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VIBRATION TRANSMISSION ACROSS CARBON NANOTUBE AND METALLIC FOIL THERMAL INTERFACE MATERIALS FOR SPACE APPLICATIONS

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Abstract: Thermal management is of fundamental importance in the design of electronic devices and components critical to system performance. Thermal interface materials (TIMs) serve as a means of reducing thermal contact resistance (TCR) by increasing real contact area at the interface, thus enhancing the flow of heat from source to sink. Although the thermal performance of many TIMs has been extensively characterized, the measurement of the transmission of vibrations across these materials is largely unexplored in the literature. In space systems, vibration isolation of sensitive electronic components is critical during launch, where peak acceleration levels can reach tens of g's. Additionally, space systems are exposed to high doses of gamma radiation due to the lack of an atmosphere to serve as an absorbing medium. With typical design lifetimes greater than five years, total radiation exposure can be significant and can affect the structure and performance of materials. Here, we report measurements of the vibration transmission across bolted interfaces that employ metallic foil and carbon nanotube TIM (CNT-TIM) cooling solutions before and after gamma irradiation. The TIMs were irradiated in a gamma cell at a rate of 200 rad/s to a total dose of 50 Mrad. The vibration isolation characteristics of the TIMs were measured from 200 to 4,000 Hz at vibration levels ranging from 1 to 20 g's using an electrodynamic shaker table. The interface materials provide 5 to 10 % vibration attenuation across the interface and exhibit a linear response with respect to vibration magnitude. It is also shown that gamma irradiation degrades the vibration isolation performance, which is attributed to a change in stiffness of the interface materials.

Key Words: Carbon nanotube; Gamma radiation; Satellite; Vibration transmission

Introduction:

Heat transfer across the interface of contacting materials is of central importance in the design and simulation of electronic and thermal systems. When two surfaces are brought into contact, the actual contact area (sum of the contact spot areas) is a small fraction of the apparent area of contact [1]. As a result, heat is restricted to flow through a small number of contact spots formed between the two mating surfaces, which gives rise to a thermal contact resistance (TCR). As a result, TCR can be quite large, causing a large temperature drop across the interface, thus raising the device temperature. Thermal interface materials (TIMs) are interstitial materials that are inserted at the contact interface to increase contact area for heat conduction and hence decrease the overall TCR of the joint. Examples of TIMs include common materials such as thermal greases [2], metallic foils [3] and elastomeric sheets [4], and more exotic materials such as conductive polymers [5], carbon nanotubes [6], [7] and graphene materials [8], [9]. TIMs serve a critical role in thermal management by enhancing heat transfer across contact interfaces, thus allowing higher heat fluxes to be removed from the system and lowering device operating temperature.

Extensive research, primarily driven by the consumer electronics industry, has been conducted to characterize the thermal performance of these various TIMs. However, significant cooling issues exist for military and space applications, which not only require high-reliability cooling solutions, but also excellent vibrational damping characteristics, for extended periods of time (up to 10 years or more) in severe environments [10]. During the launch of a satellite, for example, the system is subjected to several to tens of g's of acceleration primarily in the frequency range of 500 to 1800 Hz [11]. For vibrational damping, the bolted interface with a TIM inserted between the two contacting surfaces can be considered mechanically as a simple built up beam [12]. Pian and Hallowell [13] proposed a theoretical analysis for structural damping in a simple built up beam fastened by screws. Xiao *et al*. [14] experimentally investigated the transmission of vibration across a multi-layered bolted joint (consisting of 2 to 8 interfaces) subjected to a shock excitation. It was found that transmission decreased with an increasing number of layers and decreased as the shock amplitude was increased.

In addition to vibration during launch, space systems are subjected to a wide array of radiation sources including gamma, UV, X-ray, and charged particles—all of which have the potential to drastically affect material properties [15], [16] and the structure [17]. UV, X-ray, and charged particles are typically absorbed or reflected by the exterior components of the spacecraft; however, gamma-rays pass through all components, thus affecting the thermal interface material joints in the system. This effect of radiation on the transmission of vibration across bolted joints has not been investigated to date. Here we report measurements of vibration transmission across both bare joints and joints with thermal interface materials inserted at the contact interface before and after accelerated radiation aging in the frequency range of 200 to 4000 Hz.

Experimental Method:

<u>Materials:</u>
Three different metallic foils (copper, nickel and tin) and a carbon nanotube (CNT) thermal interface material (CNT-TIM) were investigated in this study. The metallic foils were obtained from Alfa Aesar and all had purity values greater than 99.5%. The three metallic foils were chosen for their wide range of Young's modulus and Vickers hardness values, as shown in Table 1. The TIMs were placed between a 6061 T-6 aluminum block and 304 stainless steel plate that were attached with four, #2-56 cap screws.

Table 1: Material properties of the metallic foils.

Metal	Young's modulus (Gpa)	Vickers hardness (Mpa)
Copper	120	369
Nickel	200	638
Tin	50	80

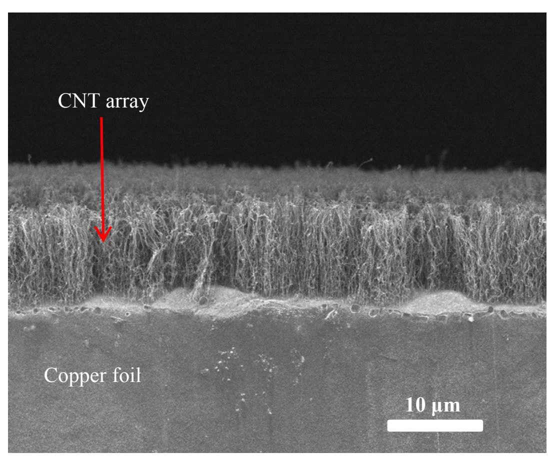

Figure 1: FESEM image of the CNT-TIM.

CNT-TIMs were fabricated in a manner similar to that described by Cola *et al*. [6]. A thermal evaporative system was used to deposit a tri-layer metal catalyst stack consisting of 30 nm Ti, 10 nm Al, and 5 nm Fe on both sides of a 100 μm thick copper foil. Vertically aligned CNT arrays were then synthesized on both sides of the foil in a SEKI AX5200S microwave plasma chemical vapor deposition (MPCVD) system described in detail in Ref. [18]. In summary, the growth chamber was evacuated to 1 Torr and purged with N_2 for 5 min. The samples were heated in N_2 (30 sccm) to a growth temperature of 800°C. The N_2 valve was then closed and 50 sccm of H_2 was introduced to maintain a pressure of 10 Torr in the growth chamber. After the chamber pressure stabilized, a 300 W plasma was ignited and 10 sccm of CH_4 was introduced to commence 2.5 minutes of CNT synthesis. The samples were imaged using a Hitachi field-emission scanning electron microscope (FESEM). Figure 1 contains FESEM images of the vertically aligned CNT arrays synthesized on copper foil. The array characteristics possessed average densities of 10^8-10^9 CNTs/mm^2, tube diameters of 30 nm, and heights near 10 μm.

Radiation Aging:

End of mission gamma radiation dose levels can vary greatly, usually from tens to hundreds of Mrads to the external components of the satellite [19]. Because gamma-rays are high energy and can pass through materials with little attenuation in intensity, similar doses are expected at the interior components of the satellite. Accelerated gamma radiation dosing of the TIM samples was conducted in a gamma cell (shown in Figure 2) at a rate of 200 rad/s to a total dose of 50 Mrad in order to simulate a 5 year design life assuming a dose rate of 10 Mrad/yr [19]. For the irradiation process, it is assumed that any gamma induced changes in the material properties will depend on the total dose, but are independent of dose rate [17]. In order to minimize thermal effects during irradiation, the samples were actively cooled and maintained at 297 K.

Figure 2: Photograph of test samples in the gamma cell.

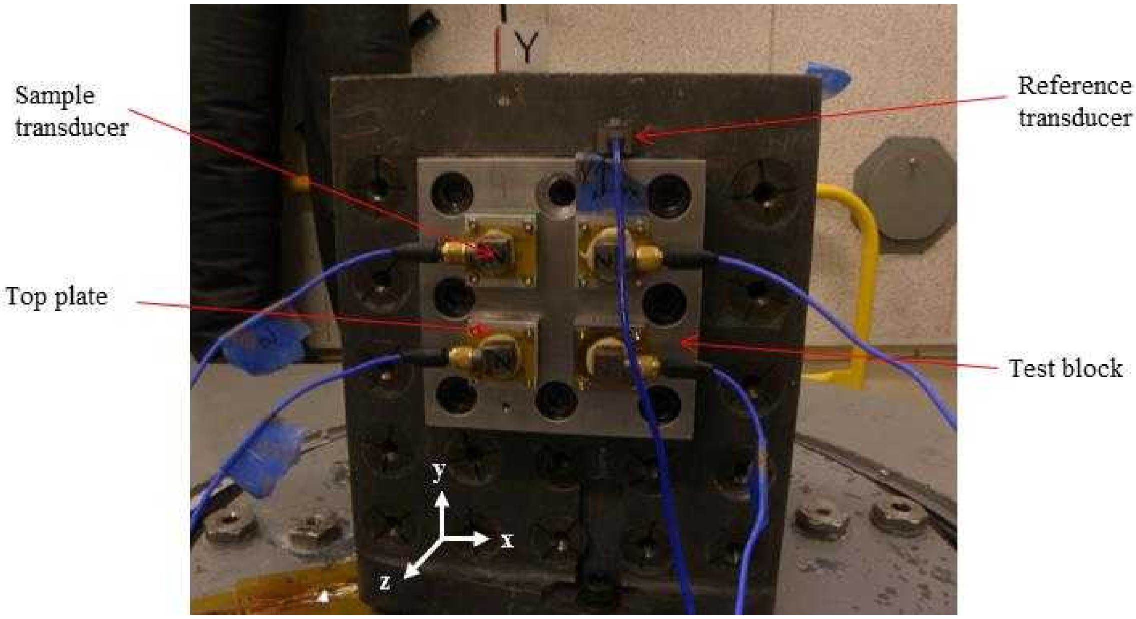

Figure 3: Photograph of the vibration test setup mounted to the shaker.

<u>Vibration Testing:</u>
1 x 1 in^2 samples were mounted between a test block and a top plate of the same dimensions and were held together by four #2-56 cap screws as shown in Figure 3. The corners of the TIMs were cut away to not interfere with the cap screws. This setup was chosen as it best represents a heat strap connection, a common application of metallic TIMs in a satellite system. All four screws were tightened to the same torque value; either 1, 3, or 5 in-lbs to cover the typical range of applied loads for #2 screws. Vibration isolation of the TIMs was characterized in both the normal (z-axis) and transverse (y-axis) directions. The x-direction was not tested due to symmetry between it and the y-axis.

Results:

The transmission of vibrations across the contact interface was measured in both the normal and transverse directions for both radiation-aged and unaged samples. The results of the testing of the unaged TIMs are shown in Figure 4 for acceleration levels of 1, 5, 10 and 20 g's. Here, the transfer function represents the ratio of vibration transmitted across the interface to that of the reference transducer. The vibrational modes of the system occur at the peaks in the figure. The vibrational modes of the system are highly dependent on the experimental setup and could change significantly with any design changes to the setup. Here, the vibrational modes are that from the overall combination of the test block, TIM/bolts, top plate and sample transducer. The first modes occur at 2650 Hz in the normal direction and 840 Hz in the transverse direction. The transfer function at frequencies well below the first mode can be attributed solely to transmission across the interface. This occurs at frequencies below 2000 Hz and 600 Hz in the normal and transverse directions, respectively. At frequencies above the first mode, the transfer function will be a function of both transmission across the interface and amplification due to the natural frequency. These results are highly dependent upon the arrangement of the test apparatus. In the low frequency regions, the CNT-TIM and nickel and tin foils provide slight attenuation (5-10 %) while slight amplification (3-5 %) is found across the copper foil and bare interface. Additionally, the transmission across the interface is linear with respect to input acceleration.

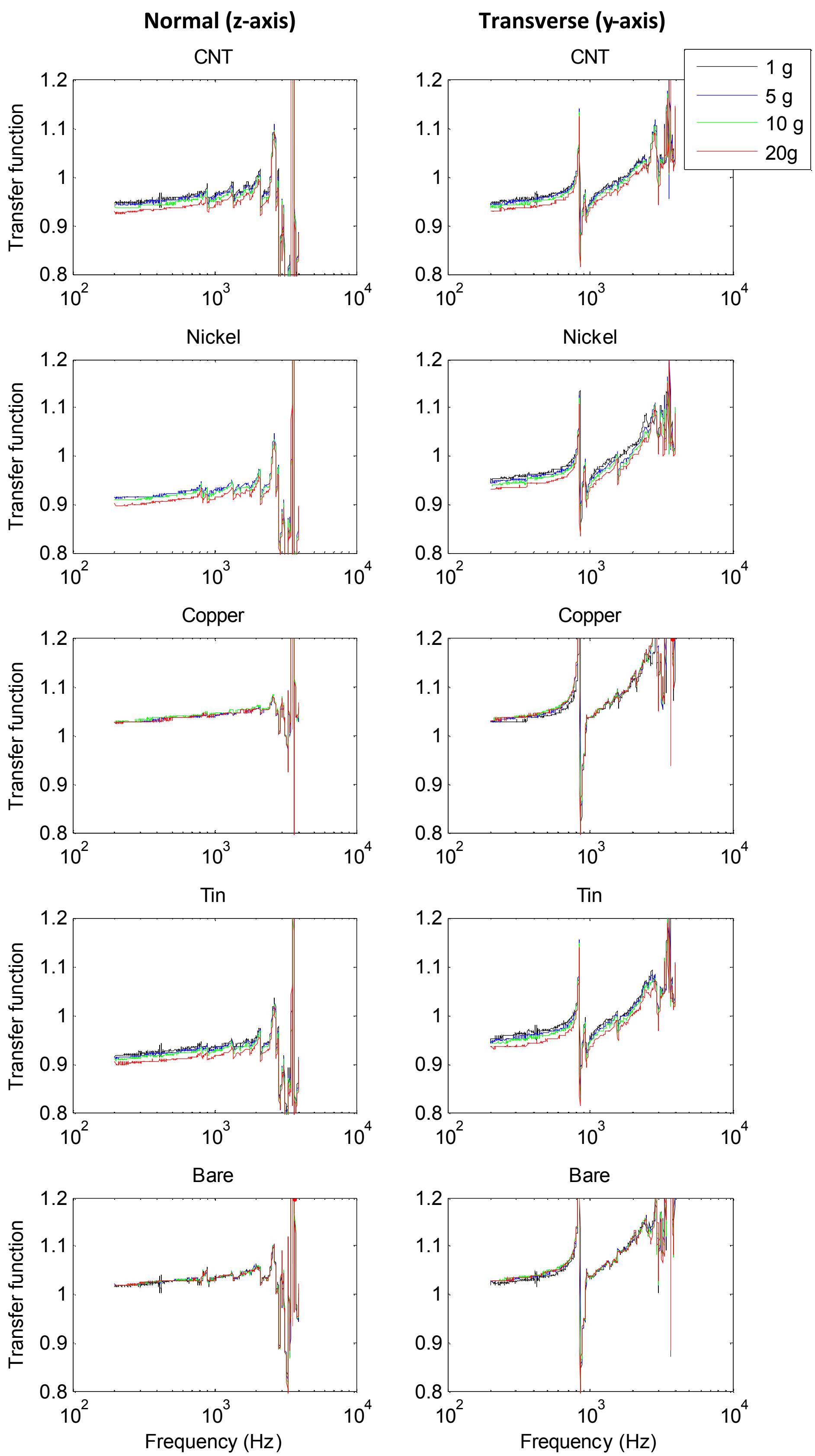

Figure 4: Transfer function from 200 to 4000 Hz for the TIM and bare interface samples at accelerations of 1, 5, 10, and 20 g's. All metallic foils are 100 μm thick. The tightening torque was 3 in-lb.

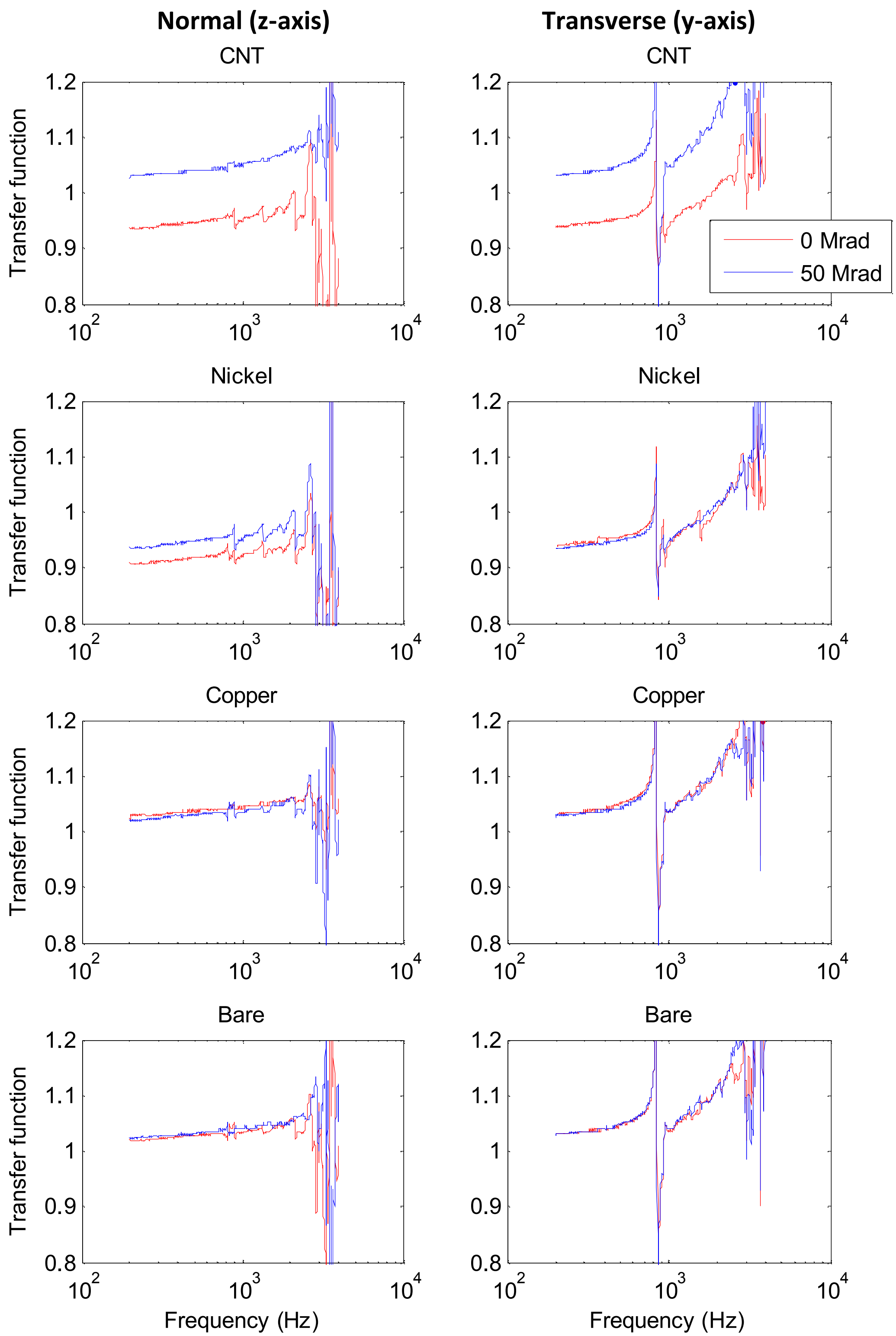

Figure 5: Effect of gamma radiation on the CNT-TIM, nickel foil, copper foil, and bare interface. Both metallic foils are 100 µm thick. The tightening torque was 3 in-lb.

Typically in space systems, vibration is only of concern during launch; however, if re-entry vibrations are of importance, gamma radiation can play an important role in vibration isolation of the TIMs. Figure 5 shows the transfer function for an input acceleration of 10 g's for both radiation-aged (50 Mrad) and unaged (0 Mrad) samples of the CNT-TIM, nickel foil, copper foil, and bare interface. It can be seen that gamma irradiation has no effect on the bare interface or the copper foil. There is a 3 % increase in the transfer function in the normal direction for the nickel foil and the transverse direction in unchanged. However, a significant increase in the transfer function, about 9% in both the normal and transverse directions, is observed. This is most likely due to a decrease in the stiffness of the CNT array due to defect creation during gamma irradiation [20].

As shown in Figure 6, tightening torque can have a pronounced effect on the transfer function of the samples. This is most evident in the CNT-TIM, and therefore, discussion will concentrate on this sample. It can be seen that in the normal direction, the transfer function decreases from 1.03 to 0.94 to 0.91 as the tightening torque is incremented by 2 in-lb from 1 to 5 in-lb. In the transverse direction, the transfer function decreases from 1.03 to 0.94 as the torque is increased from 1 in-lb to 3 in-lb. The transfer function does not change as the torque is increased to 5 in-lb. The larger transfer function at lower torque values is attributed to looseness of the interface. As the torque in increased, the TIM becomes 'fully engaged' between the test block and top plate, improving the vibration attenuating quality of the TIM. Similar results can be seen for the bare interface.

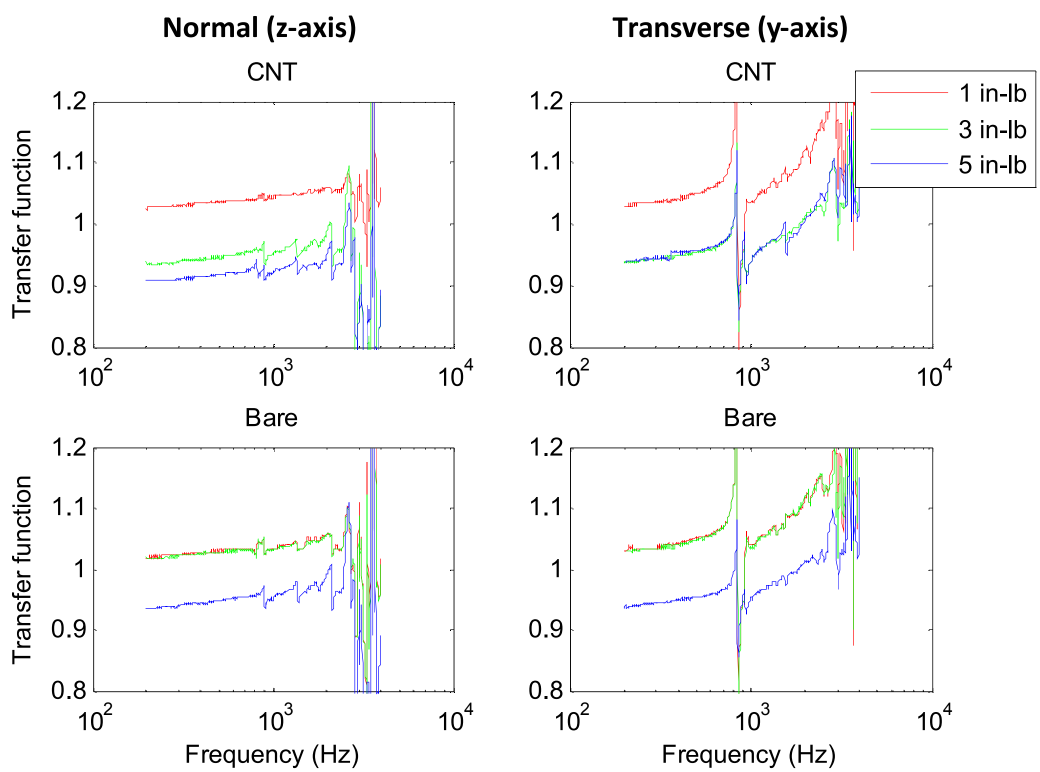

Figure 6: Effect of cap screw tightening torque on vibration response for the CNT-TIM, 100 μm nickel foil, and bare interface.

Conclusion:

The vibration isolation characteristics of CNT and metallic foil TIMs were measured and compared to a bare interface. The transmission of vibrations across the TIMs was measured using a shaker table. It was shown that CNT-TIMs, along with nickel and tin foils provide 5 to 10 % vibration attenuation while the copper foil and bare interface slightly amplify (3-5 %) vibration across the interface. In order to simulate end-of-mission operating conditions for satellite and other space systems, the samples underwent accelerated gamma radiation aging to a total dose of 50 Mrad. Although the transmission across the bare interface and metallic foils showed little dependence on gamma radiation, the CNT-TIM transmission increased significantly. This is attributed to the change in stiffness of the CNTs during radiation aging. Additionally, transmission was found to decrease with increased tightening torque of the cap screws. It is evident that CNT-TIMs are an excellent candidate for use in the design of future space systems as well as in terrestrial applications. This work represents a proof-of-concept for CNT-TIMs; however, significant research is still required for design optimization (foil substrate thickness, CNT length and density, etc.).

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