Airborne Noise Flanking of Shipboard Vibration Isolation Systems

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Theoretical and antidotal results on quiet research vessels indicate that airborne noise flanking of machinery isolation systems adversely affects their underwater radiated signature. This is especially true for diesel-generator drive systems installed on two-stage isolation mounts. Airborne noise from the diesel impinging on the nearby hull and tank structure may become a significant factor of radiating underwater energy. This path and potential methods of minimizing its impact are discussed with respect to two-stage isolation systems. Airborne noise flanking is discussed for systems with open- and closed-bottom intermediate rafts and for a totally enclosed genset.

Research vessels built to stringent underwater-radiated noise standards usually have diesel-electric propulsion drive systems. These research vessels can be deployed for fish stock assessment or for bottom mapping using sophisticated sonar systems. The electric motor is a low noise and vibration source that drives a specially designed, large, and slow-turning propeller. The power comes from two-stage isolation mounted diesel-generators or gensets. This combination of machinery can be treated along with the use of hull insulation and damping to such an extent that the acoustic energy reaching the wetted hull is minimized.

This article covers how airborne noise flanking affects the vibration effectiveness of two-stage-isolation gensets on three vessels – NATO's R/V *Alliance*[1], NOAA's FRV *Bigelow*[2], and the University of Delaware's R/V *Sharp*.[3] The 93-m *Alliance* was built to underwater noise standards developed by NATO for an acoustic research vessel. The 64-m *Bigelow* (Figure 1) and 44-m *Sharp* (Figure 2) were built to a radiated noise standard developed by the International Council for the Exploration of the Seas[4] (ICES) for vessels used for stock assessment of fisheries. In this case, the vessel's radiated noise is low enough so as to minimize fish reaction to provide accurate counts. The genset parameters for each vessel are provided in Table 1.

A simple drawing of the genset mounting system used on the *Bigelow* is shown in Figure 3 and the actual set-up for testing is shown in Figure 4. For this case, each of the four intermediate masses was specified to be 10% of the mass of the diesel/generator system. The vessel has been designed, built and delivered[5] to meet the stringent radiated underwater noise standards set by the International Council for the Exploration of the Seas (ICES).

Figure 1. NOAA Fisheries Research Vessel Bigelow.

Figure 2. University of Delaware Research Vessel Hugh R. Sharp.

Airborne Flanking Theory

Figure 5 shows the various paths for acoustic energy from an isolation-mounted diesel to get into a ship's structure. (In this figure, the diesel is shown to be single-stage isolation mounted, not two-stage isolation mounted, as is the subject of this article.) The most obvious path is the "first structure-borne path" or structural vibration path through the attachment point of the diesel to the ship's foundation. Energy transmitted through this path is reduced by the use of single- or double-stage isolation, depending on the acoustic source level of the diesel and the underwater radiated goals to be achieved. The other path, which becomes more critical as the mounting system becomes more effective, is the "second structureborne path." This path covers vibration transmitted to the ship's structure by incident airborne noise. This vibration gets combined with vibrations from the first structureborne path and can be transmitted throughout the vessel or radiated into the water.

As with excitation of the hull by incident airborne noise, the tank top (structure in the immediate vicinity of the diesel engine) can be excited by noise from the engine. With any two-stage mount system, there is a potential for airborne noise flanking that bypasses the mounts and directly excites the foundation and ship's structure.[6-8] Reference 7 shows that the ratio of power transmitted to the base via the airborne path P_a to that transmitted through the mounting system P_m is com-

Table 1. Genset design parameters.

Vessel	Genset	Power, kW	rpm	Genset Wt, t	Raft Wt, t	Vert Nat Freq, Hz
Alliance	GMT B230	2040	1200	28.9	20	3.9
Bigelow	Cat 3512	1360	1800	15.7	6.3	5.2
	Cat 3508	910	1800	11.9	4.8	4.9
Sharp	(2) Cummins KTA 19	460	1800	8.9	5	4.3

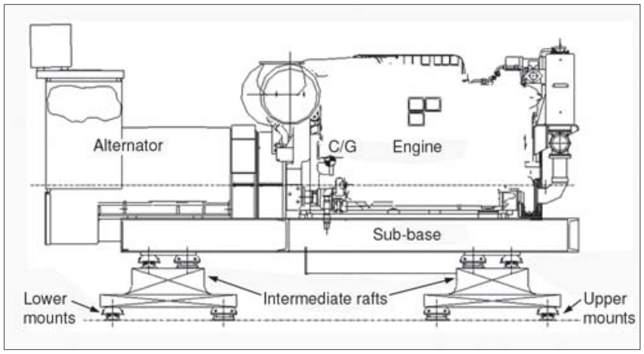

Figure 3. CAT 3512 two-stage design, Bigelow.

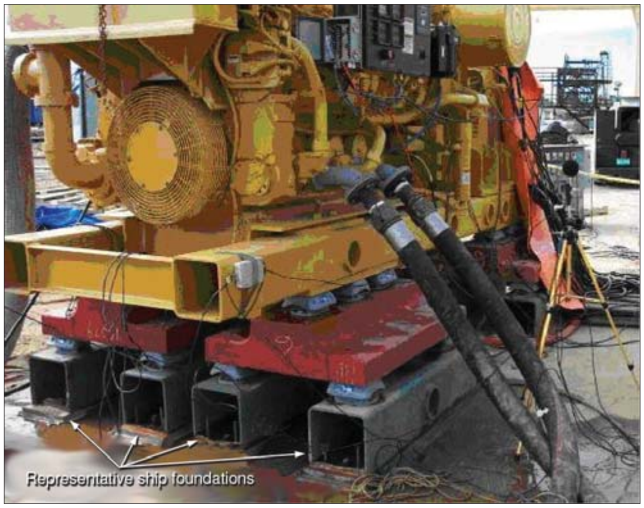

Figure 4. Factory test of genset installation.

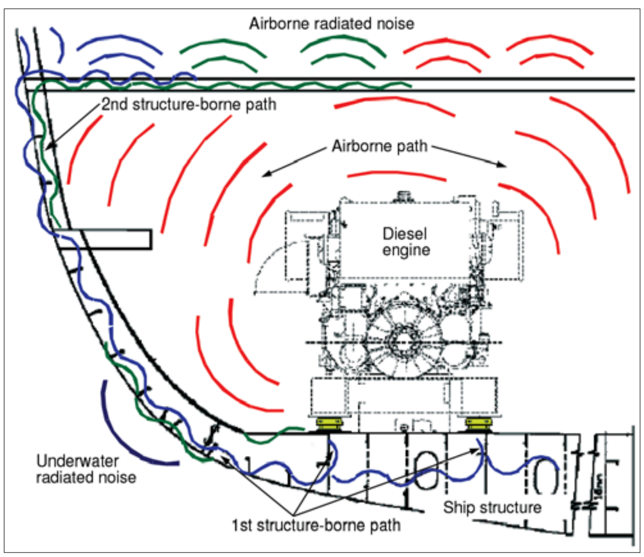

Figure 5. Acoustic transmission paths.

puted as:[7]

$$P_a / P_m = 16\pi\left(\rho_0^2 c_0^4 S^2 / k^2 A\right)\sigma_1\sigma_2$$

where:

ρ_0, c_0 = sound speed and density in air
S = radiating area of mounted equipment and subbase
k = spring stiffness
A = absorption area in space between engine and foundation
σ_1, σ_2 = radiation efficiencies of engine and foundation, respectively

In the lower frequencies, the energy transmitted by the airborne path P_a will be less important than that by the mounting system P_m since $\sigma_1\sigma_2 << 1$. At higher frequencies, where

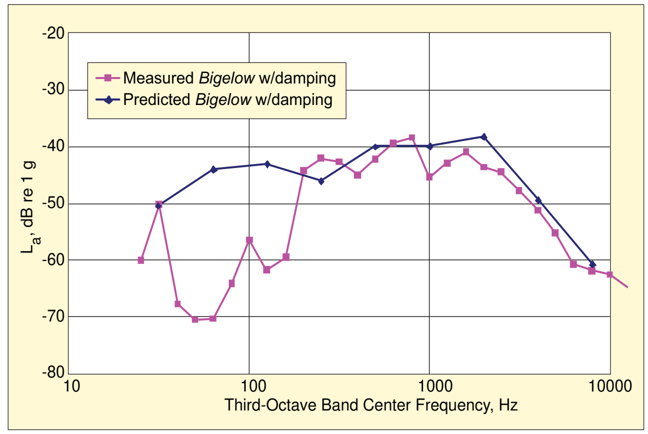

Figure 6. Predicted vs. measured tank-top response to incident sound.

the σs approach or equal 1, the airborne path is dominant if $k < 7\rho_0 c_0^2 S / \sqrt{A}$. By substituting the relationship between the mount system natural frequency f_0 and mass m in the above equation, the airborne path should control when $(f_0)^4 < 3.2 \times 10^9\ (S/m^2)$. For the area-to-weight squared ratios of many typical mid-sized marine diesels, this inequality holds true for systems with a natural frequency on the order of 4 Hz. This is on the low side of most spring and elastomeric mounts used on today's vessels.

As a further check on the potential flanking caused by airborne noise, predicted and measured vibration levels of the tank top structure on the *Bigelow* were compared. This test was conducted with all equipment except the cooling system and the gensets secured. The predicted vibration response v of a framed plate to an incident airborne pressure p was predicted according to Reference 10:

$$v^2 / p^2 = \frac{1}{2\pi^2 m_p^2 f^2}\left(1 + \frac{c_0}{\pi\eta}\left[\frac{1}{l_x} + \frac{1}{l_y}\right]\frac{(1 + f/f_c)}{\sqrt{(ff_c)}}\right) f \prec f_c$$

$$v^2 / p^2 = \frac{1}{2\pi^2 m_p^2 f^2}\left(\frac{\pi}{4\eta}\sqrt{2.1}\right) f \approx f_c$$

$$v^2 / p^2 = \frac{1}{2\pi^2 m_p^2 f^2}\left(\frac{\pi}{4\eta}\frac{f_c}{f\sqrt{1 - (f_c/f)}}\right) f \succ f_c$$

where:

m_p = surface mass of the plate
f = frequency of interest
η = damping loss factor
l_x, l_y = panel length and width
f_c = critical frequency of plate

Using the measured noise levels beneath the *Bigelow* genset, the measured and predicted vibration levels on the tank top plating are compared in Figure 6. At and above 160 Hz, measured and predicted levels show good agreement. Since the tank top plating is covered with damping tile, the loss factor used for the prediction was an η of 0.1.

The dip in the tank-top vibration between 80 Hz and 125 Hz is currently unexplained. So given the match in the levels shown in Figure 6, the tank-top vibration in this case is due primarily to the incident airborne noise and not vibration levels transmitted through the double-stage mounting system. To reduce acoustic energy entering the structure, the airborne flanking path would need additional treatment.

Flanking Investigation

To further investigate and potentially reduce the influence of airborne flanking of the resilient mounting system on the *Bigelow*, the authors installed a screen or barrier between the underside of one diesel generator and the ship's tank top. A ¾-in.-thick plywood panel was temporarily installed under the port CAT 3508 diesel generator. The plywood panel was laid on the intermediate masses approximately 0.3 m (12 in.) from

Figure 7. Plywood screen under genset.

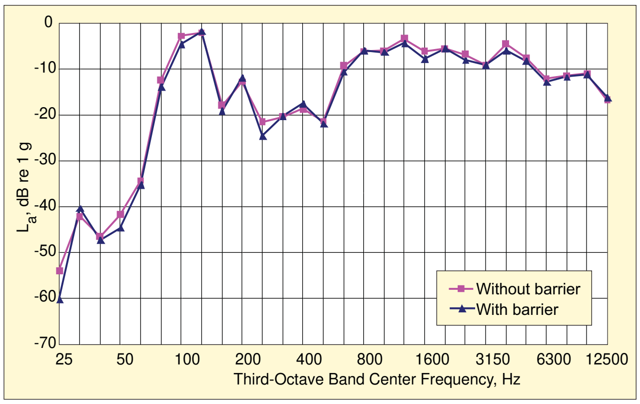

Figure 8. Vertical vibration levels on upper stage of mounts.

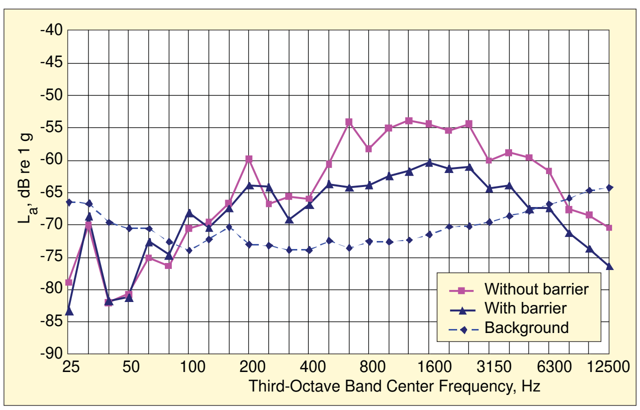

Figure 9. Tank-top vibration levels, with and without barrier.

the tank top. Figure 7 shows the plywood resting on a foam-supported framework.

The effectiveness of this treatment was determined by measuring both the sound and vibration level reductions on the structures around the diesel generators. Vibration levels were measured above and below mounts, on the tank top, on the transverse floor under the genset, and on the hull side near the diesel. Noise levels were measured in the space between the plywood panel and tank top plate. The correlation between noise reduction and vibration reduction is important for this test.

Noise levels above mounts were stable during whole test. Figure 8 shows vibration levels above mounts with and without the barrier installed.

Figures 9 to 13 show the vibration levels around the genset and noise levels in the space between the barrier and tank top. These graphs show measurable vibration and noise reductions for frequencies above 200 Hz. Underwater noise reductions are expected to be the same order of magnitude as that shown for vibration.

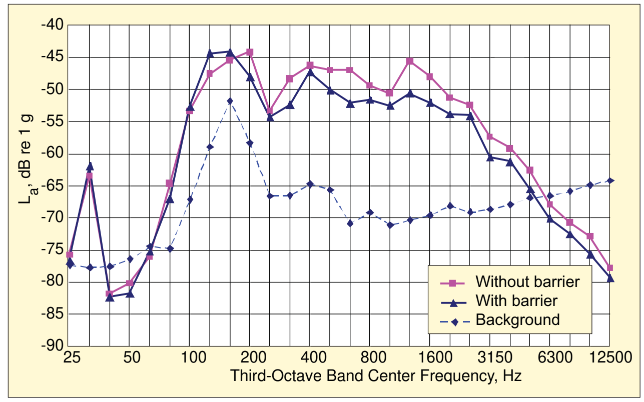

Figure 10. Transverse floor vibration.

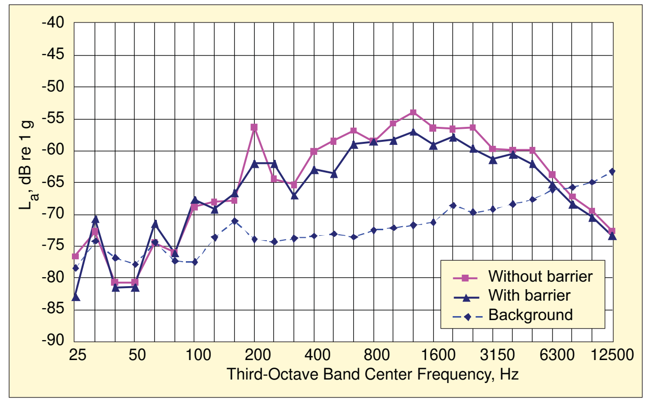

Figure 11. Side shell vibration.

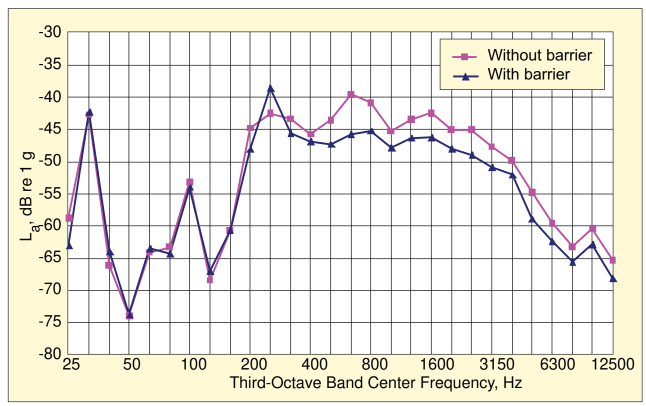

Figure 12. Vibration below mounts.

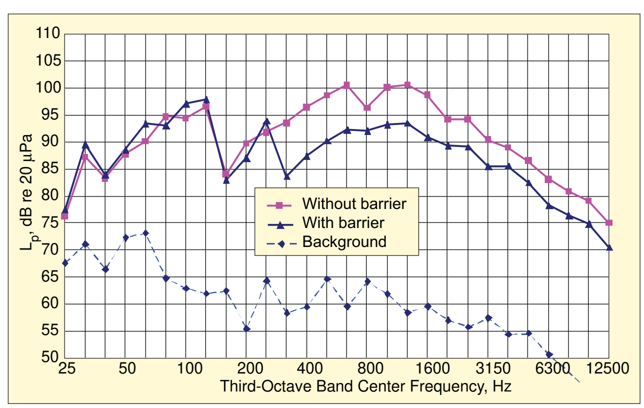

Figure 13. Noise level below genset, with and without barrier

Theory and measurements on the *Bigelow* showed considerable flanking existed on an open-bottom, two–stage, rafted genset. On the research vessel *Sharp*, the authors designed the raft to have a closed bottom to minimize this flanking path.[10] Not only was the raft bottom closed, but a flexible seal was built

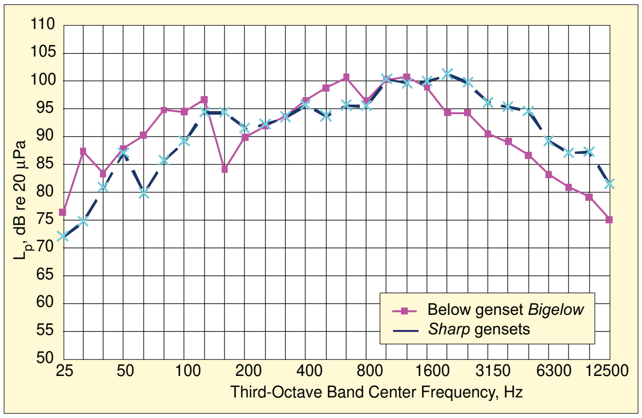

Figure 14. Noise level near gensets, Sharp vs. Bigelow.

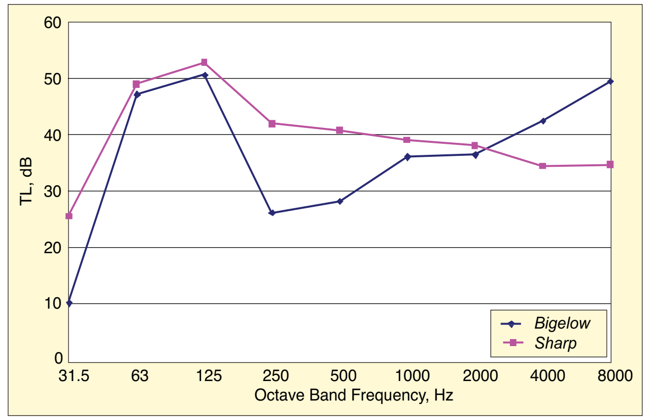

Figure 16. Isolation effectiveness, Sharp vs. Bigelow.

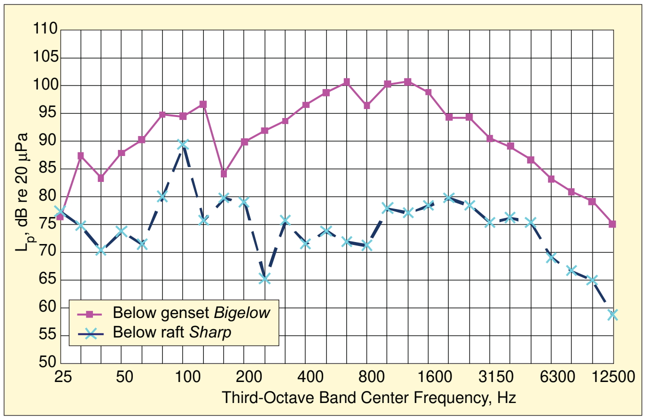

Figure 15. Noise level below genset on Sharp and Bigelow.

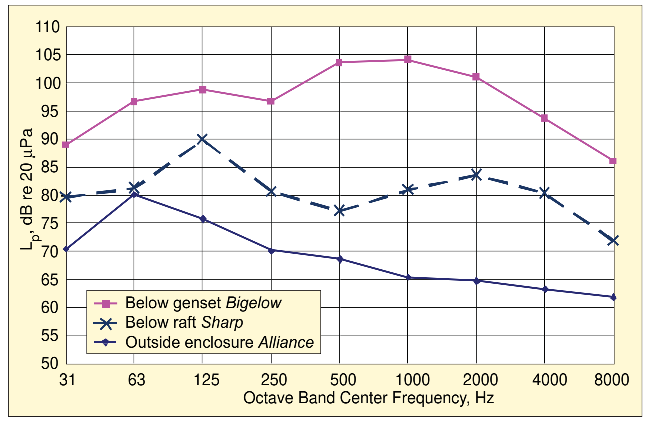

Figure 17. Noise outside enclosure, R/V Alliance.

around the perimeter of the raft at its connection to the tank top. Figure 14 shows the sound pressure levels L_p near the diesels for both the *Bigelow* and *Sharp*. These data show the sound levels near the gensets are comparable.

However, the raft with the closed bottom significantly reduces the sound impinging on the hull below. Figure 15 shows the noise levels incident on the tank top on the *Bigelow* and that comparable below the raft on the *Sharp*. The incident noise levels on ship structure are 5 to 25 dB lower on the *Sharp* due to the closure of the bottom of the raft. This also leads to higher isolation performance of the two-stage system (Figure 16). In the region from 200 to 2000 Hz, the noise below the raft is much lower, and the transmission loss of the *Sharp* system is improved over that of the *Bigelow*. The transmission loss measurements were taken dockside with other equipment secured.

One final comparison can be made. The gensets on the R/V *Alliance* are totally enclosed. This should effectively eliminate any airborne flanking from these units, assuming the enclosure itself does not become a flanking path due to its large area and 'acceptance.' Here again, 'acceptance' is the vibration response of the enclosure panels due to the incident airborne noise. The measured noise outside the *Alliance* enclosure is provided in Figure 17 (data scanned from the figure in Reference 11). These noise levels are significantly lower than those measured below the raft on the *Sharp*. Furthermore, the enclosure is isolation mounted to the rails of the raft; so airborne flanking into the raft from the enclosure should not be a factor, at least at mid to high frequencies. The *Alliance* mount transmission-loss values are compared to those of the *Bigelow* and *Sharp* in Figure 18. With little or no airborne flanking, this system provides the highest performance of all three.

Conclusions

Airborne flanking can reduce the effectiveness of two-stage, isolation-mounted equipment, particularly those with diesel-emitting, high-airborne noise levels installed on effective mounts. So any analysis of the effectiveness of a double-stage,

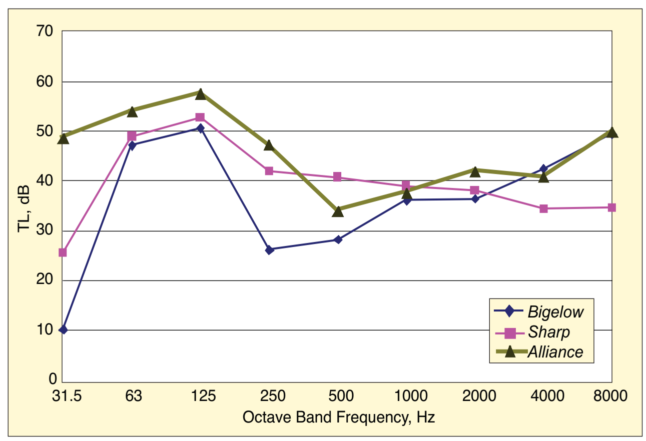

Figure 18. Mount transmission loss, three vessels.

isolation-mounted system should consider both the transmission through the mounts and through any potential airborne flanking path. If there is no airborne flanking, the effectiveness should be controlled by the stiffness of the mounting system and the ratio of the weight of the raft to that of the equipment.

Total enclosures or closing off the bottom portion of the raft or subbase will reduce the sound incident on the ship's structure and limit the adverse impact of direct airborne flanking. Full genset enclosures will effectively eliminate airborne flanking. However, full enclosures entail severe weight, space, and maintenance impacts. Limited tests show that even a screen or barrier beneath the genset can provide an effective treatment to reduce airborne flanking paths and improve vibration isolation for frequencies above 200 Hz.

Novel techniques and treatments of the rafts might further enhance the low-frequency performance of the system. These include "radiation damping,"[12] use of a very thick absorptive insulation on the underside of the raft, or use of cut-constrained layer damping to improve low-frequency performance.

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