Approach to Interior Noise Control Part II: Self-Supporting Damped Interior Shell

Curtis I. Holmer*
E-A-R Division, Cabot Corporation, Indianapolis, Indiana

A companion paper presents theoretical and experimental data identifying the significance of panel critical frequency and structural damping in controlling trim panel dynamic response from excitation at attachment points. This paper explores a logical extension to the trim panel system. The shell presents several desirable nonacoustic properties that may offer design or construction economies. Of concern here is the design considerations that can turn potential acoustic problems into significant advantages. The high stiffness, necessary to make the shell self-supporting, may provide improved low-frequency performance in the vicinity of the double-wall resonance. The low critical frequency, usually implied by this stiffness, may be controlled through design of the panel dynamic properties, judicious location of the attachment points, and effective vibration isolation. Quantitative approaches to each of these issues are explored. A successful installation in one aircraft is described.

Nomenclature

B_s = flexural rigidity per unit width of the shell, N·m
c_L = longitudinal wave speed in frame material, m/s
f = frequency, Hz
f_c = critical frequency, Hz
h = thickness of the frame flange at the attachment point, m
K_f = static stiffness of the fuselage system at the attachment point, N/m
K_i = isolator spring constant, N/m
M_s = mass of the shell panel kg
m_s = mass per unit area of the shell panel, kg/m^2
Y_f = drive mobility point of fuselage side attachment point for the isolator, m/N·s
Y_s = drive point mobility of the shell attachment point, m/N·s
Z_i = transfer impedance across an isolator, N·s/m
ρ = density of the frame material, kg/m^3
ω = $2\pi f$ rad/s

Introduction

THE previous paper[1] introduced the concept of the structurally damped trim panel as an alternate concept for designing an interior noise control treatment. Two of the significant concerns in this design involve attending to structure-borne transmission through the attachments and panel sealing. A structure that solves these problems in an unusually straightforward way is a self-supporting interior shell. The shell has the obvious direct advantage of providing an opportunity to place attachments at positions of minimum structural motion. Significant design problems and opportunities occur in other facets of the solution. This paper explores several of the acoustic design problems and enumerates some of the identified nonacoustic design opportunities. Experimental data from a completed airframe installation incorporating a self-supporting shell is described.

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*Manager, Noise Control Application Engineering. Member AIAA.

Background

In the companion paper, a representation of trim panel response to structural motion is described. The development identifies response to structure-borne noise through attachments as a principal determinant of interior noise control performance at middle and high frequencies. The dominant factors in this response are: 1) number of attachment points, 2) motion at attachment points, 3) effectiveness of vibration isolation at attachments, 4) critical frequency of trim panel, and 5) system loss factor (at frequencies above critical).

The generic directions for optimal performance are clear, i.e., reduce the number of attachments, attach at points of minimum motion, design the isolator system for maximum effectiveness, use a trim panel of maximum critical frequency, and achieve maximum practical panel damping. The flexibility available in the standard trim system (of numerous small panels) to optimize these parameters is highly restricted by the small area of a typical trim panel compared to the total cabin area in the airframe. A concept which offers maximum flexibility for design of the first two factors is the concept of a self-supporting cylindrical shell inside the structural airframe. This creates the opportunity to use the minimum number of attachments and the possibility of placing those attachments at the points of the airframe which have minimum motion.

The Shell Concept

The concept is to design an independent surface, attached to the airframe at a minimum number of locations, that has sufficient structural integrity to support itself and all of the interior furnishings attached to it. A schematic cross section is shown in Fig. 1. Loading considerations include forces associated with supported furniture (such as tables or cabinetry cantilevered from the sidewalls) and safety (restraint under crash-load or decompression design conditions). To meet these design loads, a stiff composite panel construction and a cylindrical geometry is used. Since weight is a critical concern, the successful structure will have a high stiffness-to-weight ratio and therefore a relatively low critical frequency. This latter consequence suggests that consideration for acoustics must be an integral part of a successful design process.

Attractions and Detractions of Shell Concept

The above itemizes the obvious acoustic advantages. In addition, the cylindrical form may contain an additional acoustical advantage through modification of the double-wall resonance. If accurately implemented, the cylindrical form can produce a stiffness-controlled response to significantly higher frequencies than can be produced with individual trim panels. This stiffness-controlled response can increase the low-frequency attenuation for the shell system substantially above that of mass-controlled trim panels.

Dowell[2] has described an analysis for the case of the noise reduction for two concentric cylinders without attachments. However, quantitative analytic evaluation of this advantage of the concept will require substantial extension of this analysis procedure, since his work is limited to full cylinders. The influence due to the fact that the shell is only a sector of a cylinder, and is terminated by flexible connections, remains to be determined.

Additional nonacoustic advantages identified to date include the ability to assemble the complete interior outside the airframe, increased freedom for interior design, and the opportunity to improve the trim system fire performance through appropriate material selection.

The advantage of assembly outside the airframe derives from potential labor and construction time savings. Business jet interiors are frequently highly customized. As a result, substantial interior installation labor is associated with the fitting of custom furniture. For a conventional interior, this must proceed in conjunction with avionics installation. The labor savings are expected to result from not requiring all installation personnel to be in the same space at the same time.

The increased design freedom provided by the shell derives from the fact that when properly reinforced, any point on the shell may be used to attach interior components, whereas attachments to the airframe can be easily made only at frame locations.

The potential for improved trim system fire performance derives from the use of high-strength, fire-resistant materials in the shell panel.

Potential disadvantages include unresolved weight implications, new design requirements for the crash load, decompression, and other safety issues. Since this does represent a new concept, some additional design effort to satisfy regulatory agencies must be expected.

Design Considerations

We wish to address three significant acoustic design considerations in this section and then elaborate further on the question of total system weight.

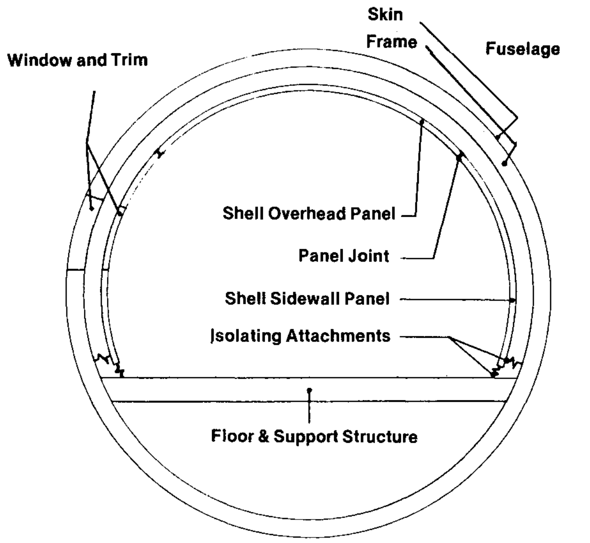

Fig. 1 Schematic cross section of shell installation concept.

Minimize Structure-borne Noise Input

There are four areas of consideration for minimizing structure-borne input through the attachment point design. These four areas include: 1) minimizing the total number of connections, 2) choosing attachment points with low vibration levels, 3) improving vibration isolation effectiveness, and 4) controlling flanking vibration transmission from fuselage frames. In the following paragraphs we will expand on each of these topics.

Minimize Number of Connections

Since the total vibratory power input to the shell panel is equal to the sum of the power received through each connection (assuming independent excitation at each point), it is reasonable that minimizing the number of connections will minimize the structure-borne noise radiation by the shell. Unfortunately, however, the number of connections is likely to be determined from static design considerations involving deflections between the support points of the shell and the maximum load transfer to the fuselage attach points. In view of this fact, the more productive path to minimizing vibratory power input is through the selection of points of low vibration as discussed in the next section. However, we should emphasize here the need to avoid unintentional connections between the shell and the airframe, caused by changes in the airframe shape under pressurization or through the distortion of the shell shape. To control this problem and also to improve the thermal isolation, it is common practice to provide an insulating blanket between the shell and the fuselage frame flanges. The acoustic effects of this blankets are also discussed below.

Select Attachment Points for Low Vibration Input

The primary motion of the fuselage exciting the trim system is that in the radial direction. In general, this motion may be expected to be of uniform magnitude around the frame at high frequencies. At low frequencies, however, there is a region on the fuselage (at the juncture with the floor supports) where it may be reasonably expected that the radial motion of the frames will be a minimum due to the reinforcing effects of the floor structure.[3] Thus, we expect that low-frequency, structure-borne input to the shell will be minimized if the attachment points are restricted to this region.

In addition to radial motion, it is expected that the fuselage frames will also exhibit rotational motion, which will also be input to the shell if not controlled. This motion can be minimized if the attachment is made through a support spanning two or more frames or if the isolation system is designed to reduce moment transfer.

Improve Isolation Effectiveness

The power transfer from the attachment point into the shell panel is determined by the effectiveness of the isolation at the attachment point. The concept of vibration isolator effectiveness was introduced by Ungar[4] and is discussed by DeJong.[5] The effectiveness of the isolator may be roughly estimated by[5]

$$\mathrm{IL} = 10 \log |Z_i(Y_f + Y_s)|^{-2} \tag{1}$$

This expression is valid as long as the isolator is very flexible and light compared with the trim panel and the fuselage attachment points. Ignoring isolator resonances, the impedance of the isolator may be estimated as

$$Z_i \sim K_i/\omega \tag{2}$$

The frequency-averaged mobilities of the fuselage and trim panel may be estimated from

$$Y_f \sim \left[(K_f/\omega) + 2.3\rho h^2 c_L \right]^{-1} \quad (3)$$

$$Y_s \sim \left[(\omega M_s)^{-1} + (B_s m_s)^{-1} \right]^{-1} \quad (4)$$

These experessions should provide adequate design estimates for the average effectiveness, which will be reduced at resonances in the fuselage frame and shell attachment points. These may be taken into account through modification of the mobility expressions, as noted by DeJong.[5] Equation (1) clearly indicates that the effectiveness of the isolator is highly influenced by the mobility at the attachment points. The directions for improvement of the isolator effectiveness are to provide increased damping in the structure at the attachment points (to reduce mobility at resonances) and to increase the bending stiffness and/or mass per unit area at the attachment point. Clearly, the increased weight and stiffness of the shell panel as compared with a typical trim panel will significantly improve the isolator effectiveness.

Minimize Excitation of Shell by Frame Flange Vibration

The thermal insulating blanket separating the frame flanges from the shell can introduce vibratory energy into the shell by conduction through the structure of the thermal insulating blanket. This path for transmission of energy may become significant relative to that conducted through the direct attachment points, because of the very large area of frame flange surface in close proximity to the shell. (This is also a potential flanking path for isolators in trim panel systems, but at a lower level because of the proportionately larger number of attachments.) The expected direction to optimize performance is to minimize transmission through this path by minimizing the density of the insulating blanket in the vicinity of the frame flanges. In particular, it should be cautioned that compressing the insulating blanket significantly will substantially increase the vibrational transmission.

Optimize Shell Panel Design

Shell Critical Frequency

As in the design of trim panels, the three factors that control the performance of the shell panel are the flexural rigidity per unit width, the mass per unit area, and the system loss factor for the panel. The flexural rigidity and mass per unit area combine to determine the critical frequency for the panel,

$$f_c = c^2 (m_s/B_s)^{1/2}/2\pi \quad (5)$$

The critical frequency in turn determines the frequency range in which damping is of great significance in determining performance. In the region near and above the critical frequency, the panel system loss factor directly determines the total radiated power for a given vibration input. Thus, maximizing loss factor reduces the radiated power in direct proportion.

A factor playing a significant role in the panel design for composite panels is the fact that the flexural rigidity is not constant, but rather is a function of excitation frequency or wavelength.[6] As an example, Fig. 2 shows the plot of measured flexural wave speed vs frequency for a panel system used in the experimental aircraft program. The wave speed c_b, which is proportional to the fourth root of B_s, is clearly frequency dependent, implying the frequency dependence of B_s. Careful design that balances face stiffness against core shear stiffness can yield a panel having a much higher critical frequency than one would expect based on static stiffness alone. The construction of the shell panel used in this study is shown in Fig. 3. The actual critical frequency, determined from the frequency where c_b is equal to the speed of sound in the air, is estimated to be 8 kHz. The critical frequency based on static stiffness is approximately 900 Hz.

The difference between these two values is due to the fact that shearing of the core construction in the panel reduces the effective stiffness of the panel at middle and high frequencies.

The weight of the panel is defined by the design requirement for low-frequency attenuation (double-wall resonant frequency). Unfortunately, no analytic solution for estimation of the double-wall resonance between two cylinders is yet available. Conservatively, we estimate the attenuation based on flat panel considerations as previously discussed.[1] We anticipate that analysis along the lines suggested by Dowell[2] will provide this design information in the future.

Shell Component Joints

The shell components are fabricated in the largest size that can be readily installed and removed from the airframe. This significantly reduces the number of joints compared to classic trim panel construction. Still, these joints must be sealed to insure that the significant transmission path is through the shell itself. The construction and installation detailing sealing these joints and providing for accurate alignment may be achieved in many ways. The details of this provide a unique challenge to the shell designer.

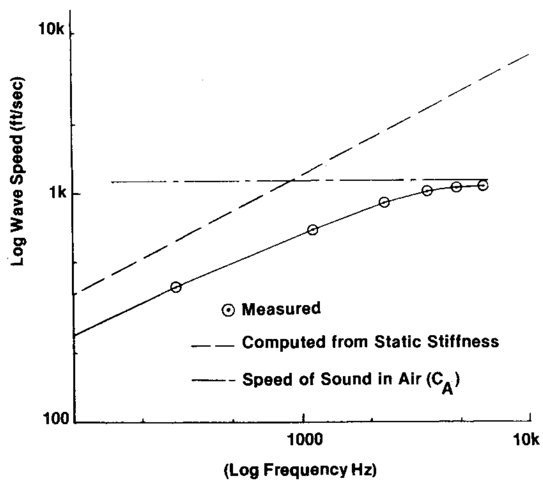

Fig. 2 Bending wave speed in shell sandwich panel vs frequency.

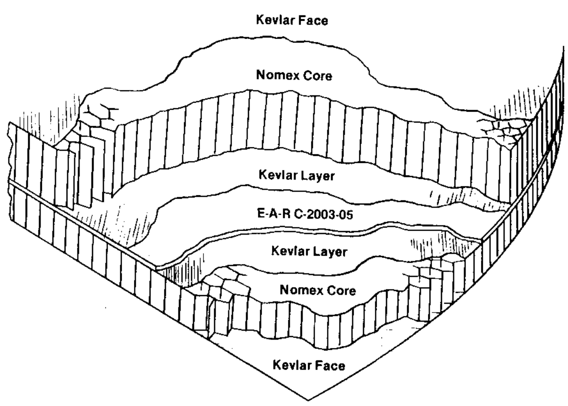

Fig. 3 Shell sandwich panel isometric view.

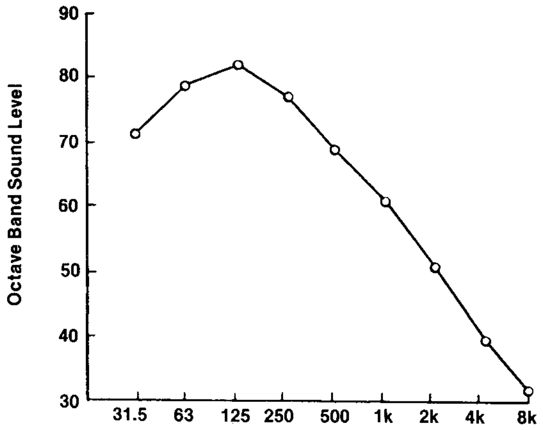

Fig. 4 Nine-seat cabin average octave band sound level vs frequency.

Other Acoustic Paths

As in the conventional trim panel system, other acoustic paths are of significance to the acoustic designer. The shell concept does, however, offer an alternate installation technique for the bulkheads, which minimizes structure-borne excitation by eliminating the connections to the fuselage. The aircraft cabin floor is, however, a significant potential source/path that requires increased attention because of the greater attenuation provided by the shell. To reduce the radiation of structure-borne noise from these high stiffness-to-weight structures, additional dumping treatment is a weight-efficient solution. Additional high frequency attenuation provided by heavyweight carpet, and lightweight, thick carpet pad is also useful.

Window constructions require attention, as they do in conventional trim panel constructions. Structure-borne excitation of interior window trim due to attachment to the fuselage is no longer a problem. Optimal performance is found to occur when no connections are made between the shell and the fuselage in the vicinity of the window and the shell penetration is sealed by an inner window.

Total Installed Weight

Superficially, the shell system might appear to be heavier than the conventional acoustic treatment approach. However, this ignores the fact that the shell replaces the trim panel structure (which is no longer required). In this case, the shell itself acts as the trim panel substrate for the attachment of decorative facings. Alternately, very lightweight trim panel substrates can be used to alter the contour of the shell for aesthetic reasons. Also additional weight-saving benefits due to the elimination of attachment hardware should not be disregarded.

Experimental Program

More than eight shells have been installed in three airframe types, including the Canadair Challenger 600, Gulfstream I, Gulfstream II, Gulfstream III, and helicopter airframes. To date, each of these installations has been accomplished on an individual owner basis: thus, detailed study of the results of the installations has been precluded. In each case, results equal to or better than those achieved in using conventional trim panel approaches have been claimed. The absence of green aircraft sound levels as well as post-installation intensity surveys leaves open the question of the actual installed performance of the shell relative to other significant paths. In view of this situation, we will briefly describe only one installation, with the associated after-test results and urge the community to address the experimental verification problem in greater detail.

The first shell interior completion incorporating the design considerations indicated above was a Canadair Challenger CL-600 aircraft serial no. 1066 initiated in 1982. The author had the privilege of participating with an extensive design team assembled by Federated Department Stores (FDS). The first flight of the completed aircraft was made in December 1983.

The interior layout includes a small galley in the entranceway, a forward cabin with club seating for four, an aft cabin with table space for four, a side-facing divan with three seats, an aft lavatory, and an in-flight accessible baggage compartment behind.

Due to vibratory input from its rigidly mounted, high-bypass-ratio fan engines, the Challenger 600 airframe creates unusually difficult challenges for interior noise control. The fan 1/rev tone occurring at approximately 115 Hz became a source of complaint from some owners. A fan-balancing program available through the engine manufacturer has reduced the problem to near acceptable levels. This shell design program was undertaken to provide additional control for this frequency regime.

The basic shell construction is formed into a radius that clears interior airframe structure by about 0.5 in. The bulkhead separating the lavatory from the main cabin is of a constrained-layer damped construction as used in Ref. 1, as are the aft lavatory and the forward cabin bulkheads. A separate shell section is installed in the lavatory. The shell is isolated from the fuselage frames by a Nomex felt blanket. The cabin floor panels supplied by the manufacturer were replaced with panels of construction similar to the shell. Other acoustically significant details included extensive use of supplemental structural damping under floor panels, skin damping treatments applied to the fuselage, polyurethane foam and glass-fiber batts for between-frame fill, and extensive use of absorptive treatments under the floor and throughout the occupied cabins and compartments. Several airframe modifications, including a particularly effective hydraulic system redesign (developed by M. Weubbling, Maintenance Manager of FDS) contributed to the high-frequency performance. Figure 4 is a plot of the cabin-average octave band sound pressure level for nine seats acquired by an independent testing agency at flight conditions of Fl390 and speed Mach 0.78. The nine-seat cabin average noise level of 72 dBA and 49.8 dB speech interference level (SIL) is believed to represent one of the quietest completions of this airframe achieved to date.

Green aircraft noise levels were acquired for this airframe, but, unfortunately, engine balancing was not completed until after the last installation of the interior. Since appropriate green interior noise levels are unavailable, the quantitative influence of engine balance vs shell performance in reducing structure-borne noise levels in the 125, 250, and 500 Hz octave bands cannot be readily separated.

Conclusions

Due to the continuing nature of this program, the following conclusions are preliminary.

1) The self-supporting damped shell concept offers a convenient, flexible method for implementing the damped trim panel concept.

2) The concept offers the potential for improved acoustic performance at low frequencies over conventional trim panel constructions through stiffness-controlled modification of the double-wall resonance.

3) Appropriate levels of isolation and damping, coupled with judicious selection of the attachment locations, is necessary to achieve optimum performance over the entire frequency range.

4) Full verification of optimum performance has not been demonstrated in flight. Sources of performance degradation have not yet been fully identified.

5) The potential low-frequency performance improvements may have implications for propfan interior noise control.

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