Wave speeds of honeycomb sandwich structures: An experimental approach

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Abstract: In this study, the influence of different design parameters, such as core density, core material, and cell size on the wave speeds of honeycomb sandwich structures was experimentally analyzed. Bending and shear wave speeds were measured and related to the transmission loss performance for various material configurations. The shear modulus of the core showed maximum influence on the wave speeds of the samples, while cell size did not have a significant influence on the wave speeds or on the transmission loss. Skin material affected wave speeds only in the pure bending regime. Honeycomb sandwich structures with a subsonic core and reduced wave speed showed increased transmission loss compared to samples without a subsonic core.

Key words: Wave speeds; Honeycomb; Noise control; Transmission loss

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1. Introduction

Lightweight honeycomb (HC) sandwich structures are used in a wide variety of applications where high stiffness and low weight is desired. These structures typically feature orthotropic HC cores bonded to high-modulus laminate skins. HC sandwich structures are designed for mechanical performance, but generally have poor acoustical performance because they are optimized for high

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stiffness and low weight. As a result, approaches are sought to improve acoustical performance without compromising the mechanical performance of the structures [1], [2] and [3].

Basic understanding of wave speed characteristics of HC sandwich structures provides useful insight for noise control solutions. For example, knowledge of the frequency-dependent wave speed is useful for designing noise control solutions for a given load-bearing structure [4]. Furthermore, Davis analyzed the wave-speed dependence of transmission loss (TL) for HC panels and concluded that the key to increasing the TL of HC panels was to achieve a subsonic bending wave speed (e.g., two-thirds the speed of sound) for the greatest possible frequency range [5]. Such reports indicate the potential utility of wave speed data for differentiating various damping treatments and other means of noise mitigation.

HC sandwich structures exhibit frequency-dependent dynamic behavior that influences the structural response to acoustic excitation [6]. The wave speeds are controlled in different frequency regimes by different components of the structure. There are three distinct regimes – pure bending, core shear, and face sheet bending – each associated with different frequency ranges [7]. Pure bending of the entire structure occurs at low frequencies and is controlled by stiffness and resonance. Core shear occurs at mid-frequencies and is mass-controlled. At higher frequencies, face sheet bending occurs, and this region is controlled by wave coincidence and stiffness. The wave speed in the structure does not abruptly change from one regime to the next as frequency changes. For aerospace applications, the primary concern lies in the low-to-mid-frequency ranges. Therefore, in the present study we focus on bending and shear wave speeds.

Sound transmission loss is one of the primary metrics used to evaluate the acoustical performance of honeycomb sandwich structures. Transmission loss (TL) is defined as the difference between incident energy and the transmitted energy through a material or structure – it is also an indication of the acoustic performance of the material as a noise barrier between two spaces. Klos et al. demonstrated the acoustical benefit, as measured by transmission loss, of reducing the wave speed for transverse vibration in HC sandwich panels [8]. Rajaram et al. observed that core shear wave speed has a strong influence on transmission loss [2]. Davis performed statistical energy analysis on HC structures and concluded that radiation efficiency is a function of the bending wave speed in the structure [5]. These findings demonstrate a need to validate the analytical predictions through systematic measurements of wave speeds in HC structures.

Although wave speeds can be calculated using various approaches, measurements of wave speeds are rarely reported because of the associated experimental difficulties. Possible approaches to measuring wave speeds include: (1) direct measurement of a wave over a period of time and (2) propagation phase measurements [9]. However, these methods involve inherent limitations because bending waves are dispersive and it is difficult in practice to distinguish which wave (bending or shear) is being measured. Furthermore, the reverberant vibration field interferes with direct measurements [4]. The wave-speed measurement method employed in the present study allows one to distinguish the wave being measured. In addition, propagation phase measurements are not used, thus avoiding the influence of the reverberant vibration field.

The purpose of this work is to validate the influence of wave speeds, particularly shear wave speeds, on the transmission loss of HC panels predicted by the analyses of both Kurtze and Watters [10] and Davis [5]. In this study, we measure the bending wave speeds of HC structures with different design parameters and distinguish the transition between panel bending and shear wave motion. The wave

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speeds for the HC structures are then compared to previously published TL measurements performed on identical structures.

2. Experimental set-up

2.1 Method

Wave-speed measurements were performed on HC beams using the modal approach. A shaker (Bruel & Kjaer Type 4810) was used to excite the beams with a random noise signal. An impedance head was attached to the shaker to measure the input force, and a laser vibrometer (Bruel & Kjaer Type 8329) was used to collect velocity data along the surface of the beams. The beam vibration velocity was measured at 64 equally spaced locations along the beam. The schematic of the test apparatus is shown in Fig. 1. Suspending the beams from the supporting structure with lightweight string simulated the free–free boundary condition [11]. A homogenous aluminum reference beam was tested to calibrate the measurement set-up. The predicted values were calculated using Eqs.(1a) and (1b)[12] where f_i is the natural frequency for mode number i, λ_i is a constant based on the mode number, L is the length of the beam, E is the modulus of elasticity, I is the area moment of inertia of beam about the neutral axis, and m is the mass per unit length of beam. The measured natural frequencies of the reference beam were within 3–5% of calculated values, as shown in Table 1. The difference between the calculated and measured modes increased as the frequency increased, with the exception of modes 14–16, where the measured modes were at higher frequencies than predicted. These high-frequency anomalies occurred at conditions that approached limitations of the test apparatus. However, most of the results reported here involved frequencies less than 3000 Hz, significantly less than the region of uncertainty. Thus, these instrumental limitations did not significantly influence the results or conclusions.

$$f_i = \frac{\lambda_i^2}{2\pi L^2}\left(\frac{EI}{m}\right)^{1/2}$$
$$\lambda_i = 1, 2, 3\ldots \tag{1a}$$

$$\lambda_1 = 4.73004074$$
$$\lambda_2 = 7.85320462$$
$$\lambda_3 = 10.9956078$$
$$\lambda_4 = 14.1371655$$
$$\lambda_5 = 17.2787597$$
$$i > 5 \Rightarrow (2i+1)\frac{\pi}{2} \tag{1b}$$

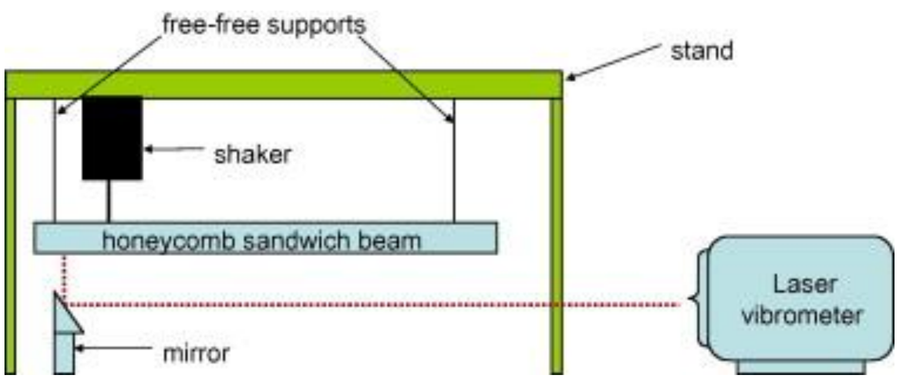

Fig. 1. *Schematic of experimental set-up.*

Table 1. *Calculated and experimentally obtained mode numbers for the aluminum reference beam.*

Mode number	Calculated mode (Hz)	Actual mode (Hz)	Difference (%)
1	80.60	78.10	3.1
2	223.9	215.6	3.7
3	438.8	425.0	3.1
4	725.3	703.1	3.1
5	1084	1047	3.4
6	1513	1488	1.7

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Mode number	Calculated mode (Hz)	Actual mode (Hz)	Difference (%)
7	2015	1959	2.8
8	2588	2500	3.4
9	3233	3109	3.8
10	3949	3778	4.3
11	4737	4503	4.9
12	5597	5284	5.6
13	6528	6128	6.1
14	7531	7966	−5.8
15	8606	8959	−4.1
16	9752	9997	−2.5

Modal analysis is based on the relationship between the modal shape and the wavelength, which is equal to wave speed divided by frequency. A simple formula relates the speed of both bending and core shear waves to the measured *n*th resonance frequency, f_n, for a beam of length L, as shown in Eq. (2). Thus, for example, if the 3rd mode occurred at 453 Hz for a beam of length 0.927 m, the wave speed at the 3rd resonant frequency would be 280 m/s.

$$c(f_n) = \frac{2 f_n L}{n} \tag{2}$$

A critical aspect of modal analysis measurements is measuring both the modal shape and the vibration spectrum. The modal shape identifies the modal orders of the individual modal frequencies and serves as a means to monitor and distinguish the desired wave types (i.e., bending and shear modes as opposed to torsional modes). The utility of the modal analysis method diminishes at frequencies above 3 kHz, where it becomes difficult to distinguish individual modes.

2.2 Materials

The material properties and dimensions of the eight commercial-grade HC beam samples are listed in Table 2, where $\boldsymbol{\rho}_{c}$ is the core density, $\boldsymbol{t}_{c}$ is the core thickness, $\boldsymbol{\rho}_{sk}$ is the density of the skin material, $\boldsymbol{t}_{sk}$ is the skin thickness, $\boldsymbol{G}_{c}$ is the core shear modulus, and $\boldsymbol{E}_{sk}$ is the elastic modulus of the skin material. Beams A–D and SSS-2 featured composite skins of carbon fiber/phenolic, while beams F–H featured composite skins of glass fiber/epoxy. All beams featured hexagonal HC cores made from a pararamid fiber paper (Nomex®), except for beams D and H, which featured cores made of an aramid fiber paper (Kevlar®). Beam SSS-2 was designed with a thinner core and thicker facesheets compared to the other samples to achieve a subsonic shear wave speed (two-thirds the speed of sound). This beam was tested to validate the predictions of Davis[5] and to compare with the results of Rajaram [2]. The 6061-T6511 aluminum reference beam was 914.4 × 50.8 × 12.7 mm. The HC sandwich beams were 927.1 mm long, 50.8 mm wide, and 10.2 mm thick. Narrow beams were chosen to facilitate identification of modal shapes and measurements.

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__Table 2.__ Dimensions and material properties of honeycomb sandwich beams.

Panel	Skin	Core	Cell size (m)	$\boldsymbol{\rho}_c$ (kg/m^3)	$\boldsymbol{t}_c$ (m)	$\boldsymbol{\rho}_{sk}$ (kg/m^3)	$\boldsymbol{t}_{sk}$ (m)	$\boldsymbol{G}_c$ ($\times 10^6$ Nm^{-2})	$\boldsymbol{E}_{sk}$ ($\times 10^9$ Nm^{-2})
A	Carbon	Nomex	0.004	144	0.0096	1600	0.0003	108	100
B	Carbon	Nomex	0.003	80	0.0096	1600	0.0003	63	100
C	Carbon	Nomex	0.003	48	0.0096	1600	0.0003	32	100
D	Carbon	Kevlar	0.004	72	0.0096	1600	0.0003	115	100
F	Glass	Nomex	0.004	144	0.0096	1900	0.0003	108	20
G	Glass	Nomex	0.003	48	0.0096	1900	0.0003	42	20
H	Glass	Kevlar	0.004	72	0.0096	1900	0.0003	115	20
SSS-2	Carbon	Nomex	0.004	28.8	0.0087	1600	0.0006	18	100

3. Results and discussion

3.1 Modal analysis

The wave speeds were measured for two categories of sandwich structures – one with carbon laminate skins and the other with glass fiber laminate skins. Within each category, simple core parameters, including core density, cell size, and skin material, were varied to determine the effects on wave speeds. In addition to the two primary categories, a subsonic panel was produced to test the analytical predictions of Davis and to compare with the TL measurements reported by Rajaram [2] and [5]. The wave speeds were plotted with respect to Mach speed to illustrate differences between the subsonic and supersonic samples. The speed of sound in air was assumed to be 1234.8 km/h to normalize the wave speeds to the Mach speed.

The wave speeds of the beams with carbon skins and HC cores of different density and materials are presented in Fig. 2. The samples all exhibit increases in wave speed with increasing frequency, which is indicative of bending waves. Bending waves are dispersive and the wave speeds exhibit a parabolic dependence on frequency, while shear waves are non-dispersive and exhibit a linear dependence [4]. The Sample SSS-2 exhibits a transition from a parabolic dependence to a linear dependence at frequencies above 1500 Hz. Therefore, the transition from bending to shear waves for the Sample SSS-2 was identified by the point on the wave speed versus frequency plot where the parabolic dependence changed to a linear dependence. Samples A–D exhibited a continuous parabolic curve, indicating that bending wave speeds occurred for frequencies below 3000 Hz. These results are consistent with predictions that the bending to shear wave speed transition for similar specimens occurred at ∼3500 Hz [4].

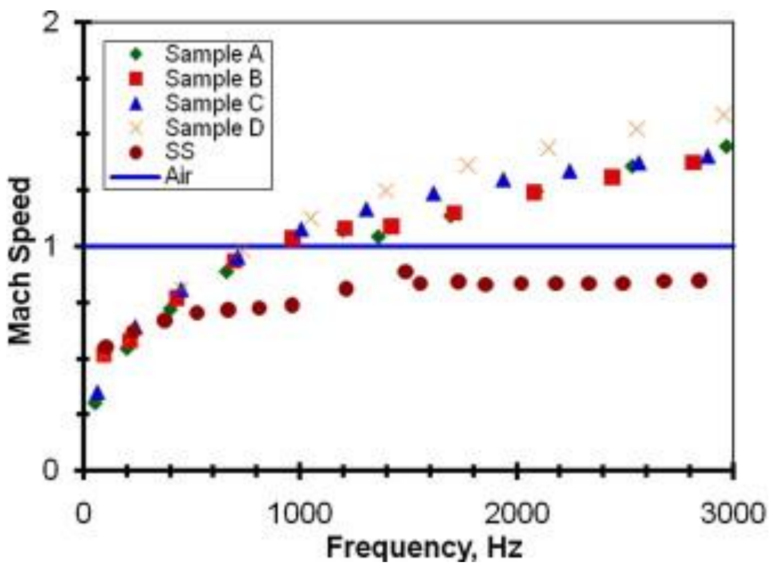

__Fig. 2__. Wave speeds normalized to Mach speed of beams with carbon fiber laminate skins and honeycomb core.

The results presented in Fig. 2 show that the core shear modulus strongly affected the wave speed trends. The influence of the core material was evaluated by comparing Sample D, constructed with the high-shear-modulus Kevlar® core, to Samples A–C, which featured Nomex® cores, which exhibited relatively lower shear moduli. In general, cores with higher shear moduli yield higher wave speeds [2]. The wave speeds for Sample D were greater than those of Samples A–C. The subsonic core of Sample SSS-2 had the lowest core shear modulus and thus exhibited the slowest wave speeds of this group of samples. On the other hand, Sample D (with the high-modulus Kevlar core) displayed the fastest wave speeds. Samples A, B and C had intermediate values of core shear moduli, and yielded wave speeds that were intermediate between those of Samples D and SSS-2. The wave speed values for Samples A–C were similar even though their shear moduli were 108×10^6 Nm^{-2}, 63×10^6 Nm^{-2}, and 32×10^6 Nm^{-2}, respectively, because the transition from panel bending regime to core shear regime did not occur within the measured frequency range. The skin and core thicknesses for these samples were identical. Therefore, in this frequency range, the wave speeds would also be similar regardless of the shear moduli of the cores.

Samples A and B were analyzed to determine the influence of core cell size on wave speeds. Sample A had a larger cell size and higher core density compared to Sample B. The wave speeds for these samples were similar across the frequency range tested. The results led to the conclusion that core cell size did not have a significant effect on wave speed.

The wave speeds of the second family of three beams with glass fiber laminate skins and honeycomb cores are shown in Fig. 3. Samples A–D featured carbon fiber laminate skins and showed steeper

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slopes for wave speeds at low frequencies and approached Mach speeds at ∼700 Hz. In comparison, the wave speeds of Samples F, G and H, which featured glass fiber laminate skins, showed lower slopes and approached Mach speeds at frequencies greater than 1000 Hz. Samples F, G and H had cores comparable to Samples A–D, and all panels had the same dimensions, from which we infer that the skin material strongly influenced the wave speed at low frequencies. In particular, the stiffer carbon laminate skins resulted in higher wave speeds compared to the glass fiber laminate skins. The wave speeds in Fig. 3 also showed a parabolic shape, which indicates bending waves for Samples F, G, and H. The panel bending regime controlled wave speeds in this range, and consequently the wave speed values were similar despite the different core shear moduli.

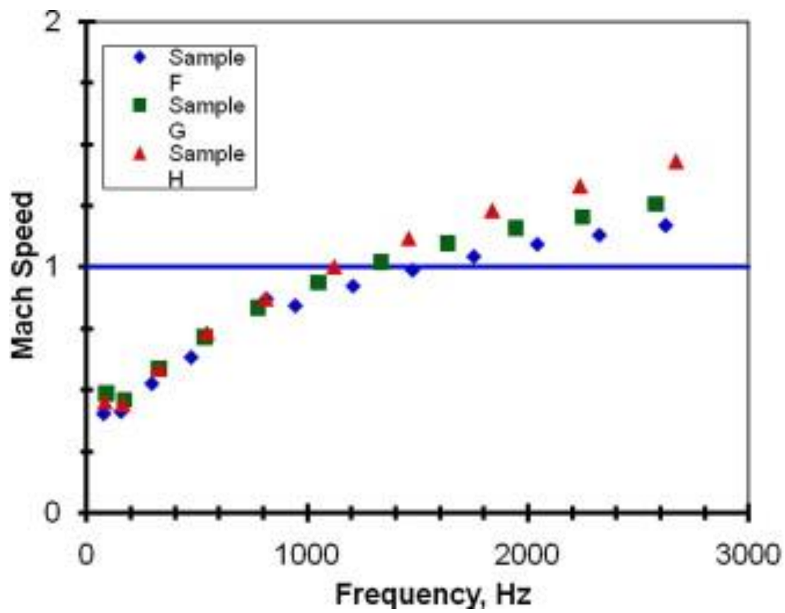

Fig. 3. *Wave speeds normalized to Mach speed of beams with glass fiber laminate skins and honeycomb core.*

Samples F and G were evaluated to assess the influence of core cell size on wave speeds. Sample F had a larger cell size and higher core density compared to Sample G. The wave speeds for these samples were similar across the frequency range tested. The results indicate that the cell size did not

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significantly affect wave speeds. These results were consistent with results from the carbon skin samples.

Samples F and H were also considered to assess the influence of core material on wave speeds. Sample F consisted of a Nomex core, while Sample H had a Kevlar core. The wave speeds for Sample H were greater than the wave speeds for Sample F, indicating that higher core shear modulus results in faster wave speeds. The wave speeds were similar for Samples F and G although the shear moduli of the cores were different.

The difficulty in differentiating modal shapes at frequencies above 3000 Hz was a limitation of the modal analysis method. Consequently, this method had a limited frequency range and the transition from bending to shear wave speeds for the samples could not be measured using this method as that transition occurs around 3200 Hz or higher. Sample SSS-2 was the exception to this limitation because the subsonic core caused a bending to shear wave speed transition at a lower frequency that occurred within the scope of this method.

3.2 Transmission loss

The wave speed characteristics of honeycomb sandwich structures are closely linked to the sound transmission loss characteristics. Rajaram et al. measured the transmission loss for the same set of honeycomb sandwich structures in Table 1[2]. Fig. 4 shows the transmission loss for the panels with carbon skins and Fig. 6 displays the transmission loss for the panels with glass skins. Because the mass of the panels varied, the performance was evaluated using the mass law deviation (MLD), defined as the difference between the measured transmission loss and the mass law predicted transmission loss. A positive or higher value for MLD indicates superior acoustical performance, while a negative or lower value for MLD indicates inferior acoustical performance. These plots are displayed in Fig. 5 and Fig. 7 for carbon and glass skins, respectively. There was little variation in the MLD values for the supersonic samples. However, the MLD for the subsonic sample was significantly greater than those of the supersonic samples, while the wave speeds were significantly lower. Core cell size and skin material had negligible effects on the measured values of TL and wave speed.

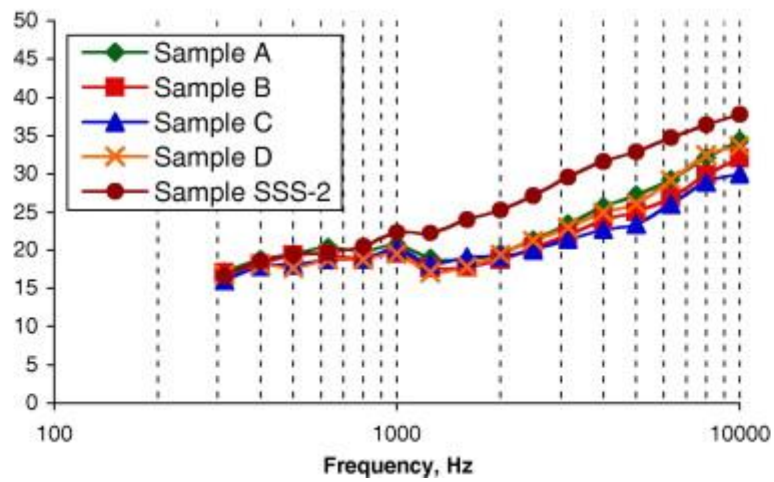

Fig. 4. *Transmission loss of panels with carbon fiber laminate skins and honeycomb core [6].*

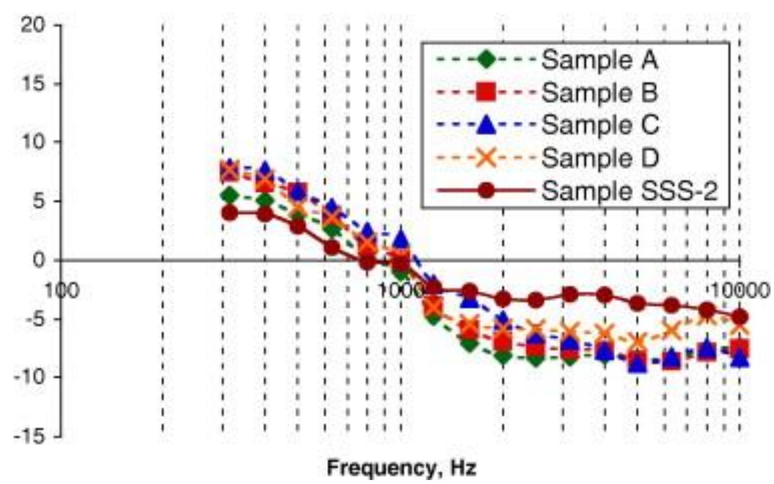

Fig. 5. *Mass law deviation (MLD) of panels with carbon fiber laminate skins and honeycomb core [6].*

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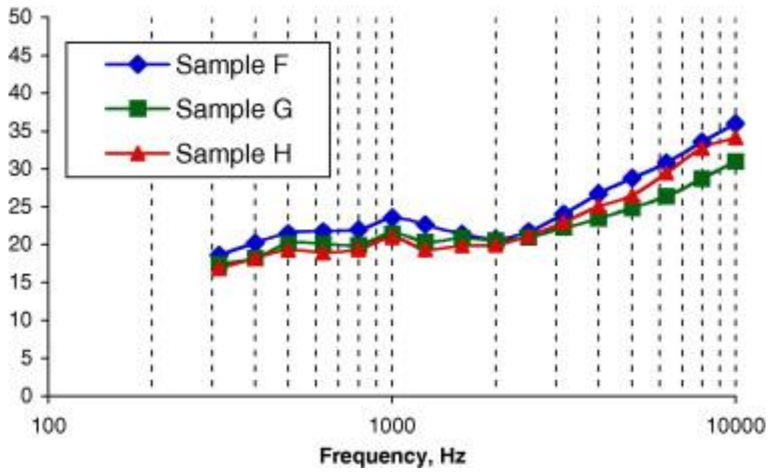

Fig. 6. *Transmission loss of panels with glass fiber laminate skins and honeycomb core [6].*

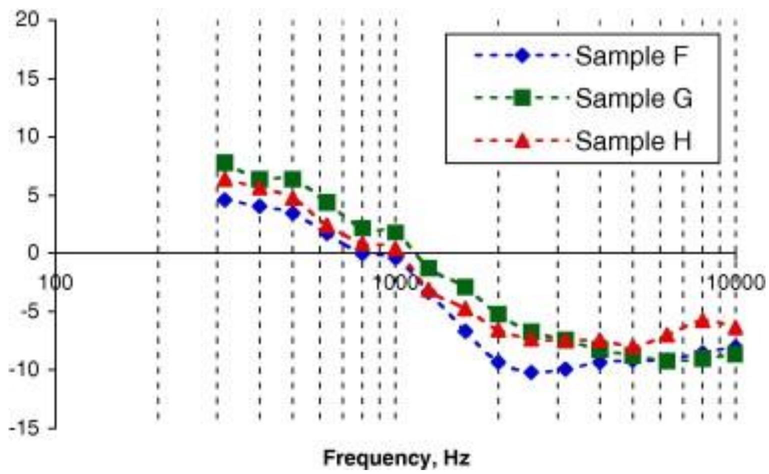

Fig. 7. *Mass law deviation (MLD) of panels with glass fiber laminate skins and honeycomb core [6].*

The transmission loss measurements on similar panels resulted in several key findings [2]. (1) Core density and transmission loss were inversely related-as core density increased the transmission loss decreased. The comparison between Samples A and C (carbon skins) and Samples F and G (glass skins) demonstrated this relationship. (2) Samples with high-shear-modulus Kevlar cores (Samples D and H) showed higher TL values at higher frequencies than the samples with Nomex cores. (3) Skin material did not significantly influence the panel TL. (4) Varying the cell size also did not significantly influence the panel TL. (5) The subsonic core of Sample SSS-2 displayed the highest transmission loss of all samples.

The present wave-speed measurements are closely aligned with previously reported TL measurements [2]. Overall, transmission loss increases with reduced wave speeds, particularly when the wave speeds are reduced to subsonic levels, which can be achieved by decreasing the shear modulus of the core. This phenomenon is best illustrated by the behavior of the panel with the subsonic core (Sample SSS-2), in which the transition from bending wave speeds to shear wave speeds occurred at a lower frequency than the supersonic samples. This low-frequency transition accounts for the superior transmission loss performance of Sample SSS-2. By shifting the transition to shear wave speeds to a lower frequency, the coincidence frequency is shifted to higher frequency. Past studies have shown that delaying the onset of the coincidence frequency also reduces the acoustic radiation from the panel [5].

4. Conclusion

The influence of core type, skin type, and cell size of HC sandwich beams on acoustic wave speed was experimentally evaluated. The shear modulus of the core showed maximum influence on the wave speeds of the samples, while cell size did not have a significant influence on the wave speeds or on the transmission loss. For sandwich structures with comparable core and skin thickness, the skin modulus influenced the wave speeds at low frequencies. For example, samples with carbon fiber laminate skins approached the Mach speeds at about 700 Hz, while structures with glass fiber laminate skins approached Mach speeds at frequencies above 1000 Hz. These observations are

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consistent with the Kurtze and Watters model [10], which predicts that bending motion of the panel controls the wave speed at lower frequencies. The sample with the subsonic core displayed the slowest wave speeds and a transition from bending to shear wave speeds at 1500 Hz. In comparison, the samples with supersonic cores showed transitions to shear wave speed at 3000 Hz or greater.

This work experimentally demonstrates that HC cores with lower shear modulus values translate into slower wave speeds and superior acoustical performance. These results validate the analytical predictions of Davis [5], whose work was based on the Kurtze and Watters model [10], that TL can be increased by designing HC structures with reduced shear wave speeds. The results are also consistent with the TL measurements of identical HC structures with subsonic cores [2]. The subsonic core showed a major difference in acoustical performance and can be used to improve the design process for commercial aircraft, automotive interiors, and other applications where lightweight yet quiet features are required.

The experimental set-up used for this study offers a potential alternative method for evaluating the acoustic properties of honeycomb sandwich structures. The results demonstrate a direct correlation between wave speed and transmission loss for HC structures. Although additional work is required to more fully quantify the TL predictions based on wave speed data, the method described here for measuring wave speeds can potentially replace more expensive and space-consuming anechoic chambers as a means for measuring acoustic behavior. The method also provides a cost-effective and practical substitute for acoustic measurements in impedance tubes.

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