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The final report for ”Diagnosis and Prognosis of Filament Wound Components Subject to Combined Loads Using Nonlinear Signal Processing of Standing and Traveling Waves” is presented here in the form of a journal article. This article summarizes the approach, test procedures, analysis methods, results, and conclusions associated with the study of frequency domain techniques for characterizing helmet and helmet padding performance through nondestructive evaluation. Upon approval, this article will be submitted to an appropriate journal for publication consideration

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Frequency Domain Evaluation of Helmet Padding Performance

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FINAL REPORT FOR ”Diagnosis and Prognosis of Filament Wound Components Subject to Combined Loads Using Nonlinear Signal Processing of Standing and Traveling Waves”

Frequency Domain Evaluation of Helmet Padding Performance

Janette J. Meyer and Douglas E. Adams

ABSTRACT

The final report for ”Diagnosis and Prognosis of Filament Wound Components Subject to Combined Loads Using Nonlinear Signal Processing of Standing and Traveling Waves” is presented here in the form of a journal article. This article summarizes the approach, test procedures, analysis methods, results, and conclusions associated with the study of frequency domain techniques for characterizing helmet and helmet padding performance through nondestructive evaluation. Upon approval, this article will be submitted to an appropriate journal for publication consideration.

1 INTRODUCTION

Traditionally, the main design criteria for an Army combat helmet has been to protect against ballistic penetration [1]. Recently, the need to protect soldiers against other types of hazards, including blunt and blast impacts, has become a significant concern [2–6]. The standard methods to evaluate a helmet's effectiveness in protecting a person from injury due to impacts are based on estimates of the amplitude and duration of peak acceleration experienced at the center of mass of the head. These methods distill the performance of the helmet and its padding down to a single number, which is compared to an established threshold to determine the pass/fail status of the helmet. While these methods provide an indication of how well the helmet and its padding attenuate the forces that are transmitted through the helmet-padding-head system, they do not give any indication of how each component contributes to the effectiveness of the system, nor can they offer any indication of how to change the design parameters of the system in order to improve performance. In this paper, two frequency-domain evaluation methods, transmissibility and impedance modeling, are presented which allow individual components to be evaluated in situ, and provide information which could potentially inform helmet and helmet padding design.

The evaluation of the effectiveness of a helmet typically depends on the type of helmet and the environment in which it will be worn. Standards such as FMVSS 218 [7] and ASTM F717 [8] have been used to evaluate helmets including motorcycle, football, and hockey helmets to ensure a basic level of protection. These standards define the procedure for performing impacts to the helmet-padding-head system, sensor requirements, headform type (DOT, ISO, NOCSAE, etc.), and other test parameters. Data acquired from these standardized tests are then evaluated based on one of several standard time-domain-based indices such as the peak value of the acceleration measured at the center of mass of the headform, the Gadd Severity Index (SI) [9], or the Head Injury Criterion (HIC) [7]. Both the SI and the HIC are based on the amplitude and duration of the peak acceleration of the center of mass of the headform. The thresholds for these indices are based on the seminal Wayne State study which established the Wayne State Tolernace Curve, shown in Figure 1. According to the study,

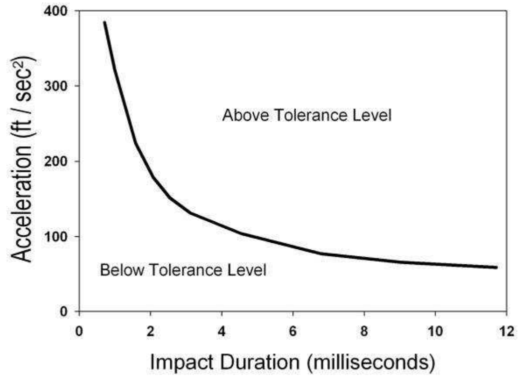


Fig. 1: Wayne State Tolerance Curve. [10]

smaller amplitude accelerations can endure for a longer time than accelerations with higher peak amplitudes before causing injury. Helmets which prevent the amplitude of the peak acceleration of a headform from exceeding the corresponding threshold are deemed effective. Many studies are currently being conducted to better understand the correlation between acceleration levels of the head and resulting injury, including concussion and traumatic brain injury. These topics are outside the scope of this research and will not be addressed in this paper.

The current standard indices provide an indication of how well energy is being attenuated by the entire head-helmet-padding system. One strength of these indices is that they provide a simple pass/fail grade for each helmet. However, they give no indication of how each component is contributing to the overall performance of the system. Frequency-based methods, including transmissibility and dynamic stiffness measurements based on impedance modeling, offer the potential to separate the contributions of each individual component. As impact energy is transmitted from the impact location on the outside of the helmet, through the helmet, through the padding, into the head and to the brain, each component filters out energy in different frequency ranges such that the forces acting on the brain are different than the forces that were applied to the outside of the helmet. The ideal helmet-padding system would attenuate all the energy at all frequencies. In reality, different helmets and paddings attenuate energy differently based on many factors including their geometry and material properties. Transmissibility and impedance modeling approaches identify the frequency ranges in which each component best attenuate energy, and therefore, could provide valuable feedback that can be used to improve the design of helmet and padding components.

In the next section, the transmissibility and impedance modeling approaches will be developed. Then, the procedure for experimentally measuring the quantities required for the two analyses will be presented. Transmissibility and impedance-based results will be presented for data acquired from an Army helmet with standard issue padding. These results will be compared to those from data acquired from the same helmet with non-standard padding, including pads filled with sand, glass beads, and polystyrene pellets. The trends observed in these data sets will be compared to corresponding time domain data acquired from standard drop tower testing. Finally, conclusions will be drawn about the potential of these frequency-domain analysis techniques to guide future helmet padding design.

2 APPROACH

The approach for both transmissibility and impedance modeling analysis rely on measurements made at the interfaces between each component of the helmet-padding-head system. Figure 2a shows a schematic of the system and the notation that will be used to indicate each measurement point. The subscripts HMO and HMI will indicate measurements associated with the outside and inside of the helmet. Measurements made at the surface of the head will have the subscripts HD, and those made at the center of mass of the head will have the subscripts CM.

Transmissibility calculations can be made for any pair of measurement points. The transmissibility, T, as a function of frequency, ω, between measurement points A and B is defined as the ratio of the measured responses:

$$T_{A,B}(\omega) = \frac{Response\ B(\omega)}{Response\ A(\omega)}. \quad (1)$$

Any type of response spectra (acceleration, force, etc.) can be used in Equation 2, but as will be described in a later section, acceleration will be used in this work. A transmissibility greater than one indicates that the response at point A is

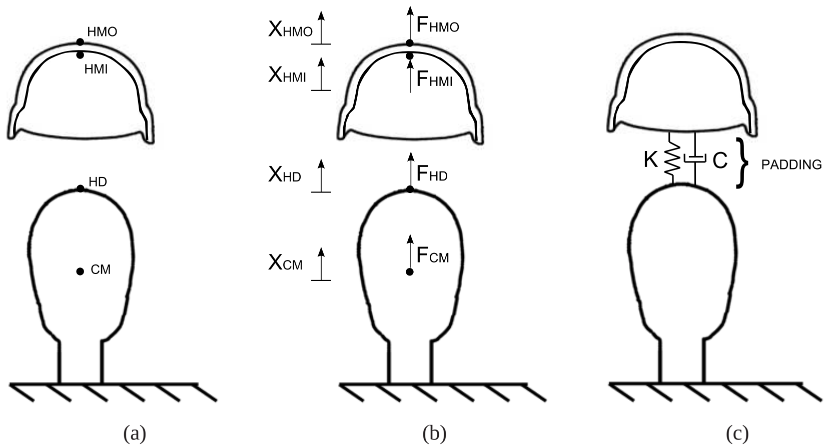


Fig. 2: (a) Measurement points, (b) force diagram, and (c) padding model used for the helmet-padding-head system.

being amplified as the signal travels to point *B*. In the context of helmet evaluation, transmissibility values much less than one are desirable between measurements on the outside of the helmet and those on the inside of the helmet ($T_{HMO,HMI}$), at the surface of the head ($T_{HMO,HD}$), and inside the head ($T_{HMO,CM}$). By calculating transmissibility values across each component($T_{HMO,HMI}$,$T_{HMI,HD}$,$T_{HD,CM}$), the attenuation/amplification characteristics of each component is quantified as a function of frequency. Using this approach, each component can be evaluated in situ, such that the boundary conditions and force preloading (from the chin strap tension, for example) are realistic.

In order to further evaluate how the properties of each component contribute to the overall performance of the system, impedance modeling can be applied. Impedance modeling has previously been used in seat comfort studies to quantify the mechanical properties of the foam padding of a car seat [11] and the impedance of a seated human in order to minimize the use human subjects during testing [12]. A similar approach can be taken to quantify the properties of the padding inside a helmet. In Figure 2b, the forces that act on the helmet-padding-head system are diagrammed. The padding on the inside of the helmet couples the helmet to the head, as shown in Figure 2c. By writing input-output relationships between the forces and responses shown in Figure 2b, the stiffness and damping properties of the padding can be estimated. First, the frequency response function, $H(\omega)$, between a force, F, applied at point A and a response, X, measured at point B, is defined as

$$H_{B,A}(\omega) = \frac{X_B(\omega)}{F_A(\omega)}. \tag{2}$$

Using Equation 2, the displacements for the helmet and the head can be expressed as

$$\begin{aligned} X_{HMI} &= H_{HMI,HMI}F_{HMI} + H_{HMI,HMO}F_{HMO} \\ X_{HD} &= H_{HD,HD}F_{HD}. \end{aligned} \tag{3}$$

The force that the padding exerts on the inside of the helmet, F_{HMI}, and on the surface of the head, F_{HD}, is

$$F_{HD} = -F_{HMI} = K(x_{HMI} - x_{HD}) + C((x\dot{_{HMI}} - x\dot{_{HD}})) \tag{4}$$

where K and C are the coefficients of stiffness and damping and x and $\dot{x}$ are the displacement and velocity at the indicated measurement point. Rewritten in terms of frequency, Equation 4 becomes

$$F_{HD}(\omega) = -F_{HMI}(\omega) = f_\omega(X_{HMI} - X_{HD}) \tag{5}$$

where $f_\omega = K + i\omega C$ and is called the dynamic stiffness of the padding. By substituting Equation 5 into Equation 2, the

(a) (b) (c)

Fig. 3: Impact testing setup.

displacements, X, and forces, F can be eliminated leaving

$$\frac{X_{HD}}{F_{HMO}} = \frac{H_{HMI,HMO} H_{HD,HD} f(\omega)}{(H_{HD,HD} + H_{HMI,HMI}) f(\omega) + 1}. \tag{6}$$

The expression on the left hand side of Equation 6 is equivalent to the frequency response function calculated from the response measured at the surface of the head due to a force applied at the outside of the helmet. Solving Equation 6 for f_ω gives the following expression for the dynamic stiffness of the padding:

$$f(\omega) = \frac{H_{HD,HMO}}{H_{HMI,HMO} H_{HD,HD} - H_{HMI,HMO}(H_{HD,HD} + H_{HMI,HMI})}. \tag{7}$$

Equation 7 gives an expression for the dynamic stiffness of the padding, a quantity which reflects the material properties of the padding, in terms of frequency response functions that can be measured experimentally. As will be further explained in the next section, the driving point frequency response functions, $H_{HD,HD}$ and $H_{HMI,HMI}$, and the cross point frequency response function, $H_{HMI,HMO}$ are measured at the component level, where the head and the helmet are not coupled. $H_{HD,HMO}$ is measured at the system level, where the head and helmet are coupled through the force of the padding, inherently through the tension of the chinstrap. This system-level measurement is important because it implicitly captures the effects of the boundary conditions and force preloads that are present so that the estimate of the dynamic stiffness of the padding reflects its in situ performance.

3 EXPERIMENTAL SETUP AND PROCEDURE

Data for the transmissibility and impedance modeling analysis approaches was acquired via impact testing on a helmet-padding-head system consisting of an Army-issued combat helmet, several standard and non-standard sets of padding, and a Denton Hybrid III 50th percentile head and neck system bolted to a steel block. Figure 4 shows the setup. PCB 352C22 single axis accelerometers were mounted on the outside surface of the top of the helmet, as shown in Figure 3c, and the corresponding point on the inside surface of the helmet. A PCB 352A24 single axis accelerometer was mounted on the surface of the head such that it was aligned with the helmet sensors when the helmet was installed. Finally, a Silicon Designs 2460-050 DC triaxial accelerometer was installed at the center of mass of the head. Impacts were made with a PCB 086D05 modal impact hammer with a rubber tip. Several National Instruments 9234 four-channel data acquisition cards were used with an NI cDAQ-9178 8-Slot USB chassis to acquire the data. Data analysis was performed in MATLAB.

Six sets of paddings were used during testing. Three sets (gray, black, and memory) were issued by the Army as part of a blind study. Therefore, the composition of the pads is unknown to the authors. Qualitatively, the pads referred to as ”black” and ”gray” were of similar stiffness and the ”memory” pads felt similar to memory foam. Three non-standard sets of pads were assembled to provide further basis for comparison. Figure 4 shows the three different materials used to fill the non-standard pads. Three millimeter diameter glass beads, white play sand, and 5 millimeter polystyrene foam pellets were encased in muslin pouches and secured in the helmet with Velcro. The shape and dimensions of the pouches were designed to match those of the standard-issue pads. The pad configuration can be seen in Figure 4d.

(a) Glass beads. (b) Sand. (c) Polystyrene pellets. (d) Pad configuration. (Gray padding shown.)

Fig. 4: Non-standard padding filling and padding configuration.

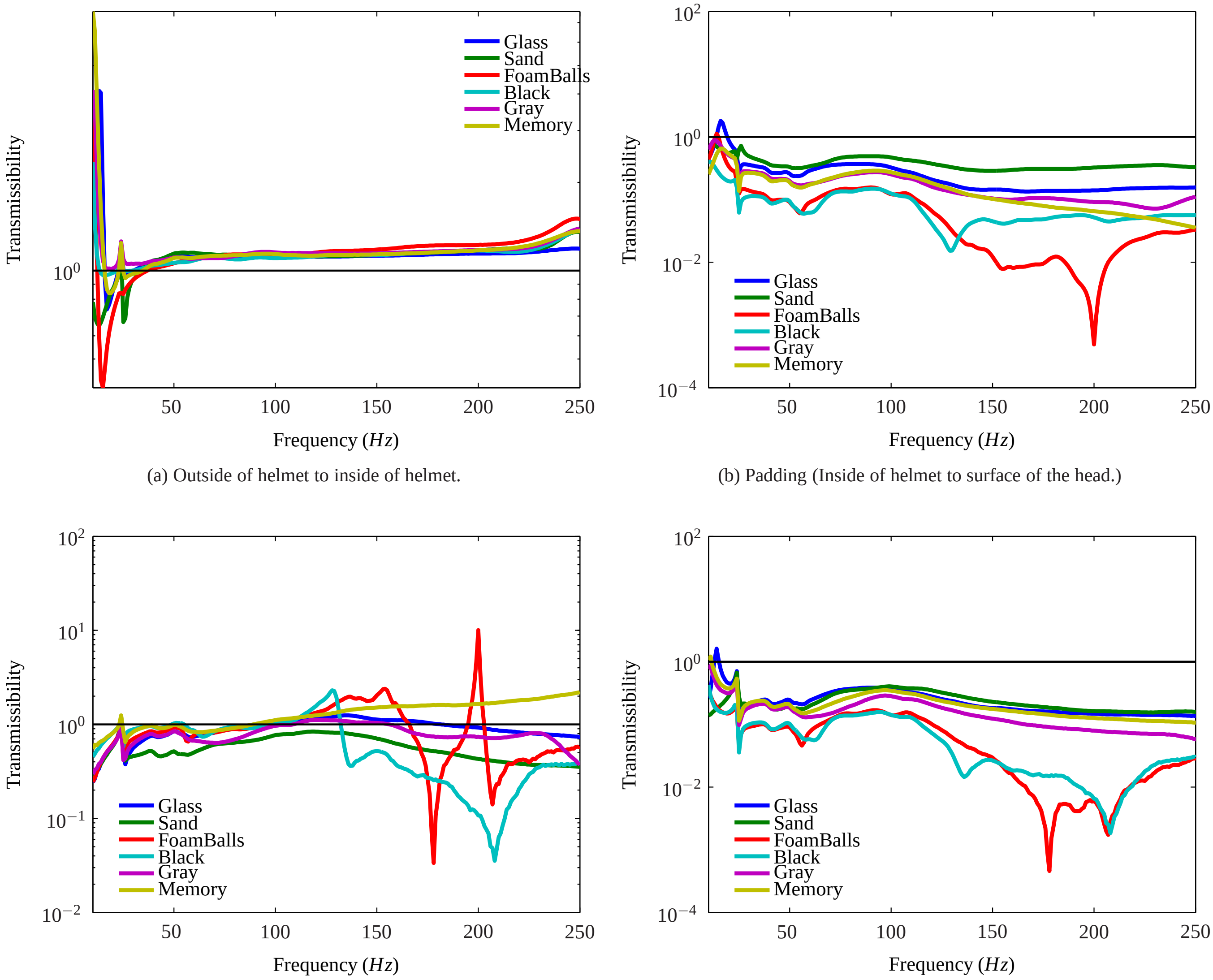
(a) (b)

Fig. 5: Drop tower setup.

Data for the transmissibility analysis was acquired from the helmet-padding-head system for each of the six padding types. Each data set consisted of five impacts ($\sim$900-1100 N) made to the top of the helmet while the response was measured at each of the sensor locations. Frequency response functions were calculated for each response measurement and the transmissibility between different measurement points was calculated by taking the ratio of the respective frequency response functions.

The data for the impedance modeling analysis required both system level (i.e. the helmet-padding-head system) tests and component-level tests. As described in Section 2, Equation 7 requires the driving-point frequency response functions, $H_{HD,HD}$ and $H_{HMI,HMI}$, and the cross point frequency response function, $H_{HMI,HMO}$, be measured while the helmet and head are not coupled. $H_{HD,HD}$, therefore, was calculated from the data acquired while impacting the surface of the head directly and measuring the response of the head at the impact point after the helmet had been removed. Due to the difficulty of impacting the concave, inside surface of the helmet, $H_{HMI,HMI}$ was assumed to be equal to $H_{HMO,HMO}$, the driving point frequency response function corresponding to the impact and measurement point on the outside of the helmet. Data used to calculate $H_{HMO,HMO}$ and $H_{HMI,HMO}$ was acquired while the helmet (with no padding) was sitting on a soft, foam block to simulate free boundary conditions. $H_{HMO,HMD}$ is a system level measurement and was, therefore, acquired while the helmet and padding were installed on the head. Chin strap tension was not measured, but before each data set was acquired, the chin strap was tightened as much as possible. Care was taken to make sure the fit of the helmet was appropriate, especially when the non-standard paddings were installed, and that contact between the sensor on the top of the head and the padding was sufficient.

It should be noted that the experimental setup described above and shown in Figure 3 is not the same as the setup that the standard helmet evaluation tests call for. The standard practice is use a drop tower in which the helmeted headform (without the neck) is dropped with a pre-determined velocity onto an impactor. The response at the center of mass of the headform is measured and one or more of the standard indices described in Section 1 is calculated from the measured acceleration data. For reference, two sets of drop tower data were acquired using the same helmet and same six sets of pads that were used in the impact hammer testing. Figure 5 shows the setup used for the drop tower testing. Drop velocities of approximately 11.5 and 16 ft/s were used. Three drops were performed for each padding at each of the drop velocities for a total of six drops per pad type. The peak acceleration and the Gadd Severity Index (SI) [9] were calculated for each drop.



(a) Outside of helmet to inside of helmet.

(b) Padding (Inside of helmet to surface of the head.)

(c) Surface to center of mass of the head.

(d) Outside of helmet to center of mass of the head.

Fig. 6: Transmissibilities calulated from impact testing of the helmet-padding-head-system. The black line in each graph indicates a transmissibility of one.

4 RESULTS

4.1 Transmissibility

Transmissibilities between the following measurement points were calculated: outside of the helmet to inside of the helmet, inside of the helmet to surface of the head, surface of the head to center of mass of the head, and outside of the helmet to center of mass of the head. This last transmissibility quantifies how well the force applied by the impact hammer to the outside of the helmet is attenuated by the total helmet-padding-head system. The other transmissibilities quantify force attenuation through each of the components of the system. Figure 6a shows the transmissibility through the helmet. A black reference line is shown at $T = 1$. Transmissibilities greater than one indicate that the force is being amplified as it travels from measurement point A to measurement point B. For frequencies between 50 and 225 Hz, the transmissibility of the helmet is relatively constant, is independent of the padding installed in the helmet, and shows that the forces in this frequency get amplified by the helmet. The transmissibilities below 50 Hz show considerable variation with the change in pad type. It is likely that the different boundary conditions provided by the different pad types caused this variation.

Figure 6b shows the transmissibility from the inside of the helmet to the surface of the head. This metric quantifies the effectiveness of the padding in attenuating the forces that were not dissipated by the helmet. For all pads except the glass- and foam-filled pads, the forces were attenuated throughout the frequency range. Both of these pads amplified forces in the 12-20 Hz range. Overall, these transmissibility results suggest that the glass- and sand-filled pads were least effective in attenuating forces, and the black pads were most effective. The foam-filled pads were very effective at high frequencies, but not as effective at frequencies below 17 Hz. The memory and gray pads had very similar transmissibilities.

Figure 6c shows the transmissibilities from the surface of the head to the center of mass of the head. It was expected that these transmissibilities would be very similar because the system between the surface of the head and the center of mass of the head did not change from test to test. However, as was the case with the transmissibility from the outside to the inside of the helmet, it appears that the response of the head is significantly affected by the boundary conditions provided by the padding. For all the padding types, most forces below 75 Hz are attenuated, with the most notable exception being the peak at 24 Hz. Above 75 Hz, the transmissibility between the surface of the head and the center of mass of the head appears to be a function of the padding type.

Finally, Figure 6d shows the overall transmissibility of the system, from the outside of the helmet to the center of mass of the head. Mathematically, this transmissibility is the product of the previous three transmissibilities that were discussed above. Qualitatively, this transmissibility is a measure of how effective the total helmet-padding-head system is at attenuating the impact force applied to the outside of the helmet. The trends in this transmissibility are similar to those in the padding transmissibility data shown in Figure 6b. The foam-filled pads and the black pads distinguish themselves as being most effective. Except at very low frequencies, the glass-filled, sand-filled, and memory pads have similar transmissibilities. The gray pads appear slightly more effective than those three pad types.

It is important to note that the frequency bands in which the brain is most susceptible to injury is not well understood. As stated earlier, many researcher are currently studying the correlation between different types of impacts and their effect on the human brain, but this topic is outside the scope of this work.

4.2 Impedance Modeling

The component- and system-level measurements that were described in Section 3 were used to calculate f_ω using Equation 7. Recall that in the derivation for f_ω, displacement frequency response functions (FRFs) were used. Experimentally, it is more common to measure acceleration-based FRFs. The relationship between displacement FRF (i.e. receptance) and the acceleration FRF (i.e. inertance) in the frequency domain is a multiple of $-\omega^2$, where ω is the frequency variable. Therefore, it is assumed here that the trends seen in f_ω calculated with acceleration FRFs will be similar to the trends in f_ω calculated from displacement FRFs.

Figure 7 shows the magnitude, the magnitude of the real part, and the magnitude of the imaginary part of f_ω calculated from data acquired with each of the six padding types installed in the helmet. By analyzing Equation 6, it can be determined that small values of f_ω are most desirable. As f_ω tends toward zero in Equation 6, the right hand side tends to zero. Physically, this means that the smaller the magnitude of f_ω, the less coupled the response at the surface of the head is to the force being applied to the helmet. Based on this reasoning, it can be observed that the trends in the amplitude of f_ω match well with what was observed in the transmissibility data. The sand-filled padding exhibits the overall highest magnitude for f_ω, while the black and the foam-filled pads have the lowest overall amplitudes. In the low-frequency range below 50 Hz, the magnitudes of f_ω calculated for the different pad types are similar. The most obvious differences in the f_ω values occur at frequencies above 100 Hz.

Also shown in Figure 7 are the magnitudes of the real and imaginary parts of f_ω. When f_ω is calculated using displacement data, the real part estimates the stiffness (K) of the padding and the imaginary part estimates the damping scaled by the frequency ($C\omega$). The values shown here are scaled by $-\omega^2$ because the calculation for f_ω was done using acceleration data. In general the trends observed in plot for the magnitude of f_ω are also observed in the magnitude of the real part of f_ω. There are several frequency bands in which the magnitudes of the imaginary part of f_ω exhibit unique trends for each type of padding. Without knowing the correlation between frequency band and risk of injury, it is difficult to draw conclusions about which trends may be desirable. If those correlations are established, this method provides a means for evaluating which paddings perform the best in certain frequency bands. By correlating the properties of the well-performing pads with the frequency bands in which they are most effective, designs for paddings that protect across broader frequency bands may become evident.

4.3 Drop Tower Testing

Three metrics were calculated from the data acquired from the drop tower tests. First, the peak acceleration was identified for each type of padding. Those results are shown, along with the raw time histories, in Figure 8. For the higher drop velocity ($\tilde{1}6\ ft/s$), the peak accelerations (red circles) were highest when the glass- and sand-filled pads were installed. The gray and memory foam pads performed the best. For the lower velocity drops ($\tilde{1}1.5\ ft/s$, black x's), the sand- and glass-filled pads again performed poorly, but the performance of the other pad types were less distinguishable. The second metric calculated for the drop tower data was the Severity Index (SI) and is shown in Figure 8d. The trends in the SI were very similar to those in the peak acceleration data.

The third metric calculated was the autopower spectrum of the acceleration measured at the center of mass of the head. The purpose of this analysis was to correlate the trends observed in the frequency domain with the time-domain metrics

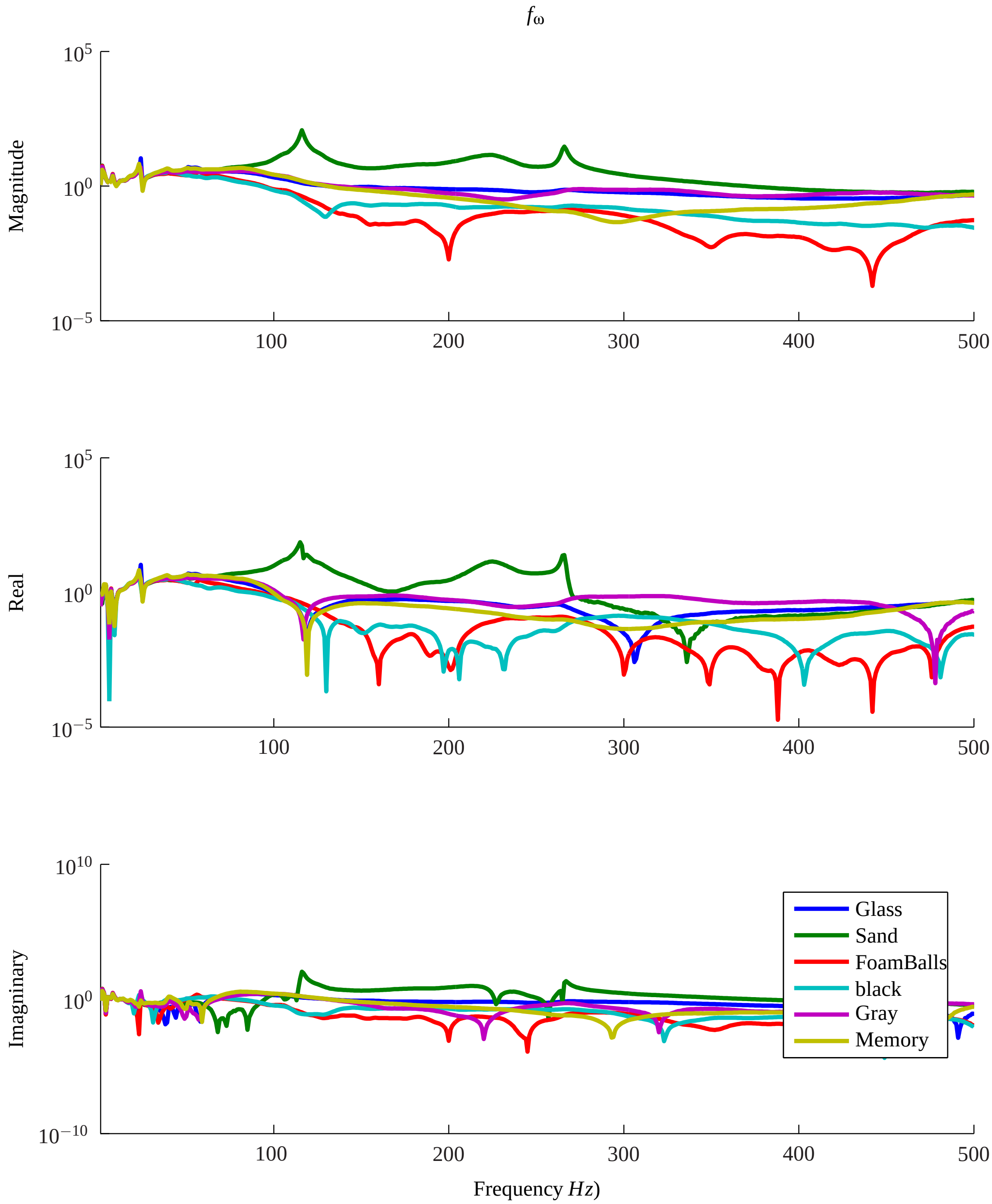
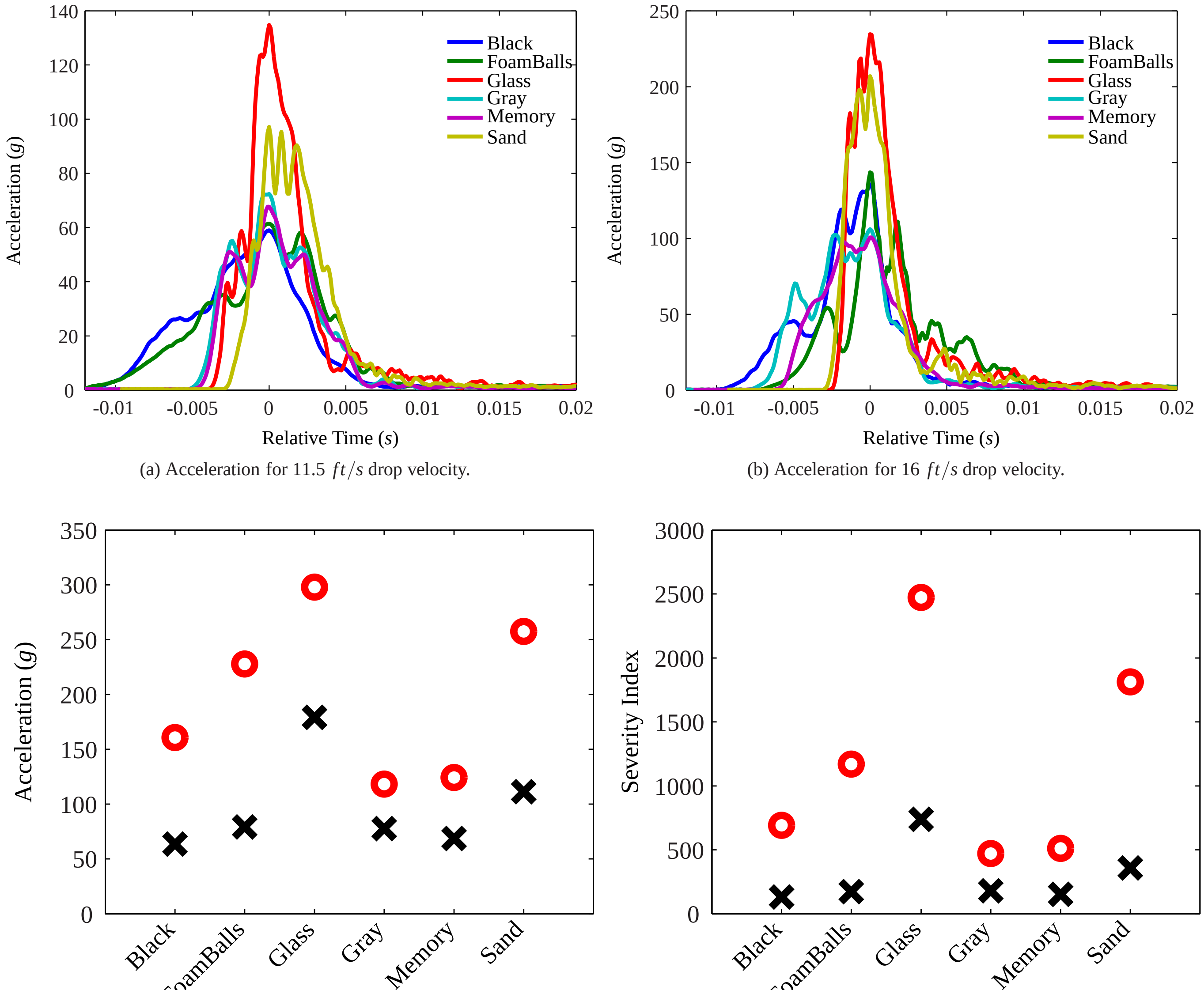


Fig. 7: The magnitude, magnitude of the real part, and magnitude of the imaginary part of f_ω.

described above. Figure 9 shows the spectra calculated from the acceleration measurements acquired with the different pad types installed and at each of the two drop velocities. The frequency range shown was chosen because it contains at least 95% of the signal energy. The autopower spectra exhibit the largest differences at frequencies above 50 Hz, although differences below 50 Hz are also apparent. The glass- and sand- filled pads have the highest amplitude across most of the frequency range. As the other metrics indicated, the differences between the other pads diminish for the lower drop velocity.

5 CONCLUSIONS

The current standards for evaluating a helmet's effectiveness in protecting a person from injury due to impacts are based on estimates of the amplitude and duration of peak acceleration experienced at the center of mass of the head. These methods



(a) Acceleration for 11.5 ft/s drop velocity.

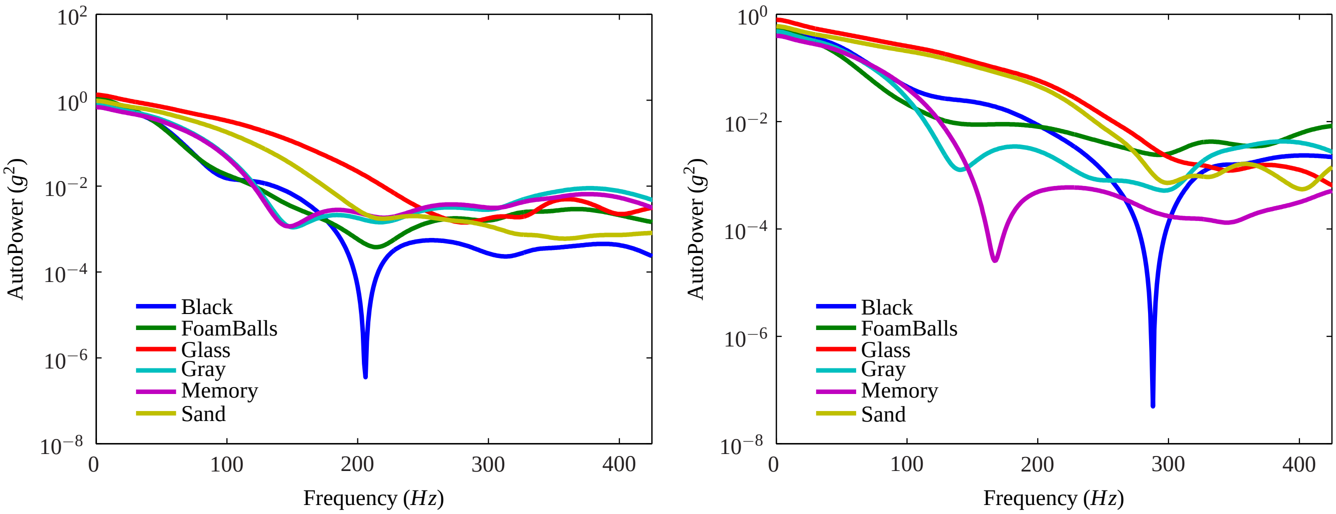
(b) Acceleration for 16 ft/s drop velocity.

(c) Peak Acceleration.

(d) Severity Index.

Fig. 8: Results from drop tower testing of combat helmet with different padding types using drop velocities of ~ 11.5 ft/s ($\circ$) and ~ 16 ft/s ($\times$).

reduce the performance of the helmet and its padding down to a single number, which is compared to an established threshold to grade the performance of the helmet. While these methods provide an indication of how well the helmet and its padding attenuate the forces that are transmitted through the helmet-padding-head system, they do not give any indication of how each component contributes to the effectiveness of the system. In this paper, two frequency-domain analysis techniques were presented. Transmissibility analysis was applied in order to characterize the contribution of each component of the helmet-padding-head system to the overall performance of the helmet. Impedance modeling was presented as a means to identify the material properties of a padding which lead to good performance. These two methods were applied to data acquired during impact testing on an Army combat helmet with standard and non-standard paddings installed. Both methods were able to identify the sand-filled pads as the poorest performers and foam-filled and black standard-issue pads as the best performers. Furthermore, the frequency range above 50 Hz was identified as the range in which the biggest differences in performance were observed. Data from drop tower testing was also analyzed in order to correlate the trends observed in the frequency domain with the standard metrics. Good correlation was observed between the amplitude of the autopower spectra calculated using the accelerations measured at the center of mass of the headform and the peak accelerations and severity indices calculated from the time-domain data. The data acquired from the higher drop velocity more clearly distinguished the differences in the performance of the different pads. Based on this observation, it is possible



(a) Autopower spectra for 11.5 ft/s drop velocity.

(b) Autopower spectra for 16 ft/s drop velocity.

Fig. 9: Frequency-domain results from drop tower testing of combat helmet with different padding types.

that the results from the frequency domain analyses would better show the differences in padding performances if higher force levels were used. Finally, in order for frequency domain analyses to be more meaningful, correlation between force levels in different frequency bands and injury must be established. When the frequency bands in which forces can the cause the most harm are known, frequency domain techniques such as transmissibility and impedance modeling will allow more effective padding and, therefore, safer helmets to be designed.

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