in noise with minimal weight increase. A reduction of 5 dBA and 5 dB in the speech interference level in the cabin average noise was achieved with only a 0.7% increase in the maximum gross takeoff weight. Only simple add-on skin, trim, and bulkhead damping treatments were used.

Nomenclature

D = thickness of space separating fuselage skin from trim panel system, m
H = trim panel thickness, in.
M_1 = mass per unit area of fuselage structure, kg/m^2
M_2 = mass per unit area of trim panel system, kg/m^2
c = speed of sound in medium separating panels, m/s
f_0 = double wall resonance frequency, Hz
f_c = critical frequency of trim panel, Hz
n' = number of attachments/unit length, m^{-1}
n'' = number of attachment points/unit area, m^{-2}
β = vibration isolation effectiveness
ΔR = transmission loss improvement from addition of trim panel
ρ = effective density of fluid medium separating panels, kg/m^3

Introduction

AIRCRAFT interior noise control, as currently practiced in the industry, involves the utilization of weight as the principle control mechanism. The physics of the complex process of interior noise transmission involves several mechanisms, for which current acoustic theory recognizes several additional panel parameters, including flexural rigidity and internal damping.

In this paper, we will review the role of these parameters and, in so doing, identify an alternate approach for interior noise control. The effectiveness of applying this new approach is demonstrated through discussion of its application in two different airframes.

Present State-of-the-Art

Several authors[1-3] have discussed, in considerable detail, the present state-of-the-art in interior noise control for high-speed aircraft. In particular, Wilby[1] has provided a relatively complete review of current practice. His discussions refer, however, to a single "limp trim panel," which we have not seen on most aircraft. Instead, we find that current practice involves the use of two distinct layers—"acoustic" and "decorative"—as shown in Fig. 1.

The first layer consists of glass-fiber blanket and weighted layer. The inboard layer is an "appearance treatment" that is presumed to act independently of the acoustic treatment. System analysts will quickly recognize that any presumption of independence in the subsystems of a complex system has limited validity at best. Such is the case here. In early designs, the primary materials for decoration were lightweight fabrics on light-gage aluminum with a very high critical frequency. The introduction of weighted materials directly to these trim panels for additional control presumably did not meet "crash-load" design requirements. This led to separate supports for the acoustic and decorative layers. So long as the decorative trim panel retained its high critical frequency, the presumed independence did in fact occur. The introduction of high-stiffness composite systems for decorative trim panel construction in the last decade has altered this independence by proving an effective radiator for the vibratory energy in the structures to which it is attached. This "flanking path" can and does seriously degrade the expected performance of the acoustic treatment.

Alternate Approach

The alternate approach discussed here is to recognize this influence of the decorative trim panel. We concentrate the design effort on creating a trim panel construction that has the desired static and dynamic properties to minimize radiation within a given weight budget or, alternately, to minimize the weight within a given noise level objective. In performing this design analysis, we recognize the following significant panel properties:

1) Panel critical frequency (inversely proportional to panel bending wave speed).
2) Double-wall resonance (inversely proportional to product of panel weight/unit area and airspace behind).
3) Structure-borne transmission through attachments.
4) Panel system loss factor (a measure of structural damping).

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5) Panel sealing to insure that the panel is the controlling transmission path.

Subsequent sections of this paper provide quantitative expressions for determining properties 1 and 2, relative expressions for property 3, and references for property 4. In addition, rational means for estimating desirable values for each term are discussed. The role of the operating environment (particularly temperature) and appropriate frequency range for effective damping treatment performance is emphasized.

While the trim panel design is important, it is rarely the only significant transmission path to the interior. All surfaces bounding the cabin (including bulkheads, floor panels, windows, and the ventilation system) require comparable attention. While this paper cannot analyze these areas in equal detail, examples of these treatments are described in the experimental programs. The results for some specific bulkhead treatments are presented.

Design Considerations for Aircraft Interiors

Generic Attenuation Curve

Figure 2 gives a generic attenuation curve for the transmission loss produced by a trim panel system attached to the airframe structure. This attenuation curve is applicable whenever the intensity radiated by the green airframe is due primarily to the forced motion of the local structure with unity radiation efficiency. This is expected to be true for either sound field or turbulent boundary layer (TBL) excitation of the skin.

This curve does not apply when a significant fraction of the motion at the trim panel attachment point is caused by structure-borne excitation propagated from distant sources in the airframe. In many cases, the latter may be attenuated by appropriate structural damping treatments applied to the structure-borne transmission path.[4] Thus, the influence of such structure-borne excitation at the attachment point will not be considered further here.

The generic attenuation curve can be broken into four distinct regions as a function of frequency. As indicated on the graph, these four regions are, respectively, A) double-wall resonance-controlled, B) mass law transmission-loss-controlled, C) attachment-point-forced transmission, and D) attachment point coincidence-controlled. The physical mechanisms controlling the transmission in each of these regions are discussed further below.

Double-Wall Resonance

The characteristic features of the double-wall resonance-controlled regions are a resonance that reduces the transmission loss improvement to near 0 dB, followed by an increase in the transmission loss improvement with a slope of 12 dB/octave. The resonance has been widely discussed in literature.[1,5] For nearly flat panels, the expression for this resonance is given by

$$f_0 = (2\pi)^{-1}\left(\frac{\rho c^2}{D}\,\frac{M_1+M_2}{M_1 \cdot M_2}\right)^{1/2} \qquad (1)$$

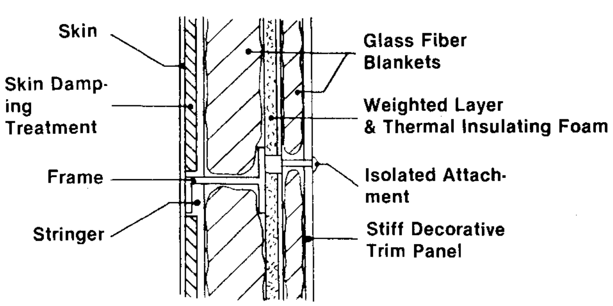

Fig. 1 Cross section of representative current technology interior treatment.

The transmission loss improvement above this frequency is simply a 12 dB/octave curve passing through 0 dB improvement at the double-wall resonant frequency. This expression assumes that the driving point impedance of the fuselage and the trim panel systems can be treated as simply mass-like. The case where the impedance is not mass-like in this frequency region is discussed further in the companion paper.[6]

The double-wall resonance is characterized by the out-of-phase motion of the trim panel system with the skin and trim acting as simple masses connected by a fluid spring. The first term in the parentheses in Eq. (1) will be recognized as an effective spring constant for a fluid with a bulk compressibility given by ρc^2. In the limit where the impedance of the fuselage in this frequency region is much, much higher than that due to its mass alone, due to high stiffener mass or cylindrical stiffening effects, the effective value of the second term in the parentheses may be replaced by $1/M_2$. The role of the glass-fiber in-fill in this resonance is to change the values of ρ and c describing the effective fluid properties. Further, the flow resistance of the in-fill controls the magnitude of response in the immediate vicinity of f_0.[1]

Mass Law Control Region

This region is included for completeness and represents an upper limit to the double-wall resonance phenomenon associated with the direct transmission of sound from the cavity through the trim panel structure. A suitable estimate for its value is the mass law transmission loss of the trim panel system plus the transmission loss of any glass-fiber blanket

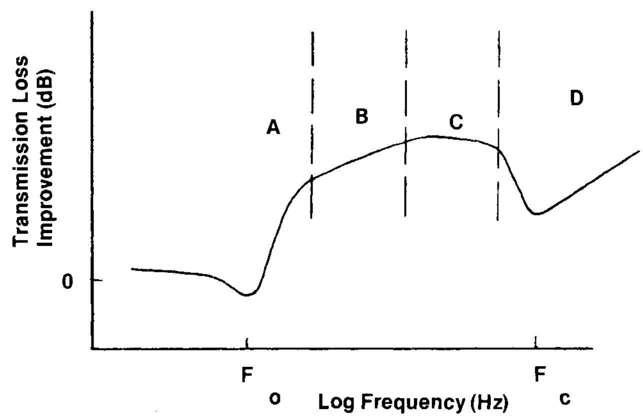

Fig. 2 Generic attenuation curve for mounted trim panels (letter-identified regions described in text).

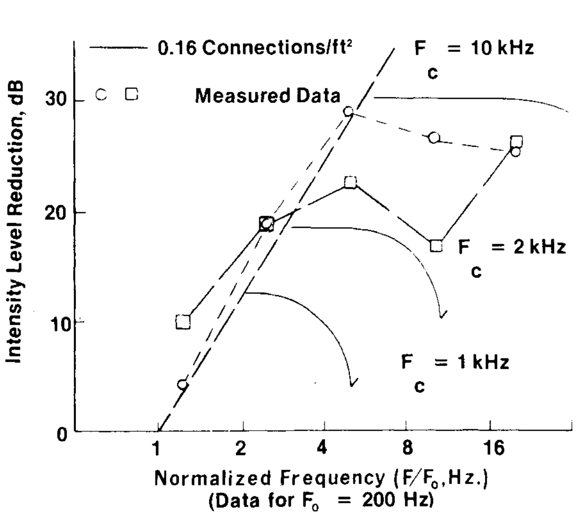

Fig. 3 Measured vs computed attenuation for overhead trim panels (in-flight performance).

between the trim panel and the skin. Reference 5 discusses these estimations.

Attachment Point Forced Transmission

This region, defined at the lower-frequency end by the intersection with mass law transmission or the 12 dB/octave slope of the double-wall resonance, represents the radiation by the trim panel from the vicinity of attachment points. The magnitude of the attenuation achieved is a function of the critical frequency of the trim panel, the mode of attachment and attachment density according to[5]

$$\Delta R_{\text{point}} = 10 \log\left(8\frac{\beta^2 n'' c^2}{\pi^2 f_c^2}\right) \quad (2)$$

$$\Delta R_{\text{Line}} = 10 \log\left(0.64\frac{n' c}{f_c}\right) \quad (3)$$

These expressions for attachment through the point and line connections represent the radiation from the trim panel at the attachment points and assume sufficient damping within the trim panel structure so that the resonant motion below the critical frequency is not a significant fraction of the total radiated energy. It will be noted that the attenuation provided by the point attachments is much greater than that produced by the line attachments. The above expression provides for a term due to vibration isolation at the attachment points. This term represents the effective attenuation[6] provided by the isolation. However, it should be noted that our empirical experience is that no isolators are sufficiently soft so as to provide effective vibration isolation between the lightweight trim panels and the typical attachment points on the airframe and still meet the crash-load design requirements. Thus, an appropriate estimation is to assume a unity for the attenuation due to the vibration isolation at the attachments.

Resonant Trim Panel Radiation

At and above the critical frequency of the trim panel, current theory does not provide a closed-form estimation of the attenuation provided. However, we can make some observations from the case of sound radiation from point-excited beams.[7] We expect the principle controlling factor to be the average system loss factor for the trim panel. The critical frequency of the panel is difficult to estimate[8] and, for most engineering applications, is most readily determined from direct measurements of bending wave speed in the trim panel.

(We note in passing that useful "guestimates" for trim panel critical frequency are, for aluminum panels, $f_c = 500/H$. For composite structural panels such as materials with low-density cores and high-strength faces, the critical frequency is usually between 125 and 250 divided by total thickness in inches.[9]) Since composite trim panels are frequently in the ⅛-¼ in. thickness range, typical values for the critical frequency of these trim panels is in the range of 500-2000 Hz. Interior noise design criteria that emphasize the higher frequencies, such as the speech interference level (SIL), will require that careful attention be given to performance in this high-frequency region.

Experimental Evidence for the Existence of the Generic Performance Curve

Figure 3 presents in-flight experimental data for overhead trim panels obtained in a large business jet, with a treatment cross section conforming to that shown in Fig. 1.

The data were acquired on two separate flights at cruise speed and altitude, first in a green aircraft and subsequently in a fully outfitted aircraft, using intensity measurement techniques. The data are presented in the form of intensity level reduction averaged over the trim panels in the forward cabin (as shown in Fig. 3 by squares) and the aft cabin (as shown by circles). The estimated double-wall resonant frequency for this

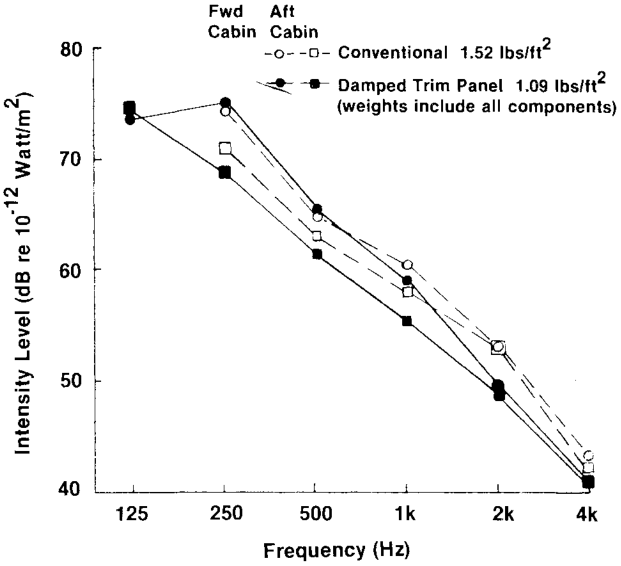

Fig. 4 Comparison of overhead trim panel intensity level for conventional vs damped trim panels.

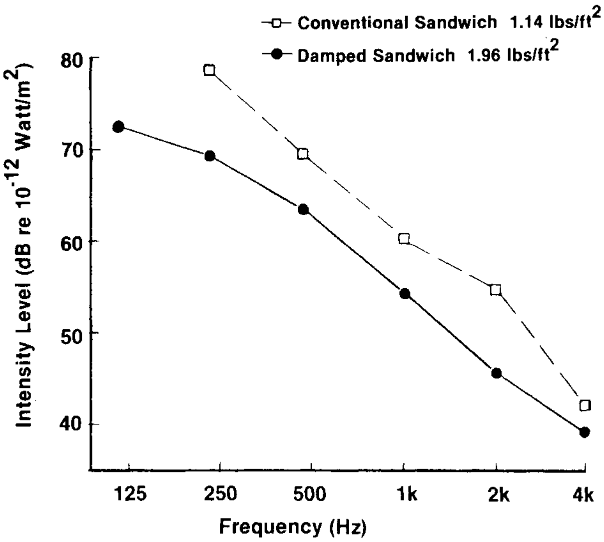

Fig. 5 Comparison of bulkhead radiated intensity for conventional vs damped constructions.

system was 200 Hz and the estimated trim panel critical frequency for the ⅛ in. thick, honeycomb core, trim panels was estimated to be 2 kHz. The nominal size of these trim panels were 4×6 ft with attachments only at the four corners. The data for the forward cabin followed the estimated theoretical curve for 2 kHz critical frequency with good agreement. The data for the aft trim panels do not agree quite so well. It is believed that the green aircraft intensity levels in the aft cabin area were overestimated due to the energy from other sources, which in turn resulted in an overestimate of the intensity level reduction. The data as presented are values integrated over one octave band at preferred octave center frequencies from 250-4000 Hz. As can be seen for this case, flanking of trim panel attenuation due to trim panel attachments is the probable controlling mechanism for the 1-4 kHz region. Thus, the speech interference level contribution from trim panel radiation is completely controlled by transmission through the trim panel attachment points.

Generic Guidelines

The above generic performance curve and associated expressions provide a basis for the rapid estimation of the treat-

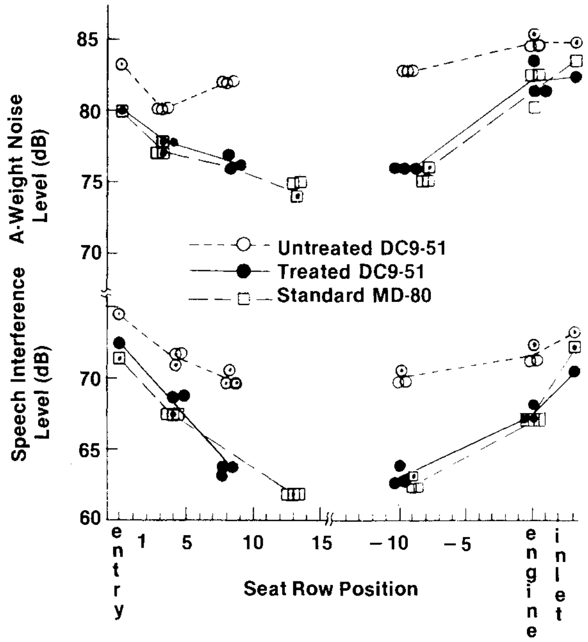

Fig. 6 Noise levels vs comparable seat location for DC9-51 and MD-80 aircraft.

ment performance. In addition, the following design guidelines are offered to assist in the treatment optimization process.

In the region of double-wall resonance, the equal roles of the mass and thickness of the separating airspace should be noted. In the region above the double-wall resonant frequency, the attenuation provided by the treatment increases by 6 dB per doubling of the trim panel mass per unit area or 6 dB per doubling of the airspace depth. Thus, optimal performance region A is usually achieved when all of the available mass is concentrated as far from the fuselage as possible. It is further observed that variation of the glass-fiber properties, within practical limits, produces little variation in the resonant frequency, so that weight optimal treatments tend to be those that use minimum density glass-fiber fill.

In the region where the attenuation is controlled by forced transmission from the attachment points, we observe that the maximal attenuation values are achieved when point attachments rather than line attachments are used, that the trim panel has the highest possible critical frequency, and that the number of attachment points per unit area is minimized. In the region at and above the critical frequency, the optimal performance is obtained when the trim panel system has the highest possible system loss factor.

Trim Panel Damping Treatment Design Considerations

Damping treatments for trim panels can consist of two generic types, extensional and constrained layer.[10] The extensional treatment involves the simple addition of a damping material layer to one side of the trim panel. Damping is then achieved by hysteretic losses when this material is placed in extensional strain due to flexural vibrations in the trim panel. In the constrained layer system, the damping treatment consists of one or more layers of damping material with an outer layer acting to place the damping layer in shear when the trim panel undergoes flexural deformation. Dynamically, these treatments differ in that the constrained layer damping treatment shows greater peak damping for a given amount of material, but with greater frequency dependence on the system loss factor. Further, this system must be designed more carefully to insure that maximum damping occurs in the frequency range of interest.

It must be noted that all high-performance damping materials exhibit considerable temperature dependence in their damping properties.[4] Thus, it is crucial to the achievement of optimal performance that the operating temperature of the substrate be known to permit matching to the material properties. In aircraft especially, there is a wide range of substrate temperatures in the airframe, depending upon the altitude range for cruise performance and whether or not the structure has strong thermal connections to the skin. The optimal temperature range of high-performance damping materials is typically only about 25°C and the range of temperatures observed in various substrates in flight can easily exceed 50°C. Thus, different damping material formulations must be used in areas with different temperatures.

Table 1a Conventional treatment weight

Component	Weight, lb
Airframe damping	155
Glass-fiber batts	101
Weighted layer composite	
Overhead[a]	283
Sidewalls[a]	156
Floor	67
Cockpit treatments	55
Entry way and baggage compartment	114
Miscellaneous (hardware, etc.)	34
Total weight, acoustic materials	950

[a]Includes thermal insulating foam.

Table 1b Damped trim panel treatment

Component	Weight, lb Recommended	Actual
Airframe damping (C-3201)	123	77.5
Glass-fiber batts	85	82.5
Glass-fiber quilted blanket	119	106
Trim panel damping		
Overhead	131	140
Sidewalls	28	0
Floor	49	20
Bulkhead damping	68	56
Miscellaneous	15	5
Total	598	487

Other Design Considerations for Interior Noise Control

This discussion has centered on trim panel surfaces associated with the fuselage. Other surfaces of the interior, including the floor and bulkheads separating the cabin areas, also play a significant role in radiating noise to the cabin. Since the bulkhead and floor structures are intimately connected to the fuselage for structural reasons, it is not surprising to find that these surfaces exhibit significant motion due to excitation by the fuselage structure. Since these structures are frequently of high-stiffness/low-weight design, they also exhibit relatively low critical frequencies. Structural damping again plays a significant role in determining the amount of energy radiated. Frequently, these structures are also thicker than the sidewall trim panels and may be expected to have even lower critical frequencies. Damping thus plays a role over a larger frequency range than is the case for the sidewall trim.

Experimental Programs

Gulfstream III

The first airframe program utilizing this approach was undertaken in conjunction with Gulfstream Aerospace Corporation in Savannah, Ga., in their model G-III aircraft. The Gulfstream III is a large, 14-19 passenger, twin-engine business jet in the 70,000 lb gross takeoff weight class. It is frequently custom outfitted for executive transport and is widely recognized as having very low interior noise levels.

The cabin arrangement for a G-III includes an entrance way just aft of the cockpit, which is followed by the forward cabin bulkhead with a door and a forward cabin area separated from the aft cabin area by a visual divider. Behind the aft cabin area is a galley that provides a light food and beverage service, and a lavatory separated from the galley by a bulkhead and door. Behind the lavatory is an in-flight accessible baggage compartment.

Conventional treatment of the G-III involves the use of a treatment package derived from that designed for the G-II model. This treatment was weight optimized through an extensive development program described by Goss.[11] The revised treatment design was based on a series of intensity analysis measurements performed by the author on a conventionally treated aircraft in September 1982. The design objective for this treatment program was to replace the conventional treatment with a new design providing equivalent acoustic performance at a reduced weight. In the following paragraphs, we identify the prominent sources of the weight savings and noise control improvement.

Table 1a identifies the weight of the acoustic treatment components used in the conventional treatment, as described in the outfitters guide provided to the organizations that install this treatment. The corresponding schedule of weights for acoustic materials incorporated in the new concept aircraft are shown in Table 1b. Also shown are the actual weights installed in the first aircraft completed with this scheme.

The intensity survey, which was the basis for the recommended treatment package, revealed that the significant sources in the forward cabin included the overhead trim panels, forward bulkheads, floor, and aft cabin. The aft cabin intensity survey revealed that the principal sources were again the overhead trim panels, but that the second most important sources were the aft cabin bulkheads and the galley just behind them. In the galley, the rear galley bulkhead was a significant source, as was the forward galley bulkhead. In the lavatory, the aft structural bulkhead was a predominant source.

Table 2 shows the results of in-flight noise level surveys for this aircraft compared with the quietest of the previous installations of the conventional treatment. Review of these levels reveals that, in terms of a speech interference level, the design objective of no increased levels was clearly achieved. The A-weighted level differences indicate that there was some slight increase in the forward and aft cabin areas. There was a hydraulic tone, unique to this first completed aircraft, that affected the A-weighted comparison in the aft cabin and galley, which was corrected later. Outside of the cabin the objective of decreasing noise was achieved. Improvements in the cockpit area are attributed primarily to improved performance skin damping treatments used there. Improvements in the lavatory are associated with improved treatment concepts for the aft lavatory bulkhead.

In the main cabin, the treatment strategy consisted of reducing weight where indicated from the intensity analysis without affecting performance and applying additional treatments to significant sources such as the aft cabin bulkhead and floor. In view of these noise levels, and the weight savings of approximately 48% indicated in Table 1, the design objectives were deemed to have been met and exceeded.

Figure 4 shows the achieved performance in terms of intensity level for the overhead trim panels in the cabin. The dashed lines indicate average intensity levels for trim panels in the forward and aft cabins in the conventionally treated demonstrator. The solid lines and filled data points indicate the measured average intensity level for the overhead trim panels in the corresponding locations with the new treatment. The design objective for these panels was the achievement of equal performance at reduced weight. The 28% weight reduction achieved here conformed to the design objective. The intensity was equal or slightly lower at the lower frequencies, where the weight of the system controls performance. At high frequencies, the increased damping provided a 3-5 dB reduction.

The weight reduction was achieved by using an extensional damping treatment on the inboard side of the trim panel to replace the weighted layer on the outboard side. The increased distance between the trim panel mass center and the fuselage allowed a lower trim total weight to produce nearly the same double-wall resonant frequency. An improvement trim panel isolator design was also used, but its effectiveness could not be determined independently.

Figure 5 shows the effectiveness of a damping treatment on reducing bulkhead radiated noise. This bulkhead supports the galley equipment and restrains that equipment in the 9 *g* deceleration crash-load design. For these reasons, it is of high-strength construction and is rigidly attached to the airframe structure. For this component, the design objective was reduced radiation with minimum weight increase. Because of the very high stiffness of the ¾ in. thick composite bulkhead, a constrained layer treatment was used on the exposed surface of each face. The radiated intensity reduction is 4-8 dB at 250-4000 Hz. The reduced vibration here also reduced the vibration and hence noise radiation from attached galley equipment.

This treatment program is considered to be an unqualified success. At this time, more than 12 additional airframes have been completed using this approach with progressively improving results.

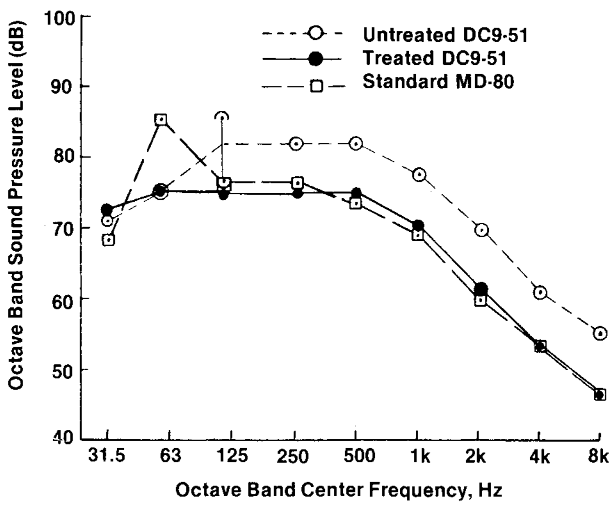

Fig. 7 Octave band sound level vs frequency for aisle seat in aft one-third of cabin for DC-9 and MD-80 aircraft.

Table 2 Change in interior noise levels (difference of damped treatment from weighted layer treatment)[a]

Area	Change in noise level measure, dB A-weighted level	SIL (1k, 2k, 4k)
Cockpit	−5.9	−6.6
Entryway	+1.6	−3.1
Forward cabin	+2.4	+2.0
Aft cabin	+1.4[b]	−0.9
Galley	+3.3[b]	−5.5
Lavatory	−4.2	−14.0

[a] Flight level 430, speed Mach 0.80.
[b] Data on aircraft with damped trim affected by hydraulic system problem at 420 Hz.

DC9-51 Interior Treatment

This program was undertaken by Muse Air Corp., who are adding 10 model DC9-51 aircraft to their existing fleet of MD-80 aircraft. The MD-80 aircraft is the latest model of the DC-9 series and is significantly quieter inside due to extensive design modification for noise control. Muse Air's design goal was to maintain the same high quality in-flight experience for its passengers on the DC9-51 as on its MD-80s. The treatment described here was designed for Muse Airlines by William K. Connor of Tracor Applied Sciences, Inc., Austin, Texas and installed by Tracor Aviation, Inc. of Goleta, Calif. The program design objective was to provide add-on noise control treatments so as to produce an interior noise level in the DC9-51 that closely approximates the noise level experienced in the MD-80. The program reported here was performed between October and December 1983.[12] Installation on additional aircraft is continuing.

Figure 6 presents the measured interior noise levels as a function of seat position for the standard DC9-51 (dotted line) and the standard MD-80 (dashed line). In the left-hand portion of the figure, sound levels are plotted vs row location from the forward end of the aircraft. Data in the right side of the figure are plotted relative to the seat row adjacent to the engine inlet due to the differing length of cabin for the −80 vs the −51. Within the main cabin, measurements were taken at all three seats on the right side of the cabin and where more than one seat had the same measured level, multiple points plotted in this figure.

The treatment was designed by Tracor Applied Sciences to be installed in the aircraft in conjunction with a standard interior refurbishment. This refurbishment included new seats, trim panels, and overhead baggage compartments identical in construction to those installed in the Muse MD-80 fleet. The noise control treatment incorporated the following elements:

1) Skin damping treatment (E-A-R C-3201-25ALPSA†): 80% coverage of skin between floor and overhead baggage bins, full length of cabin, and 100% coverage of aft pressure bulkhead.

2) Trim panel damping treatment (E-A-R C-2003-05PSA) applied in 80% coverage to dado panels and window trim between the floor and the underside of the baggage compartment.

3) Bulkhead damping treatment (E-A-R C-2003-05 PSA) applied 100% to cabin side surfaces.

4) Floor damping treatment (E-A-R C-2003-05 PSA) applied 100% to cabin side of floor panel throughout the cabin length.

The total installed weight was 920 lb. The trim panels in all three aircraft are molded plastic panels approximately 0.52-0.7 psf. The trim panel damping treatment weighs 0.45 psf. Both the floor and bulkhead panels were of aluminum honeycomb construction with aluminum faces. The critical frequency of the trim panels, ignoring stiffening due to the molded shape, is estimated to be approximately 10 kHz, while that for the bulkhead and floor panels is estimated to be in the 500 Hz octave. Except for the installation of the damping treatments on the backside of the trim panels prior to installing them in the aircraft, the installation proceeded quite routinely and was accomplished within the two-week budget period that included all other refurbished items.

The measured noise levels on the completed aircraft with the damping treatment are also shown in Fig. 6. As can be seen from these data, the achieved A-weighted and speech interference levels are equivalent to those in the MD-80 at all locations.

Figure 7 presents a plot of octave band noise levels at a common seat location in the rear of the third aircraft for all three airframes. This figure shows an improvement in noise level with the treatment in the −51 of 6-8 dB in the frequency range of 125-8000 Hz. This is in excess of the observed cabin average change of 5 dBA and 5 dB SIL, but does indicate the general trend. The reasons for the relatively constant improvement over frequency in seat location are not obvious in view of the generic curve described above, since several different mechanisms are expected to be operating throughout this frequency range. Unfortunately, scheduled usage of these aircraft has prohibited further detailed investigation of specific mechanisms and operation.

†Product designations are used to document material properties in lieu of in situ measurements of performance.

Conclusions

We have reviewed the physical mechanisms responsible for interior noise reduction in trim panel systems for aircraft and identified several mechanisms in addition to mass that play a role in the physical phenomenon. In particular, we have identified that, in many aircraft constructions, structural damping can play a significant role in improving high-frequency attenuation. Implementation of this alternate approach to aircraft interior noise control has, in one case, produced weight savings in excess of 40% while maintaining equivalent noise levels. In a second example, in a different airframe, more than 5 dBA and more than 5 dB SIL reduction in cabin noise level was achieved at a weight cost of less than 7 lb/seat. We trust that these examples will encourage the aircraft interior noise control designer to consider the effects of structural damping in future designs.

Acknowledgments

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