Development of Quiet Honeycomb Panels

Daniel L. Palumbo and Jacob Klos
Langley Research Center, Hampton, Virginia

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Daniel L. Palumbo and Jacob Klos
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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I. Abstract

Sandwich honeycomb composite panels are lightweight and strong, and, therefore, provide a reasonable alternative to the aluminum ring frame/stringer architecture currently used for most aircraft airframes. The drawback to honeycomb panels is that they radiate noise into the aircraft cabin very efficiently provoking the need for additional sound treatment which adds weight and reduces the material's cost advantage. A series of honeycomb panels were made which incorporated different design strategies aimed at reducing the honeycomb panels' radiation efficiency while at the same time maintaining strength. The majority of the designs were centered around the concept of creating areas of reduced stiffness in the panel by adding voids and recesses to the core. The effort culminated with a reinforced/recessed panel which had 6 dB higher transmission loss than the baseline solid core panel while maintaining comparable strength. Attempts were made to damp the panels' vibration energy by the addition of lightweight particles to the honeycomb cells. These designs were very difficult to build given the particles' tendency to pollute the bond interface between the honeycomb and the face sheet. Well constructed panels exhibited very little benefit from the treatment that could not be attributed to the added mass alone.

II. Introduction

The application of composite materials to aircraft structures will decrease aircraft mass and change how aircraft are designed and constructed. The expectation is that the new materials will reduce the life cycle cost of the aircraft through lower manufacturing and operational costs. A representative model of current aircraft sidewall construction is shown on the left in Fig. 1. The sidewall is composed of 3 major components, the aircraft skin, longitudinal stringers and circumferential ring frames. All the components are aluminum and are riveted together. The mass per unit area of the stiffened aluminum panel is 1.2 lb/ft² (5.9 kg/m²).
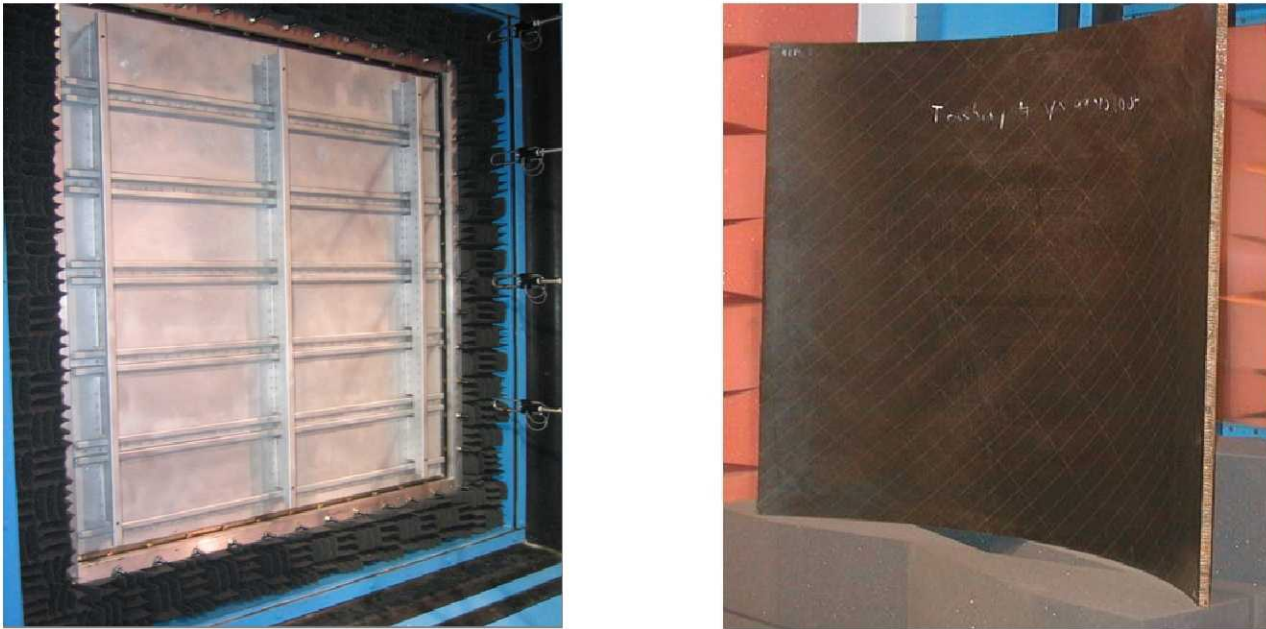

Fig. 1 Stiffened aluminum sidewall construction (left) is typical of most aircraft today. On the right is a composite honeycomb sandwich panel similar in construction to Hawker Premier fuselage.

Contrast the aluminum sidewall to the honeycomb sandwich composite panel shown on the right in Fig. 1. Visually the differences are striking. The interior is smooth and the panel is much thinner than its aluminum counterpart, <1" (2.54cm) for the composite panel vs. >2.5" (6.35cm) for aluminum panel. This gives the designers the freedom to set a smaller diameter fuselage for a comparable interior space, saving even more weight beyond the 35% reduction the materials already provide, (the mass per unit area of the honeycomb panel is 0.79 lb/ft² (3.9 kg/m²)).

However, this weight savings comes at a cost in increased levels of interior noise. This trend is observed in transmission loss measurements where the acoustic power incident on the 'source' side of a panel is compared to the power on the 'receiving' side. A high transmission loss implies reduced interior noise. Fig. 2(a) shows the transmission loss of the stiffened aluminum panel compared to a flat honeycomb composite panel of construction similar to the curved panel in Fig. 2. As can be seen, the honeycomb panel loses as much as 10 dB in transmission loss to the aluminum panel. This deficiency will have to be compensated by added acoustic treatment, reducing the weight benefit the manufacturer and it's customers expected to achieve. Note that the acoustic treatment weight penalty is particularly onerous in this case because the honeycomb sidewall already provides sufficient thermal insulation. The insulation blankets in an aluminum aircraft are needed to provide thermal isolation from the -50° C external temperatures. The acoustic damping provided by the blankets is an added benefit with little added cost in either dollars or weight. The cost penalty for acoustic damping in a honeycomb composite aircraft is now solely born by the noise requirement.

For these reasons, it is important to understand why the honeycomb panel has such poor noise performance and to investigate ways in which the noise penalty can be reduced while maintaining the weight advantage these new materials bring to aerospace vehicle design. The following section will discuss some of the theory behind the honeycomb composite panel's behavior. Subsequent sections will present the results of testing various instances of honeycomb panels that were built to understand how the goal of increased transmission loss without appreciable weight gain might be achieved.
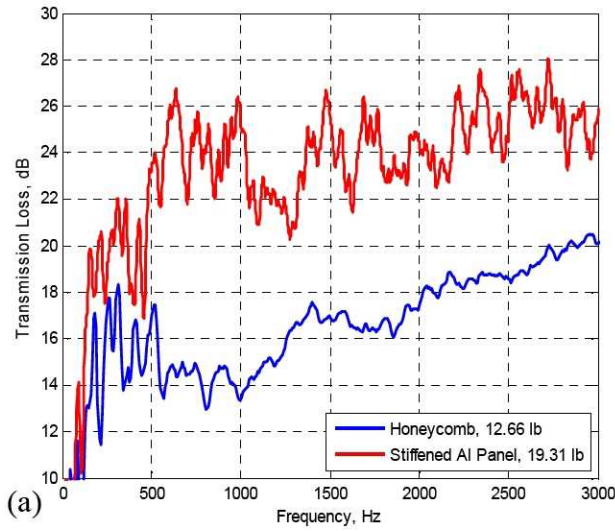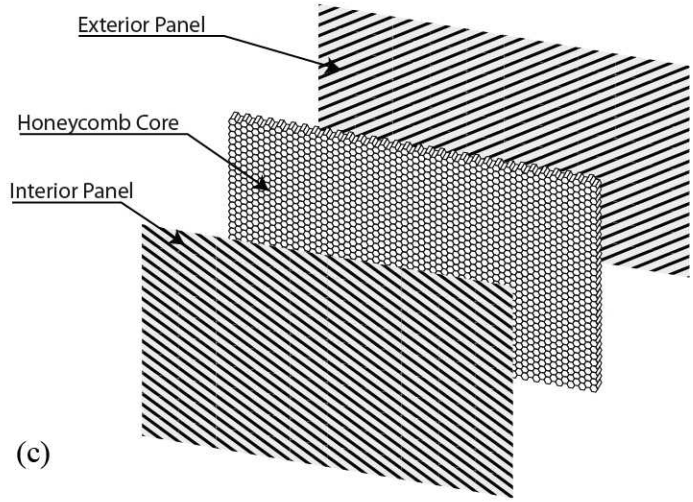
Fig. 2 Transmission loss of stiffened aluminum panel and solid core honeycomb panel (a), band average difference in TL (b), and components of honeycomb sandwich panel (c).

A. Structural Acoustics Background

A sandwich core composite panel is composed of three components, the core and the inner and outer face sheets, Fig. 2(c). The components can be made of many different kinds of materials depending on the application. For example, the core is often foam in lightweight partitions, but is stiffer honeycomb in load bearing panels. Likewise, the face sheets can be sheet metal, fiberglass or carbon fiber. The benefit of the sandwich core design is that a lightweight and semi-rigid core material acts to increase the stiffness of the face sheets by virtue of their constrained displacement away from the composite panel's neutral axis. In this way the strength of the composite panel is greater than the sum of its parts.
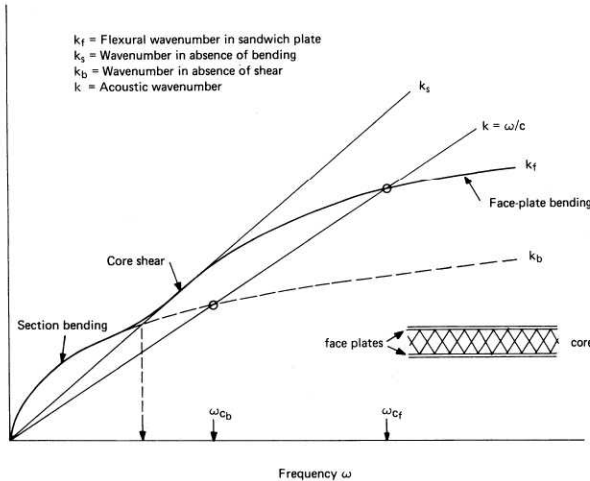

Fig. 3 Dispersion curves for sandwich panels from Fahy[1].

The light weight and increased stiffness results in higher wave speeds, and thus lower wavenumbers, in the material. This is significant because once the wavenumber in the panel falls below the wavenumber in air, the panel radiates sound more efficiently. The wavenumber/frequency spectrum can be divided into 3 domains depending on the type of wave propagating[1], Fig. 3. The lower frequencies are dominated by bending waves whose nature is determined by the composite panel properties. The mid-frequencies contain shear waves that are governed mostly by core properties. The higher frequencies are dominated by flexural waves in the face sheets. For the honeycomb panels tested here, the shear wave is considered to be the major source of the panel's increased radiation efficiency.

The effect of the decreased mass and increased stiffness of the honeycomb panel can be seen in the respective panels' wavenumber spectra, Fig. 4. In the wavenumber spectrum plots displayed here and elsewhere, the total power in the panels is calculated as the sum of the squared velocity over the surface of the panel. The velocity was normalized by the input force during acquisition. The color axis is in dB taking the total power in the solid core honeycomb panel as reference. The majority of the vibration energy in the stiffened

aluminum panel is well above the sonic wavenumber (the black line), characteristic of a subsonic panel. The energy is also scattered due to the discrete nature of the panel's construction. In contrast, the power in the honeycomb panel, though much less than the aluminum panel, is concentrated around the sonic wavenumber, indicating its lighter weight, increased stiffness and more uniform construction. The panel is seen to be substantially supersonic by 400 Hz.
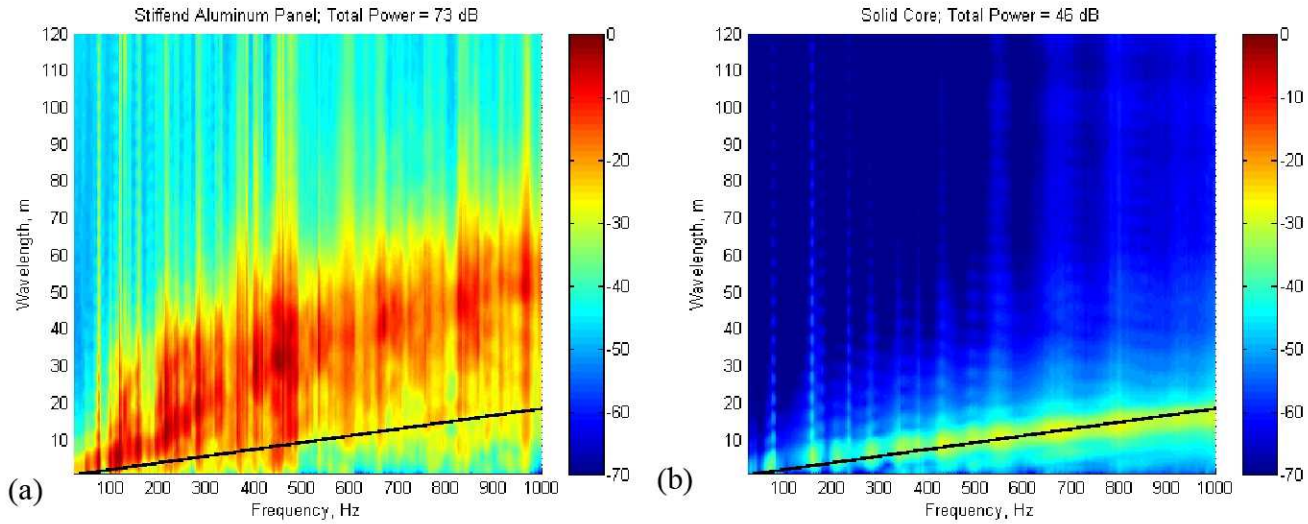

Fig. 4 Wavenumber spectra of stiffened aluminum panel (a) and solid core panel (b) compared to sonic wavenumber, black line.

The uniform construction of the honeycomb panel enables the excitation of almost ideal modes. The velocity response and related wavenumber spectrum for the honeycomb panel at 340 Hz is shown In Fig. 5. Note the very well defined 2,2 mode. The wavenumber spectrum of this response shows the energy concentrated around the sonic circle. This curve illustrates why a panel's radiation is not always reduced by increasing panel stiffness. For a given excitation, a panel's velocity response will be inversely proportional to its stiffness. Intuitively, one might expect the sound radiation to decrease as panel stiffness increases. However, as stiffness increases, the panel's energy, as represented by the modal nodes in Fig. 5(b), moves towards the sonic circle, increasing the proportion of the total panel energy that is radiating efficiently. This increase in radiation efficiency overwhelms the decrease in vibration up to the point where most of the energy is within the sonic circle. After that, an increase in stiffness will reduce noise radiation as expected.
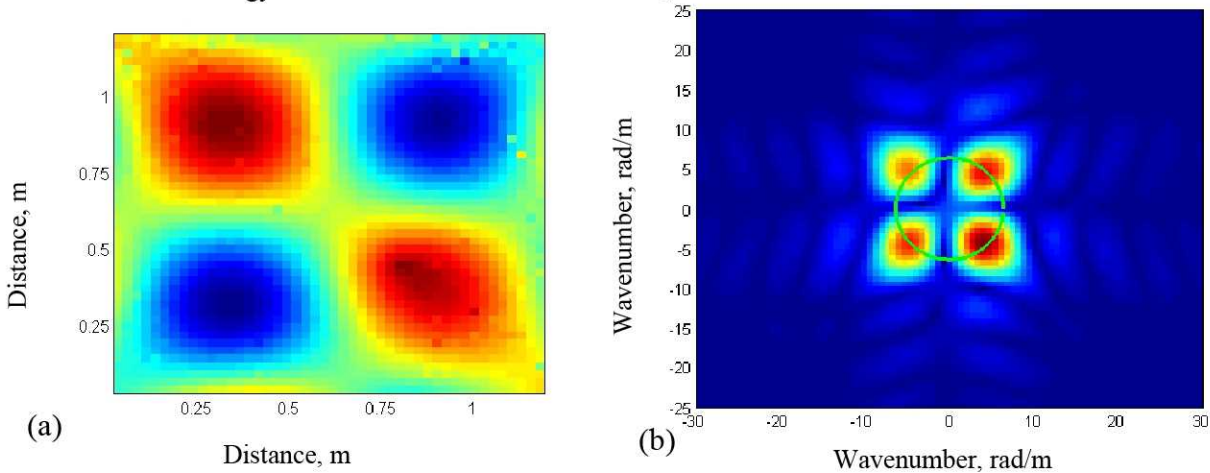

Fig. 5 Velocity response (a) and wavenumber spectrum (b) of solid core honeycomb panel at 340 Hz, 2,2 mode. Sonic circle shown as green line in (b).

This behavior is demonstrated in Fig. 6 where transmission loss is plotted for panels with decreased (a) and increased (b) stiffness with respect to the baseline honeycomb panel. In all cases of the decreased stiffness, the transmission loss is increased. In most cases

of increased stiffness, the transmission loss is increased as well. The baseline panel is seen to have been designed with close to the worst case stiffness when considering noise radiation.
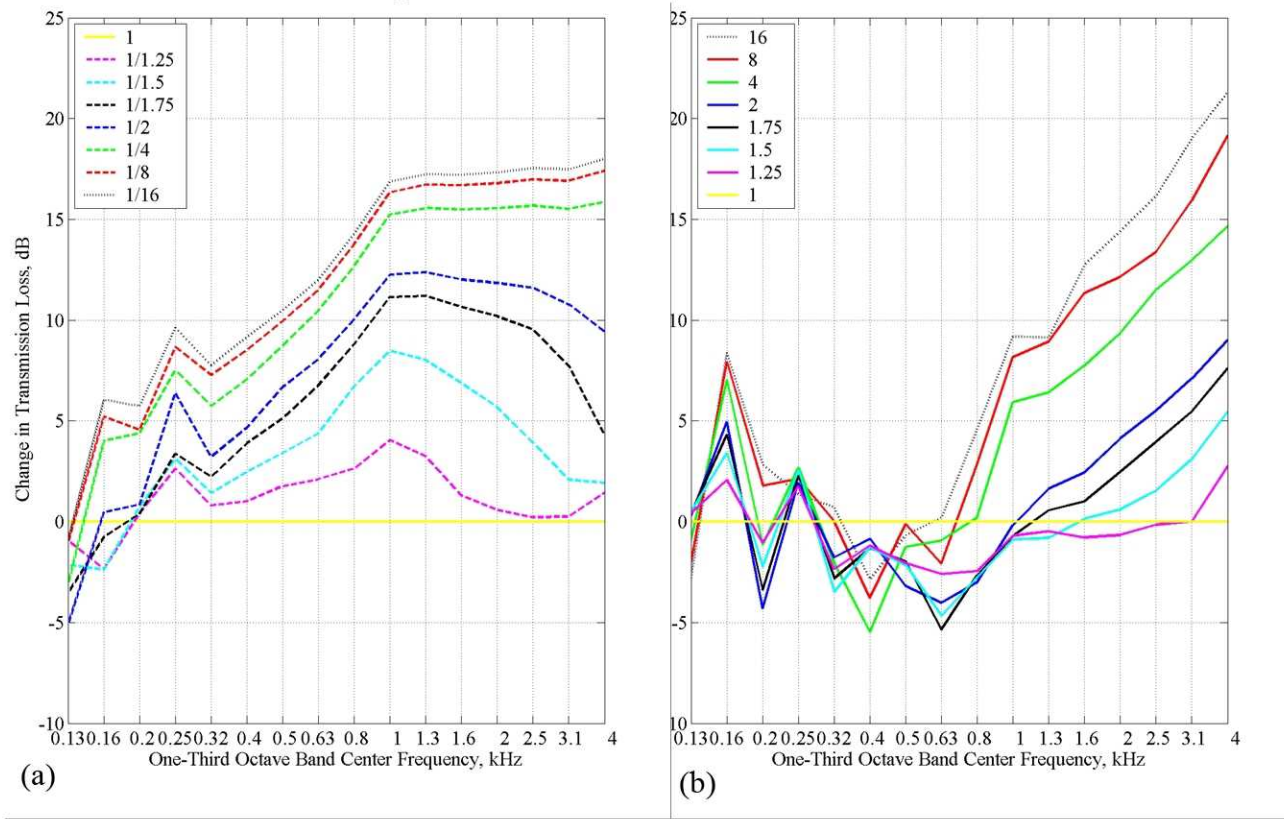

Fig. 6 Effect on transmission loss of decreasing, (a), and increasing, (b), stiffness of solid core honeycomb panel.

B. Approach to the problem

The design challenge presented was how to reduce the panel's radiation without increasing its mass and without decreasing its load bearing capability. The approach taken was to reduce the surface area of the panel which supported supersonic waves. This was accomplished by milling the core in different locations so that one or both face sheets were not bonded to the core in these locations. The initial 2 designs which resulted from this approach were the voided and recessed core panels, Fig. 7 (a) and (b) respectively. The voided core had areas where the core was completely removed. This resulted in a core structure which resembled the aluminum panel's ring frame/stringer architecture. The voids also created areas of double wall features which would have a positive acoustic benefit.

To make the recessed core, core material was milled to a prescribed depth, from one side of the panel. This was done initially to accommodate automated lay-up tools which would need a continuous surface on at least one side of the panel to lay down the carbon fiber tape. As will be seen in later sections, the remaining core not only provided acoustic benefit by damping transverse modes in the cavity, but also served as a base for increasing the panel's stiffness through the addition of a third, internal face sheet.

Another consideration in taking this approach was that it would break up the baseline panel's uniform architecture and scatter the panel's vibration energy into many wavenumbers, thus reducing the energy concentrated around the sonic circle. While this effect was observed, its benefit was hard to quantify. Finally, it was expected that the voided and recessed panels would lose stiffness with respect to the baseline panel. To address this, finite element models of the panels were created and an optimal design was achieved which gave up some of the acoustic gains for additional stiffness[2,3].

It should be noted that all the panels were made using the same core material with the same core dimensions. The composite panel's stiffness could have been increased, for example, by increasing the core thickness. This dimension of the design space was not explored.
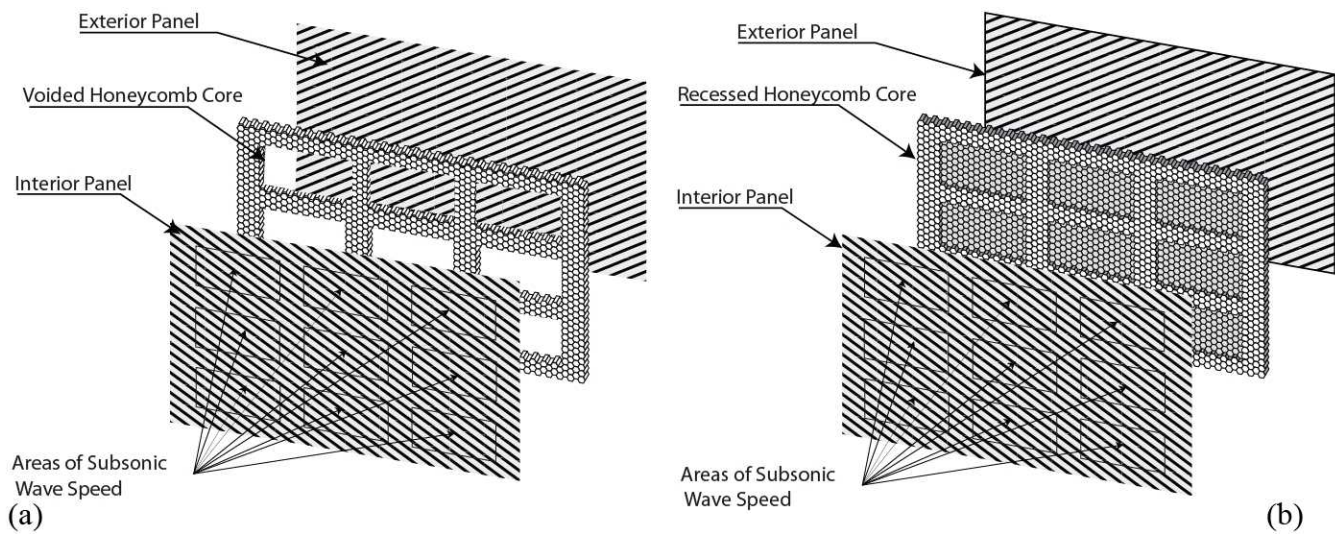
Fig. 7 Components of voided (a) and recessed (b) core composite panels.

C. Panel specifications and test procedures

A flat model of a stiffened aluminum sidewall (pictured in Fig. 1(a)) was used as a basis for comparison to the honeycomb panel. As mentioned earlier, the panel is composed of 3 distinct components, the skin, ring frames and stringers. All the components are aluminum. The skin is 0.050" (1.27mm) thick. The ring frames (the vertical stiffeners in Fig. 1(a)) have a cross section shown in Fig. 8(a) and are also made from 0.050" (1.27mm) material. The stringers have a cross section shown in Fig. 8(b), but are made from 0.040" (1.02mm) material. The components are riveted together as is typical of aircraft construction. The complete panel is 4'x4' (1.22mx1.22m) with a 1" (2.54 cm) flange provided for clamping into the test window (the 'working' section of the panel is then 46" (1.17m)) square. The sub-panel dimensions are 17.25 in. (43.8 cm) x 5.5 in (14 cm) and the completed panel weighs 19.31 lbs (8.8 kg).
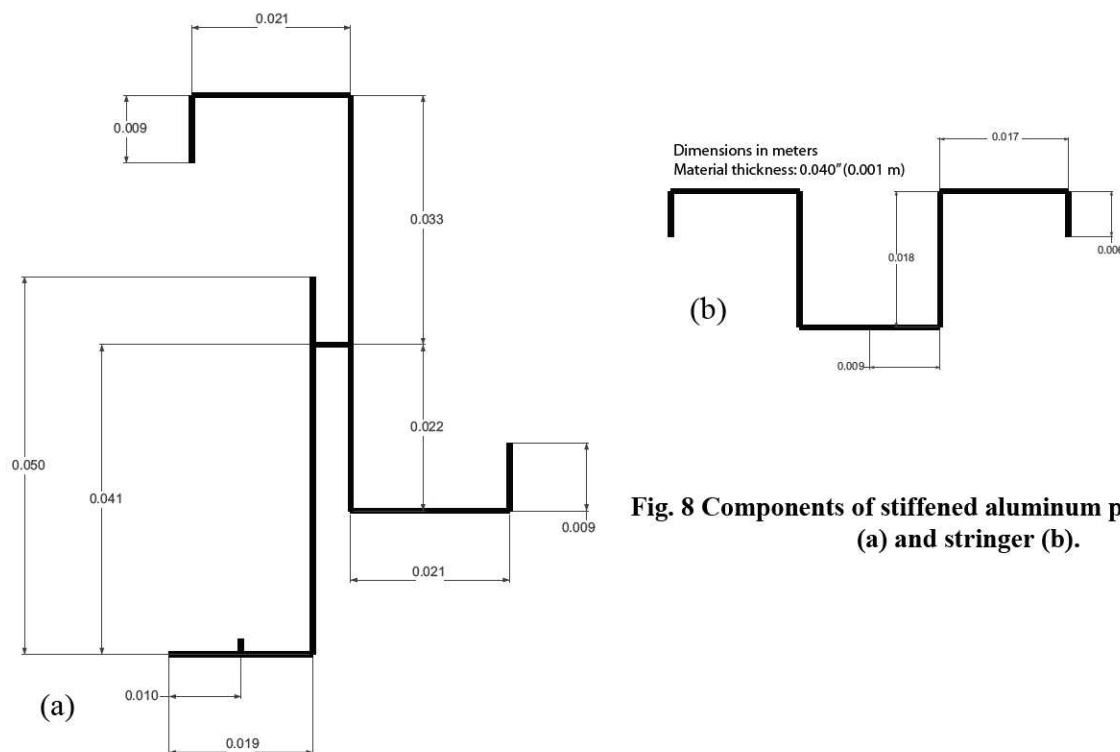

Fig. 8 Components of stiffened aluminum panel, ring frame (a) and stringer (b).

Dimensions in meters

(0.00367,0.003175)   (0.00734,0.003175)

0.00367   0.003175 (0.125")

(0,0)   60
0.001835

(0.01101,0)

0.00734

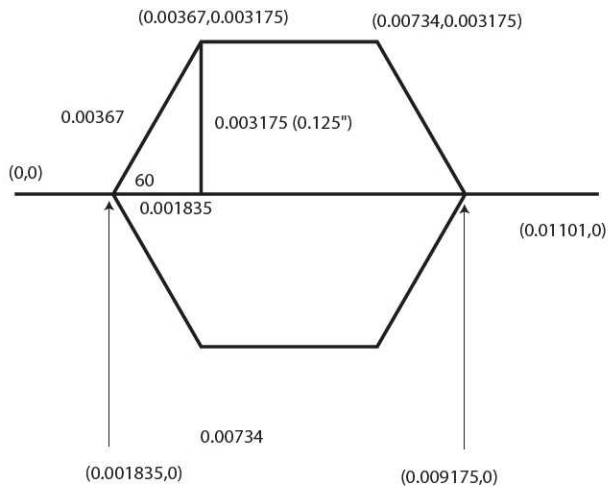(0.001835,0)   (0.009175,0)

Fig. 9 Dimensions of Nomex core hexagonal cell.

The honeycomb panel is also composed of 3 major pieces, the 2 face sheets and the core. In practice, the face sheets are typically carbon fiber lay-ups. For test purposes, the face sheets were made from 0.020" (0.51mm) aluminum. This gives the panel the same approximate stiffness as one with carbon face sheets, with little added mass. The core is 0.75" (1.91cm) thick Nomex with hexagonal cells. See Fig. 9 for cell dimensions. The density of the core was 3 lbs/ft.^{3} (38 kg/m^3. The core and one face sheet is 46" (1.17m) square. The second face sheet is 48" (1.22m) square providing a 1" (2.54cm) flange that can be clamped into the test window. The baseline honeycomb panel weighed 12.66 lb (5.7 kg).

The panels were tested for transmission loss and velocity response in NASA Langley's Structural Acoustic Loads and Transmission (SALT) facility. The SALT facility is composed of an anechoic chamber (receiving room), Fig. 10, and a reverb chamber (source room), Fig. 11, with a test window which is visible in both figures separating the two

Fig. 10 The anechoic chamber in the SALT facility.

Transmission loss is calculated as the ratio of acoustic power radiated by the receiving side of the panel to the acoustic power incident on the source side. The incident acoustic intensity on the source side was derived from the average power in the reverb chamber as estimated by an array of 12 randomly spaced microphones. The transmitted normal acoustic intensity was measured in the anechoic chamber using Bruel & Kjaer 2683 intensity probes on a 2 in. x 3 in. (5.08 cm x 7.62 cm) grid 5 in. (12.7 cm) from the panel's

surface. A 12mm spacer was used with the intensity probe which resulted in a 15 dB pressure-residual intensity index over the analysis band. The measured pressure-intensity index was 5 dB.

Fig. 11 The reverb chamber in the SALT facility.

The wavenumber spectra are calculated as the spatial Fourier transform of the velocity response over the panel. The panels were excited with pseudo-random noise having a bandwidth of 100 to 2000 Hz using a 10 N shaker through a PCB 288D01 impedance head located at a point on the panel over solid core. In most cases this was 8 in (20.3 cm) form one side and 16 in (40.6 cm) from the other. The normal velocity structural response was measured with a Polytec PSV-300 scanning laser vibrometer. Velocity measurements were taken on a 1 in. x 1 in. (2.54 cm x 2.54 cm) grid.

III.   Voided Core Panels

A. Voided Core, 3x3 10" (25.4cm) squares, panel 2, 11.15 lbs (5.2 kg)
The honeycomb core with milled 10" (25.4cm) voids is shown in Fig. 12(a). The transmission loss (TL) of the assembled panel is compared to the solid core panel in Fig. 12(b). The acoustic behavior of the voided panel is complicated by the many resonances, both structural and acoustic, introduced by the design. The voids will exhibit a mass-air-mass resonance due to the double wall construction and undamped cavity. This resonance can be seen as a pronounce dip in the TL at 400 Hz, followed by a distinct increase in TL. The increased TL achieved by the action of the double-wall is reduced by a second dip in TL which is seen to occur at about 650 Hz. This resonance is due to transverse modes in the cavity. The voided panel achieves a 6.9 dB increase in TL between 1 kHz and 2 kHz. Above 2 kHz, the increase in TL drops to 4.6 dB. The increase in TL is achieved in spite of a 12% decrease in mass compared to the solid core panel.
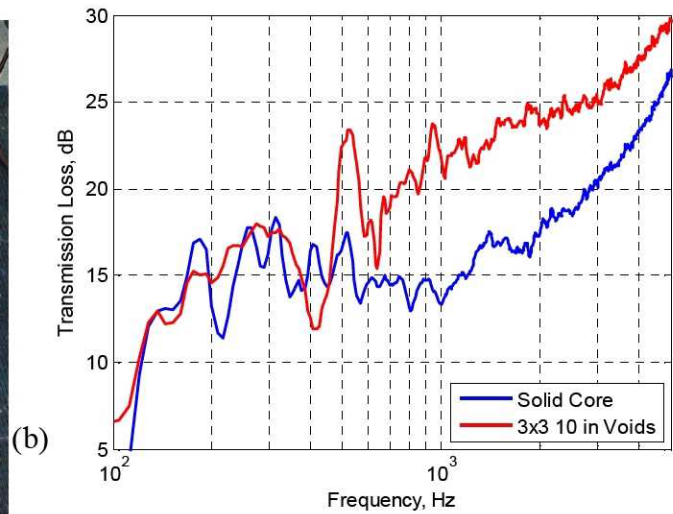
(c)	Average Difference in TL Over Frequency Band			
	100-500	500-1000	1000-2000	2000->5000
	0.5	6.0	6.9	4.6

Fig. 12 Nomex core with 10" voids (a), transmission loss (b), and band average difference in TL, (c).
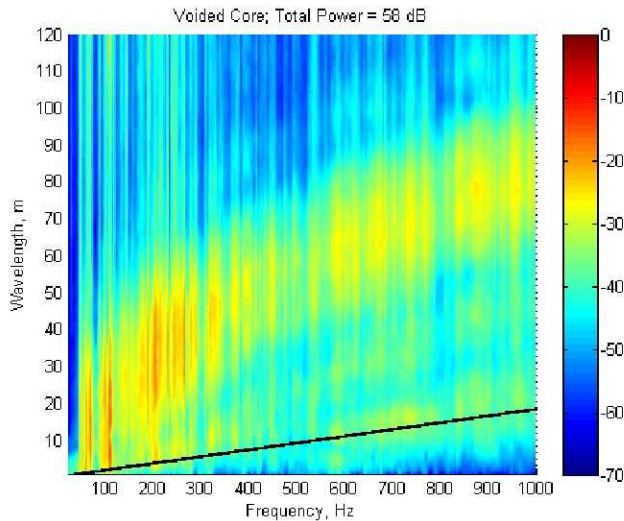

Fig. 13 Wavenumber spectrum of 3x3 10" voided panel.

The wavenumber spectrum of the velocity response of the voided core panel in Fig. 13 has more in common with the aluminum panel, Fig. 4(a), than the solid core panel, Fig. 4(b). The total vibrational power is increased by 12 dB over the solid core panel. This is due to the unconstrained vibration of the panel over the voids. This part of the panel is substantially subsonic and produces most of the energy observed in Fig. 13 above the sonic line.

An open question at this point is what the relative strength of the voided panel would be with respect to the aluminum and solid core panels. Assuming that the recessed core panel (described in "Recessed Core, 3x3 10" (25.4cm) squares, panel 4, 12.15 lbs (5.5 kg)" on page 12) has a strength similar to the voided core, it can be inferred from deflection tests done on the recessed core panel that the voided core panel lacked substantial strength (see "Deflection tests" on page 16). Even if the core thickness is increased to recover stiffness, the panel sections over the voids would have to be reinforced to sustain pressurization loads. An optimum combination of thicker core and reinforced voids might result in a viable design.

B. Voided core, 3x3 6" (15.2cm) squares, panel 7, 12.06 lbs (5.5kg)

This variant of the 10" voided core panel was produced to test the effect of varying the dimension of the voided area on panel TL performance. The reduced surface area of the voids reduces the effects of the resonances associated with the voids such that the mass-air-mass resonance which was so pronounced in the 10" panel is not readily visible in the 6" panel. The reduced dimension of the void increases the transverse modal resonance to above 1 kHz thereby increasing the effect of the mass-air-mass resonance at lower frequencies. As might be expected, this panel exhibits reduced TL performance compared to the 10" voide core panel.
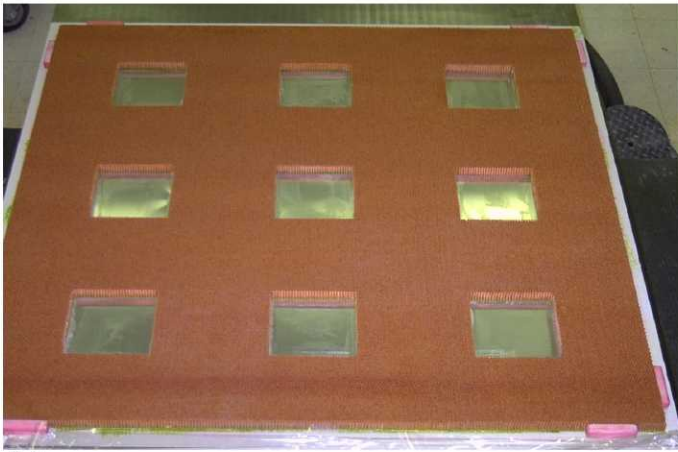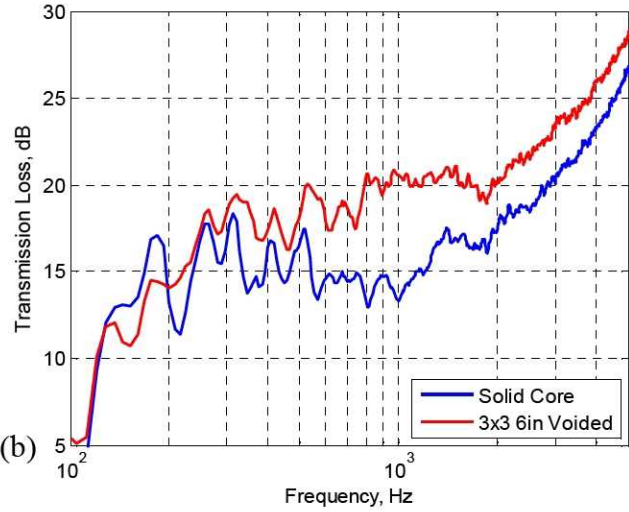
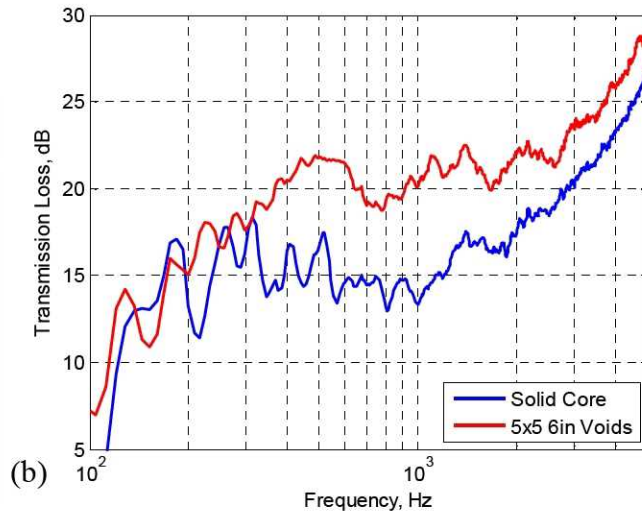| Average Difference in TL Over Frequency Band			
100-500	500-1000	1000-2000	2000-5000
1.2	4.9	3.9	2.6

Fig. 14 Voided core with 6" square voids in 3x3 configuration (a), transmission loss (b) and band difference in TL, (c).

C. Voided core, 5x5 6" (15.2cm) square, panel 14, 10.8 lbs (4.9 kg)

    The 5x5 void core panel was produced as a reference for the reinforced panel described in section "Reinforced core, 5x5 6" (15.2cm) squares, panel 15, 13.2 lbs (6.0 kg)" on page 14. The panel achieves close to a 7 dB increase in TL in the range 500 Hz to 2000 Hz after which the increase in TL drops to 5 dB.

Average Difference in TL Over Frequency Band			
100-500	500-1000	1000-2000	2000-5000
1.5	6.5	7.0	5.2

Fig. 15 Voided core with 6" squares in 5x5 configuration (a), transmission loss (b) and band average difference in TL, (c).

D. Voided core, 3x3 10" (25.4cm) square, fiberglass filled, panel 6, 11.37 lbs (5.2 kg)

Filling the voids with fiberglass removes the effects of acoustic resonances in the voids resulting in a 10 dB gain in TL above 500 Hz. A small dip in TL at the mass-air-mass resonance of 400 Hz is still visible. The combination of thicker core, thicker exterior face sheet and fiberglass filling may produce a strong yet substantially quieter panel.
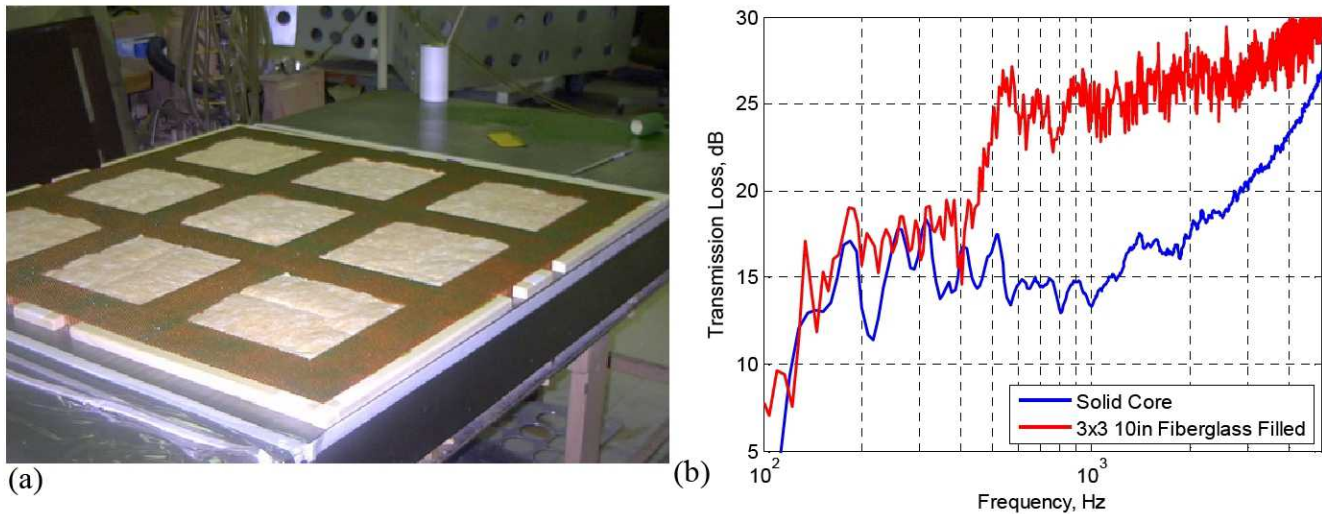
(a)

(b)

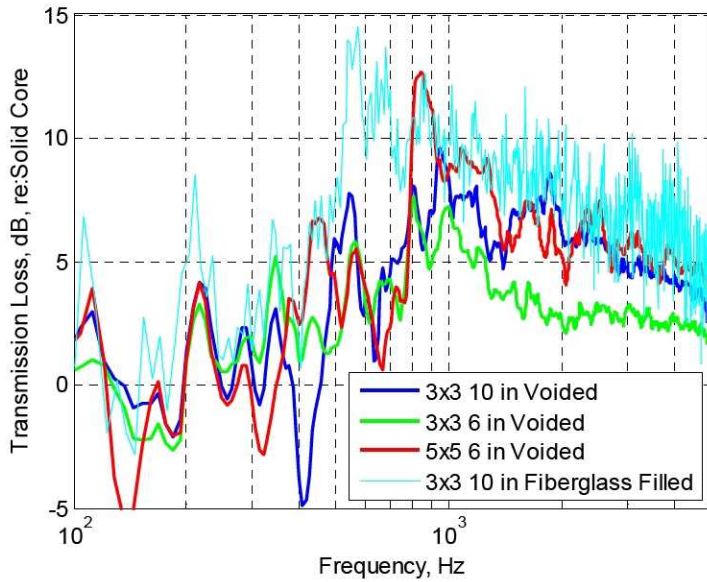**Fig. 16 Voided core with fiberglass fill (a), transmission loss (b), and band difference in TL, (c).**

(c)

Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
2.6	10.3	9.5	5.8

E. Comparison of voided core panels' performance

The difference in TL between the baseline, solid core, panel and the modified panels is plotted in Fig. 17. Below 500 Hz the panels' behaviors are similar. Above 500 Hz the fiberglass filled panel has the best performance with the 3x3 6" panel returning the poorest performance.

Average Difference in TL Over Frequency Band

Panel	100-500	500-1000	1000-2000	2000-5000
3x3, 10"	0.5	6.0	6.9	4.6
3x3, 6"	1.2	4.9	3.9	2.6
5x5, 6"	1.5	6.5	7.0	5.2
Fiber Filled	2.6	10.3	9.5	5.8

Fig. 17 Voided core panels' transmission loss with respect to baseline solid core panel (a) and band average differences in TL, (b).

IV. Recessed Core Panels

A. Recessed Core, 3x3 10" (25.4cm) squares, panel 4, 12.15 lbs (5.5 kg)

The recessed core design was originally conceived to facilitate construction of assemblies using automated tape machines. In this process, the tape machine lays down the interior face sheet, the honeycomb is applied, then the tape machine lays down the exterior face sheet. This process would not work well with the voided core as the tape would sag over the voided areas. Using recessed core, however, the honeycomb can be laid down with the recesses facing the interior. This would present a continuous surface on the exterior, so the tape machine would have no trouble applying the exterior layers of tape. The recesses in this panel are cut to a depth of 1/4" (0.64cm). During testing it was observed that the orientation of the recesses, i.e., whether they faced the source room or the receiving room, did not alter the transmission loss. Orientation would, of course, matter during vibration measurements which were done over the recessed side of the panel.

The recessed core had unanticipated acoustics benefits. The transmission loss, Fig. 18(b), is similar to the fiberglass filled panel, Fig. 16(b), with the exception of a dip in the TL around 600 Hz. This resonance is due to the same transverse modes that occur in the voided core panel that are now largely eliminated by the core except in the recess. The 'exterior' face sheet is bonded to the core so the effective mass and stiffness of the exterior face sheet increased, altering the mass-air-mass resonance and the effectiveness of the double wall.

(a)

(b)
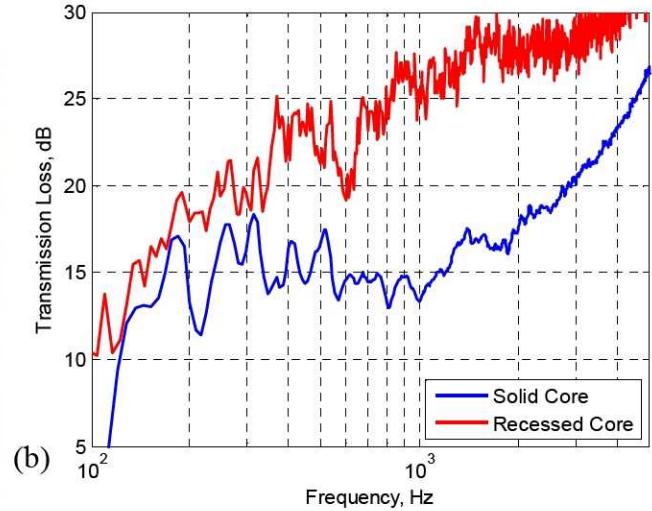
Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
5.1	9.7	11.1	7.8

(c)

Fig. 18 Recessed core with 3x3 10" squares recesses, 0.25" deep (a), transmission loss (b) and band average difference
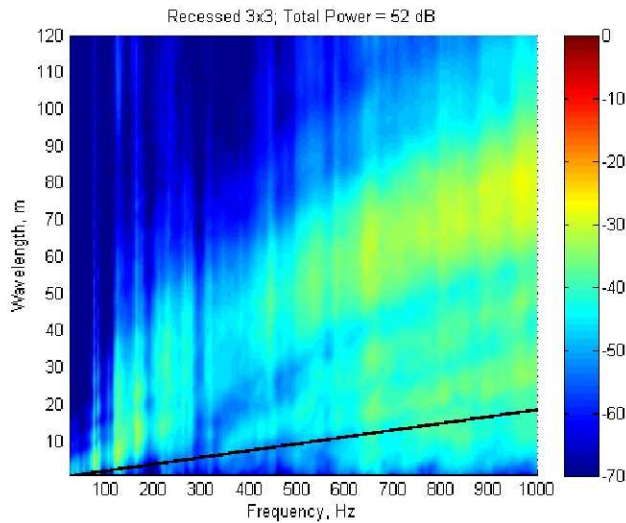

Fig. 19 Wavenumber spectrum of 3x3 10" recessed panel.

Compared to the voided core, the wavenumber spectrum of the recessed core, Fig. 19, has 6 dB less vibrational power overall and much less vibrational power around the sonic line throughout the frequency band, as would be expected given that the TL of the recessed core is 3-5 dB greater than the voided core.

B. Reinforced core, 3x3 10" (25.4cm) squares, panel 11, 14.1 lbs (6.4 kg)

Once it was determined that a ample amount of TL headroom could be obtained using the recessed core design, the effort turned to restoring the lost stiffness. Stiffness can be restored to the panel by reinforcing the recessed core with then aluminum panels. To test the effectiveness of this approach, the 3x3 10" recessed panel was modified by the addition of 0.016" (0.4mm) aluminum reinforcing panels to the recessed areas of the core, Fig. 20(a). The TL of the reinforced panel, Fig. 20(b), is reduced 3-6 dB compared to the recessed panel, Fig. 18(b), despite increasing mass 15%. The mass of the reinforced panel is about 10% greater than the baseline, solid core panel. The decrease in TL (and increase in mass) is due primarily to the introduction of the reinforcing interior panel. The TL

13

penalty can largely be compensated by the inclusion of fiberglass in the recesses as was done in a subsequent panel, see "Reinforced, fiberglass filled, 3x3 10" (25.4cm) squares, panel 20, 13.8 lbs (6.3 kg)" on page 15.
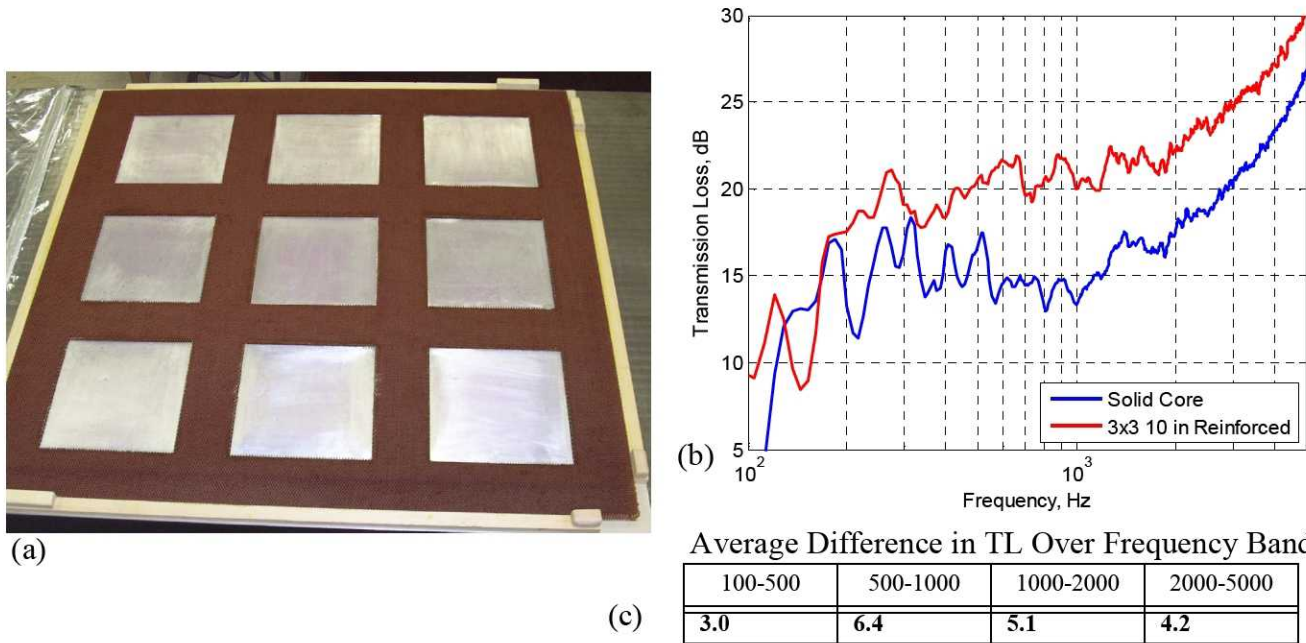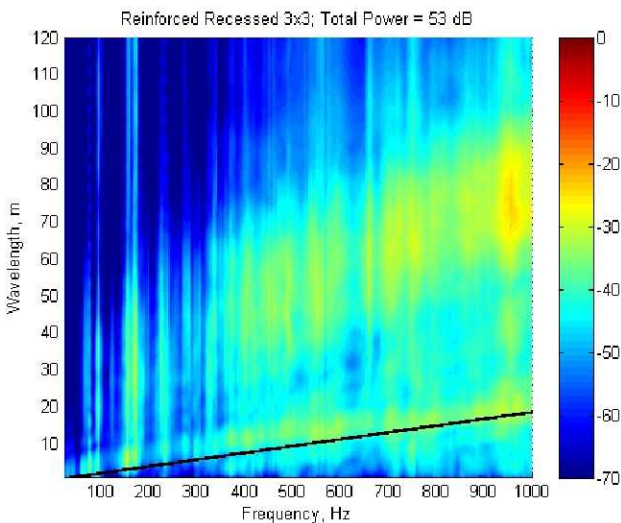

(a)

(b)

Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
3.0	6.4	5.1	4.2

(c)

Fig. 20 Reinforced recessed core with 10" square recesses, 0.25" deep (a), transmission loss (b) and band averaged difference in TL, (c).

The total vibrational power in the reinforced panel, Fig. 21, is just 1 dB greater than the recessed panel but more of that power is concentrated around the sonic line, increasing the radiated sound power. Some of the low frequency modes were moved closer to the sonic line and higher frequency modes (possibly coming from the interior panel) pop up around the sonic line. All these factors contribute to the observed decrease in TL.

Fig. 21 Wavenumber spectrum of 3x3 10" reinforced panel.

C. Reinforced core, 5x5 6" (15.2cm) squares, panel 15, 13.2 lbs (6.0 kg)

In an attempt to assess the potential of the reinforced-recessed core design, an optimization effort was conducted using finite element models [2,3]. This study was limited to varying the layout of the recessed areas and did not consider other design parameters, such as thicker core material. The result of the study was a design which featured 6" (15.2cm) square recesses reinforced by 0.016" (0.4mm) aluminum. The recesses were arranged in a 5x5 array as shown in Fig. 22(a). The panel was only 5% heavier than the baseline, solid core, panel. This was achieved by increasing the recess depth to 1/2" (1.27cm). The 5x5 panel had a 1-2 dB advantage in TL over the 3x3 panel.
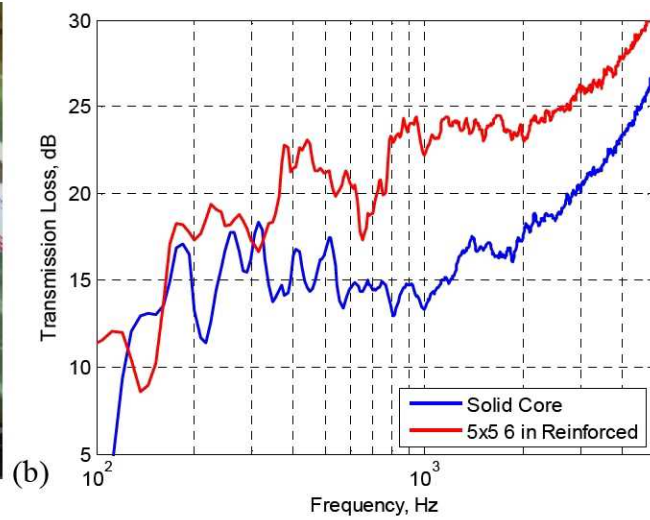
(a)

(b)

Fig. 22 Reinforced recessed core with 25 6" recesses, 0.5" deep (a), transmission loss (b) and band average difference in TL, (c). (c)

Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
3.7	7.1	7.5	4.9

D. Reinforced, fiberglass filled, 3x3 10" (25.4cm) squares, panel 20, 13.8 lbs (6.3 kg)

As the benefit of filling panel voids with fiberglass had been demonstrated on a voided core panel, the last panel in this series was a reinforced core panel with the 1/4" recesses filled with fiberglass, Fig. 23(a). Unfortunately, at the time this panel was produced, the SALT was not configured for TL tests, and only vibration tests were conducted. The resulting wavenumber spectrum, Fig. 23(b), has 5 dB less total vibration power than the 3x3 reinforced panel, and much less power around the sonic line at the higher frequencies. The fiberglass does not affect the panel's global modes at the lower frequencies.
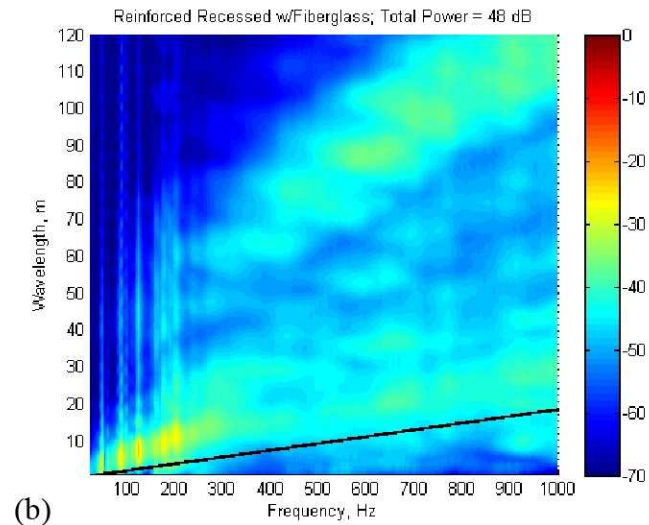

(a)

(b)

Fig. 23 Reinforced recessed core with 10 inch squares, fiberglass filled (a), wavenumber spectrum (b).

E. Comparison of recessed core panels' performance

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As TL testing was not performed on the fiberglass treated reinforced panel, the comparisons must be done in 2 phases. The first compares the available TL data of the 3x3 recessed and reinforced panels to the 5x5 panel, Fig. 24(a). The 5x5 panel achieves increases of TL of 3 dB over the 3x3 reinforced panel for 2 modes just below and above 400 Hz and 2 dB increase above 800 Hz. This increase in TL reduces as frequency increases. The improved performance of the 5x5 panel is due in part to the decrease in stiffness as discussed in the next section. The second phase compares the radiated sound power of the 3x3 panels to the solid core panel, Fig. 24(b) (note that the ordiante axis is inverted. This was done to make the results in (b) similar to transmission loss in (a)). The fiberglass treated panel tracks the untreated panel up to 600 Hz where gains of 3 dB are achieved through damping of the voids' modes.

(a)

(b)

Average Difference in TL Over Frequency Band

Panel	100-500	500-1000	1000-2000	2000-5000
3x3 Rec	5.1	9.7	11.1	7.8
3x3 Rein	3.0	6.4	5.1	4.2
5x5 Rein	3.7	7.1	7.5	4.9

(c)

Average Difference in RSP Over Frequency Band

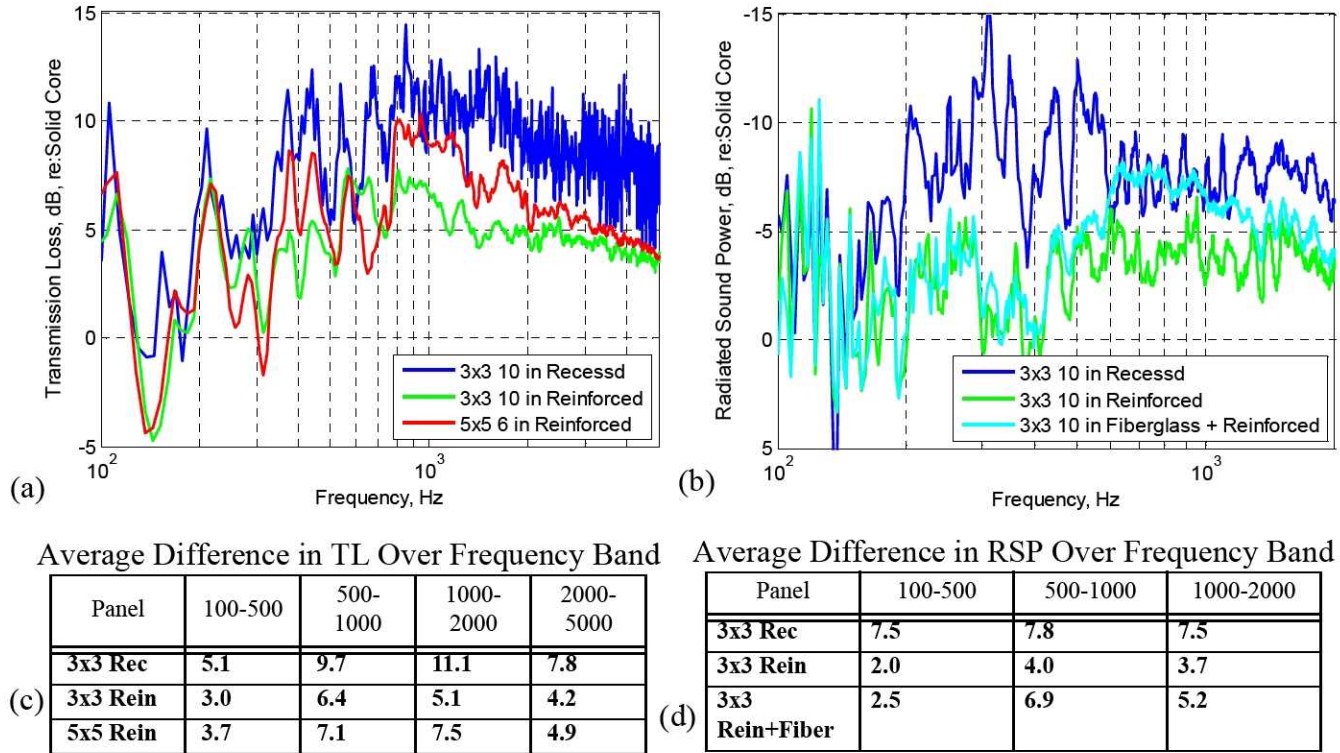| Panel	100-500	500-1000	1000-2000
3x3 Rec	7.5	7.8	7.5
3x3 Rein	2.0	4.0	3.7
3x3 Rein+Fiber	2.5	6.9	5.2

(d)

Fig. 24 Comparison of recessed core panels' performance, transmission loss (a), radiated sound power (b), band difference in TL, (c) and band difference in RSP, (d).

F. Deflection tests

An important requirement for the honeycomb panels is their ability to bear loads. As it became apparent that ample acoustic performance could be gained by milling sections of the core, attention turned to restoring the panel's load bearing ability. Finite element tests indicated that reinforcing the core recesses with thin aluminum sheets could, depending on the configuration, restore the panel's strength. To test how well the reinforcing worked, deflection tests were performed on the solid core, recessed core and reinforced core panels. The deflection tests were done at 3 points as shown in Fig. 25 on the 'external' side of the panel (unmilled side) with the panel mounted in the SALT test window. Pressure was applied through a 5 lb (22.2 N) load cell and deflection measured with a dial indicator. The results of the tests are shown in Table 1 in µ in/lb. (0.056 micron/kg). The recessed panel deflection rate is an order of magnitude larger than the solid core panel. The recessed panel may have gained transmission loss, but it lost significant stiffness. The reinforced panel deflection rates are much closer to baseline with the maximum difference occurring at point 2 which deflected 40% more than the baseline. The optimized 5x5 panel's maximum difference also occurred at point 2, but was 100% greater than baseline. Recall that the 5x5 panel recesses were twice as deep as the 3x3 panel (1/2" vs. 1/4") reducing the thickness, and, therefore, the stiffness, of the reinforced section.
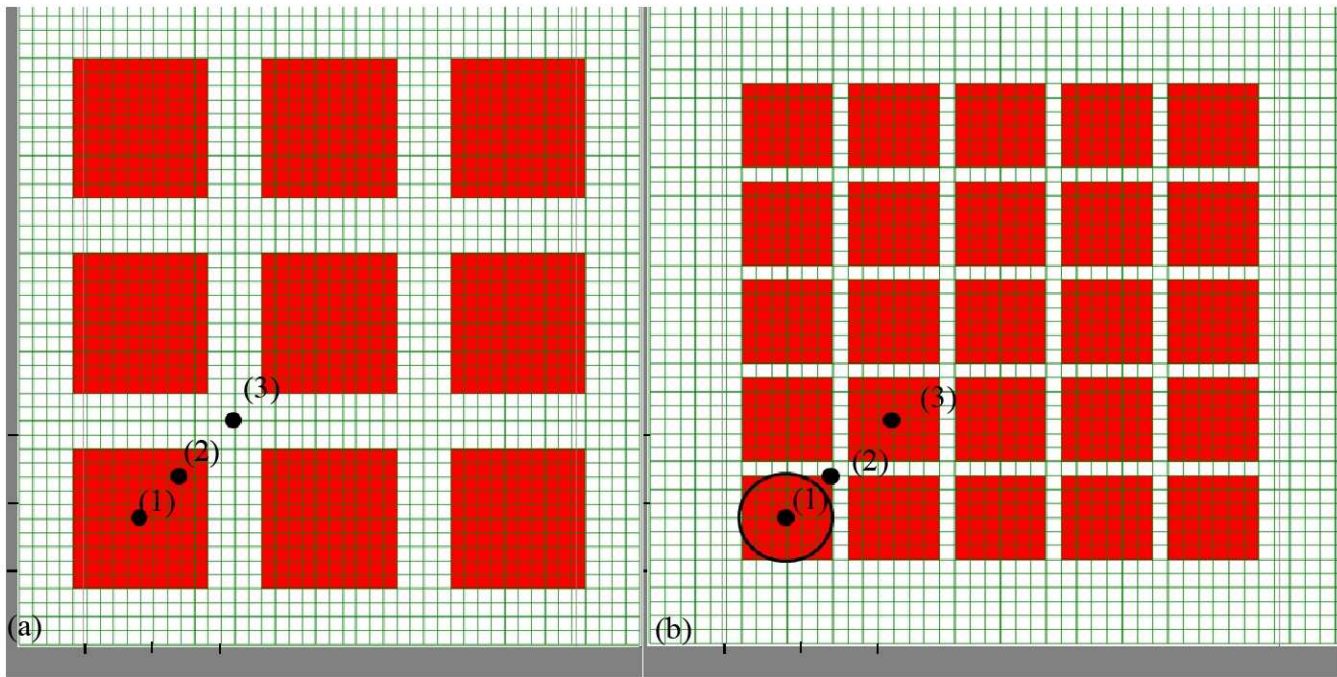
Fig. 25 Test points for deflection tests, 3x3 panels, (a) and 5x5 panels (b).

Table 1: Deflection Data

|	Pt 1 μ in/lb.	Pt 2 μ in/lb.	Pt 3 μ in/lb.
Solid Core	300	390	500
Recessed, 3x3 10"	5000	3700	1200
Reinforced, 3x3 10"	360	540	660
Optimized, 5x5 6"	560	800	950
Domed, 5x5 6"	460	450	670

V. Domed Core Panels

Previous panel features were squares which produced sharp corners and edges. This type of construction is avoided in practice because it leads to concentrations of stresses and eventually delamination of the composite. To address the issue, a series of panels were assembled with domed recessed areas.

A. 5x5 6" (15.2cm) domes, polycarbonate disks, panel 16, 13.4 lbs (6.1 kg)

This panel featured 6" (15.2cm) diameter domes cut to a maximum depth of 1/2" 1.27cm). The recesses were reinforced with polycarbonate disks made using a stereo lithography machine. This panel achieved TL behavior similar to the 3x3 10" reinforced panel with a gain in TL of about 3-5 dB over baseline above 500 Hz. The domed panel was subjected to deflection tests similar to those performed on the recessed panels, Fig. 25(b) and Table 1. The domed panel had a maximum deflection 50% greater than the baseline solid core panel at point 1, a figure comparable to the 3x3 reinforced panel and an improvement of 20%-40% over the 5x5 optimized panel.
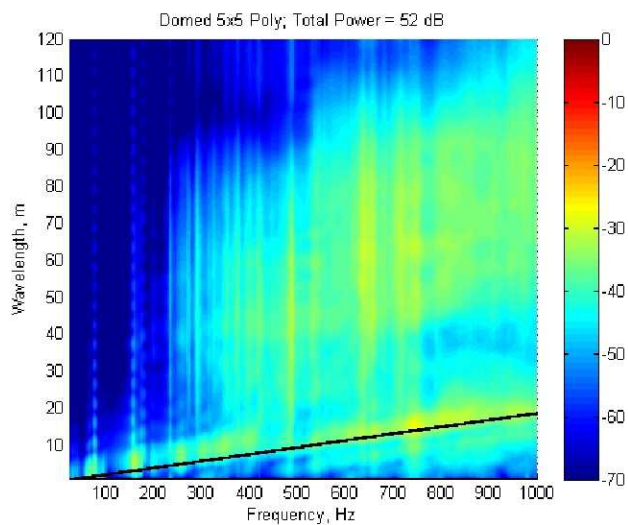

(a)

(b)
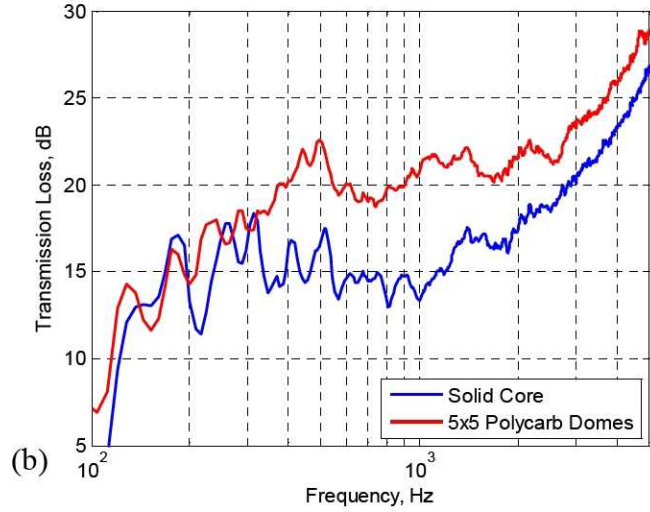
Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
2.9	5.4	4.9	2.8

(c)

Fig. 26 Reinforced recessed core with 6" domes, 0.5" deep, polycarbonate inserts (a), transmission loss (b) and band average of difference in TL, (c).

The wavenumber spectrum of the domed panel is similar to the 3x3 10" reinforced panel as well, Fig. 27. Of interest, the low frequency modes seem to be attenuated.

Fig. 27 Wavenumber spectrum of 5x5 polycarbonate domed

B. 5x5 6" (15.2cm) domes, carbon inserts, panel 17, 13.2 lbs (6.0 kg)

In an attempt to increase the stiffness of a domed panel, the polycarbonate domes were replaced with carbon fiber domes. The modification did not appreciably alter the TL. The polycarbonate panel has more TL in the range of 1-2 kHz, but less in the range 500-1000 Hz. Unfortunately deflection tests were not conducted on this panel.

(a)

(b)

(c)
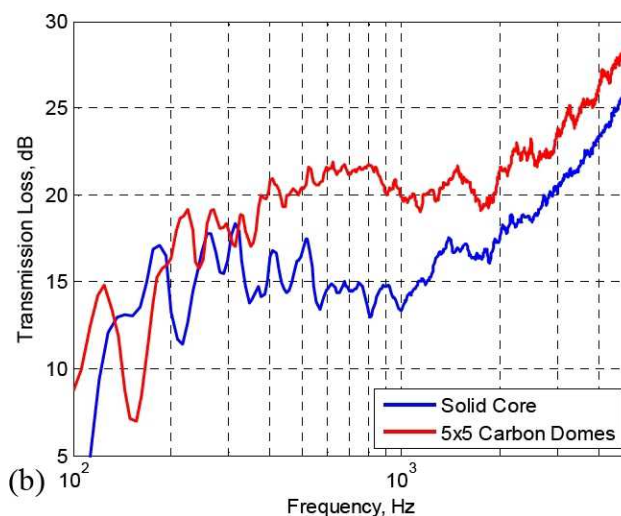
Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
2.6	6.6	3.9	3.0

Fig. 28 Reinforced recessed core with 6" domes, 0.5" deep, carbon fiber inserts (a), transmission loss (b) and band average of difference in TL, (c).
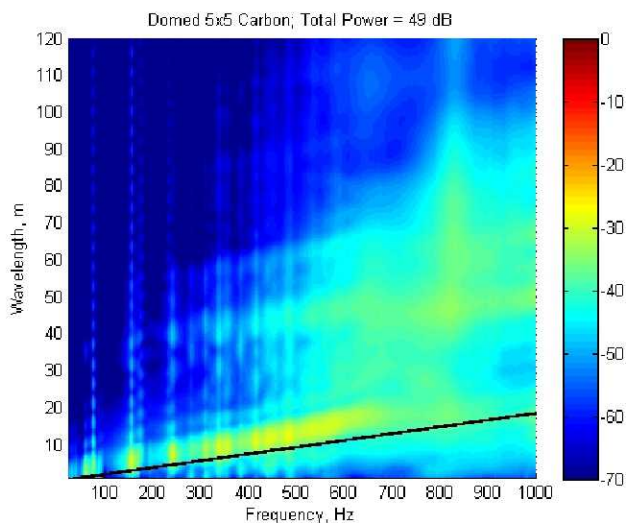
**Fig. 29 Wavenumber spectrum of 5x5 carbon domed panel.**

Looking at the wavenumber spectrum, Fig. 29, it appears that the carbon fiber inserts did increase the panel stiffness. The total vibration power in the panel is 3 dB less than the polycarbonate based panel and the low frequency modes hold more energy, but are still subsonic.

C. Staggered 6" (15.2cm) domes, carbon inserts, panel 18, 12.23 lbs (5.5 kg)

The row/column organization used for panel recesses thus far has the disadvantage that it creates fold lines along which panel modes can form. A staggered pattern was created in an attempt to disrupt the regular pattern, Fig. 30 (a). Although the panel produced marginal gains in TL, Fig. 30(b), over the other domed panels, the TL is noticeably lacking modal peaks. Performance might be increased further as this pattern is still regular along the diagonal and, thus, introduces fold lines along the diagonal axes. At this point in panel development, it became obvious that arbitrary distributions of mass and stiffness could be achieved using the reinforced/recessed approach and an optimization effort with greater degrees of freedom than had been employed thus far was necessary.

(a)

(b)

(c)
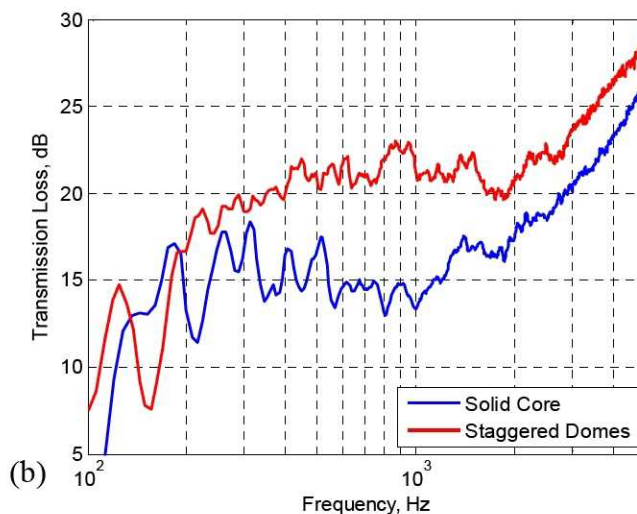
Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
3.4	7.1	4.6	3.0

Fig. 30 Reinforced recessed core, 6" carbon domes, staggered configuration (a), transmission loss (b) and band average of difference in TL, (c).
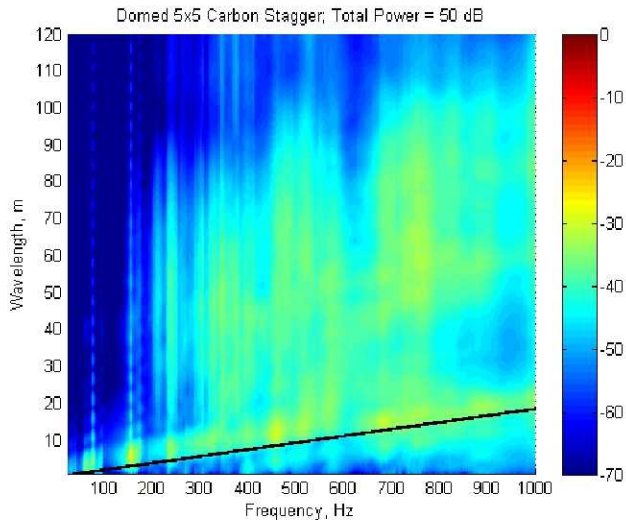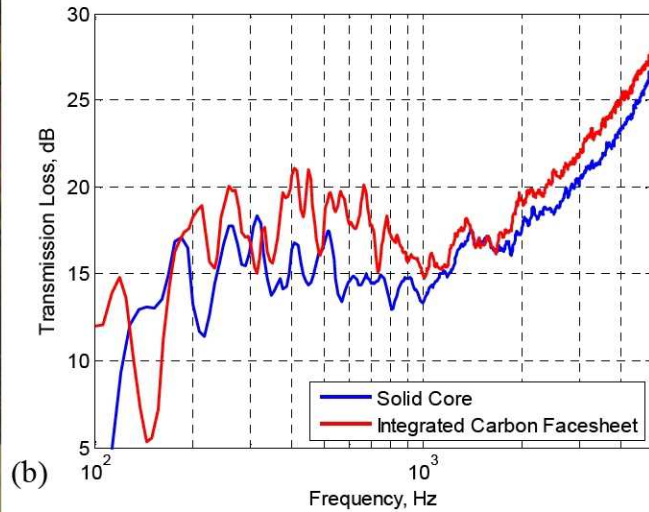
Fig. 31 Wavenumber spectrum of staggered domed panel.

The staggered panel had 1 dB more vibration energy than the carbon insert panel and had more energy scattered in the higher wavenumbers at mid-frequencies where energy was moved away from the sonic line. At high frequencies it appears more energy is concentrated around the sonic line.

D. 5x5 6" (15.2cm) domes, carbon face sheet, panel 19, 13.8 lbs (6.3 kg)

This panel was built to see if the reinforcements could be built into the face sheets. The idea was that flat aluminum discs could be placed over the recesses at a later time, completing the double wall. The face sheet was molded in carbon fiber. Unfortunately, due to a deficiency in specification, the panel was built with the carbon inserts as well. This increased the panel mass and reduced the value of the data. With the panel configured as it appears in Fig. 32(a), several dB of TL were gained over the solid core panel. This may be due to the panel being slightly less stiff and more massive resulting in a slightly lower wave speed. The panel was never tested with the flat discs installed.

(a)

(b)

Average Difference in TL Over Frequency Band			
100-500	500-1000	1000-2000	2000-5000
2.0	2.9	0.8	1.5

(c)

Fig. 32 Reinforced recessed core, 6" carbon domes, carbon face sheet (a), transmission loss (b) and band average of difference in TL, (c).
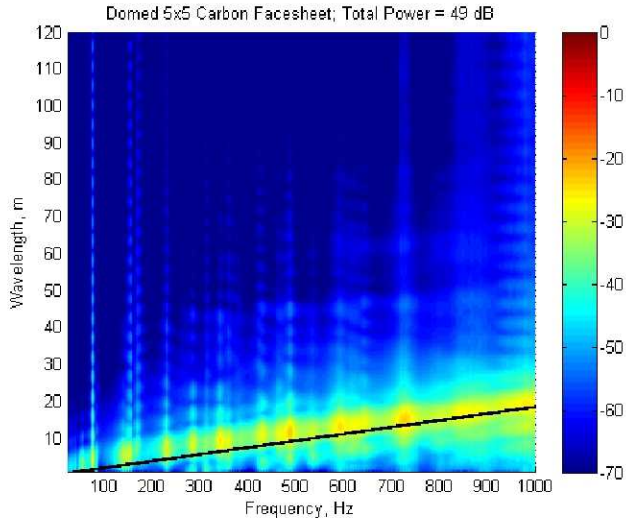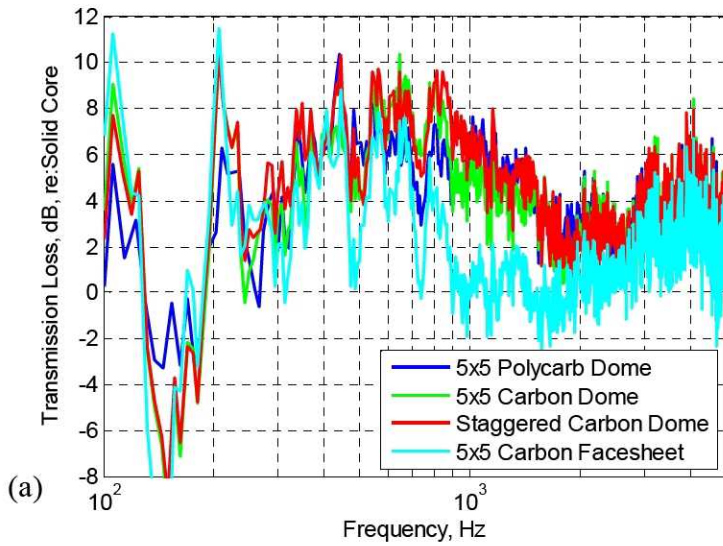
Fig. 33 Wavenumber spectrum of domed carbon face sheet
panel.

Although the panel has 3 dB more vibrational energy than the solid core panel, the TL is slightly better. Reduced stiffness and increased mass has reduced the wave speed in the panel just enough to produce lower radiation efficiencies, Fig. 33.

E. Comparison of domed core panels' performance
The TL gain of the 4 domed panels relative to the solid core panel is plotted in Fig. 34. The staggered panel appears to have a slight edge even though it has 8% less treated area. The TL performance of these panels is comparable to the 5x5 optimized panel indicating that domes can be used effectively to reduce noise radiation.

(a)

Average Difference in TL Over Frequency Band

Panel	100-500	500-1000	1000-2000	2000-5000
Polycarb	2.9	5.4	4.9	2.8
Carbon	2.6	6.6	3.9	3.0
Staggered	3.4	7.1	4.6	3.0
Face sheet	2.0	2.9	0.8	1.5

(b)

Fig. 34 Comparison of transmission loss of doomed panels with respect to
solid core panel (a) and band averaged difference in TL, (b).

VI. Particulate Damping

There is some evidence in the literature that vibration reduction can be achieved using particle damping. The most common approach is to use lightweight particles to impart damping through the motion and collisions of the particles[4]. A second approach is through radiation damping whereby the particle treatment increases the radiation efficiency of the structure[6]. A series of tests were conducted to determine if the composite honeycomb panel could be damped by including lightweight particles in the core. Two types of particles were tested. One was a microsphere made of polyimide[7] that was shown to have excellent high temperature characteristics and seemed to offer, through its viscoelastic properties, the promise of adding damping to the panel[5]. The second particle system was perlite. This material is lightweight and flame resistant. The major drawback to using these materials in sandwich core panels is confining the material during assembly. To insure a good bond between the face sheet and the core, the contacting edges of the honeycomb cells must be free of contaminates. The light weight of the particles and their tendency to take an electrostatic charge, made it difficult to assemble the last face sheet without the particles getting into the epoxy. This caused problems with several panels as will be explained in the next sections.

A. Double wall panel with microsphere filled honeycomb

As a first test of the microspheres' structural acoustic damping ability, a section of Nomex honeycomb was filled with microspheres. The microspheres were contained using a thin fabric. The resulting treatment was tested in a double wall system which was created by an 'exterior' panel of 0.020" (0.51mm) aluminum and an 'interior' panel of 0.032 (0.81mm) aluminum. The panels were 4'x4' (1.22mx1.22m) and were separated by 1" (2.54cm). The double wall system was tested for TL with an air gap and treatments of fiberglass, empty honeycomb and the microsphere filled honeycomb, Fig. 35. Of the 3 treatments, the microsphere filled honeycomb produced the lowest TL, even though it was the heaviest treatment. The difference in performance of the 3 systems can be seen to be largely due to the point at which the mass-air-mass resonance occurs as the slope of the 3 TL curves after resonance is very similar. Note that the empty honeycomb treatment actually has a double dip, one at the 'air' resonance and another presumed to be at the honeycomb resonance. The microspheres effectively eliminate the air resonance, leaving a largely structural path between the 2 panels at a higher resonant frequency.
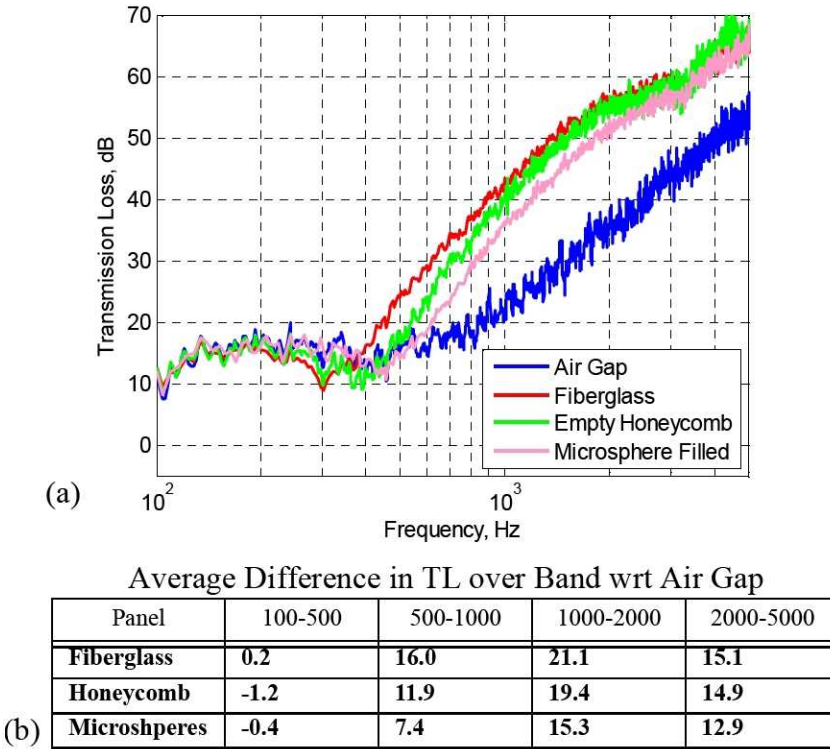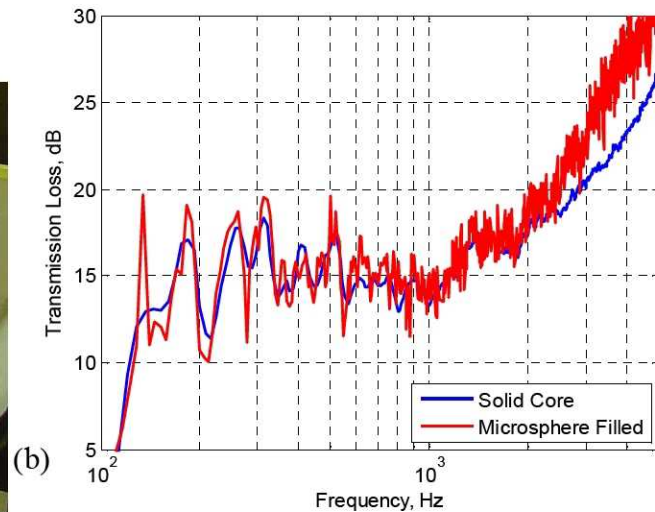

(a)

Average Difference in TL over Band wrt Air Gap

Panel	100-500	500-1000	1000-2000	2000-5000
Fiberglass	0.2	16.0	21.1	15.1
Honeycomb	-1.2	11.9	19.4	14.9
Microshperes	-0.4	7.4	15.3	12.9

(b)

Fig. 35 Transmission loss of double wall panels, (a) and band average difference in TL with respect to air gap, (b).

B. Solid core honeycomb with microsphere fill, panel 9, 13.77 lbs (6.2 kg)

Microspheres were added to a solid core panel and tested for TL. The panel exhibited little sound transmission benefit from the treatment besides a 3 dB gain in TL above 2 kHz that cannot be attributed entirely to the panel's 9% increase in mass over baseline. The carbon face sheet, domed, panel is about the same mass and gains a slight 1 dB at higher frequencies, Fig. 32(b). Significantly, the TL curve of the carbon face sheet panel is parallel to the baseline curve, implying the gain is solely due to the increased mass. The high frequency TL of the microsphere treated panel has an increased slope compared to baseline, indicating a different mechanism at work.

(a)

(b)

Average Difference in TL Over Frequency Band

100-500	500-1000	1000-2000	2000-5000
0.1	0.5	0.3	3.3

(c)

Fig. 36 Honeycomb filled with microspheres (a), transmission loss (b) and band average difference in TL, (c).

C. Solid core honeycomb with Perlite fill.

The perlite was very difficult to work with. It not only polluted the epoxy but absorbed moisture from the air, drastically increasing its mass.

Fig. 37 NASA panel with Perlite treatment about 40% complete.

1. NASA panel, panel 12, 17.8 lbs (8.1 kg)

Great pains were taken in assembling this panel to ensure that the honeycomb edge was clean and a good bond to the second face sheet could be obtained. However, this meant that the perlite treatment was exposed to air in an uncontrolled environment for a long time. As a result, the finished panel was 40% heavier than baseline. The added mass reduced the value of any data taken from the panel to the point where no further tests were done.

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Fig. 38 Rocketdyne panel with 30% Perlite fill. Area of unbonded face sheet detailed.

2. Rocketdyne panels, panels 21-23

Pratt and Whitney Rocketdyne had experience assembling honeycomb panels treated with perlite and were contracted to build 3 panels to test the effectiveness of a uniformly applied treatment and an optimally applied treatment. Rocketdyne had access to hydrophobic perlite which was said to reduce the material's tendency to absorb moisture. Unfortunately, they were not careful to avoid epoxy contamination as all the panels had severe face sheet bonding defects (e.g., Fig. 38) that made the data taken from the panels difficult to interpret.

VII.   Patents

As of this writing there are 2 outstanding patent applications on this technology. Patent application, "Composite panel having subsonic transverse wave speed characteristics", was submitted in May 2005 and deals primarily with the voided and recessed core designs. Patent application, "Composite panel with reinforced recesses", was submitted November 2007 and covers all the variants of the reinforced panels.

VIII.   Conclusions

The reinforced/recessed panel design has shown promise. It has been demonstrated that substantial noise reduction can be obtained while panel strength and mass are maintained. The ultimate utility of this design approach depends on how well the panel features can be optimized for a particular application's requirements. The optimization performed thus far did not encompass the entire design space. For example, panel thickness was not varied from one design to the next and feature shape and orientation were uniform for each design. It is believed that the 'embedded double-wall' design will always return increased TL.

IX.   References

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14. ABSTRACT

Sandwich honeycomb composite panels are lightweight and strong, and, therefore, provide a reasonable alternative to the aluminum ring frame/stringer architecture currently used for most aircraft airframes. The drawback to honeycomb panels is that they radiate noise into the aircraft cabin very efficiently provoking the need for additional sound treatment which adds weight and reduces the material's cost advantage. A series of honeycomb panels were made which incorporated different design strategies aimed at reducing the honeycomb panels' radiation efficiency while at the same time maintaining its strength. The majority of the designs were centered around the concept of creating areas of reduced stiffness in the panel by adding voids and recesses to the core. The effort culminated with a reinforced/recessed panel which had 6 dB higher transmission loss than the baseline solid core panel while maintaining comparable strength.

15. SUBJECT TERMS

Transmission loss; Wavenumber spectrum; Voided core; Recessed core

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