Comparative Analysis of Alpha Case Laser Doppler Vibration Testing at Polytec, Inc., Dexter, MI
March 12 – 15, 2018

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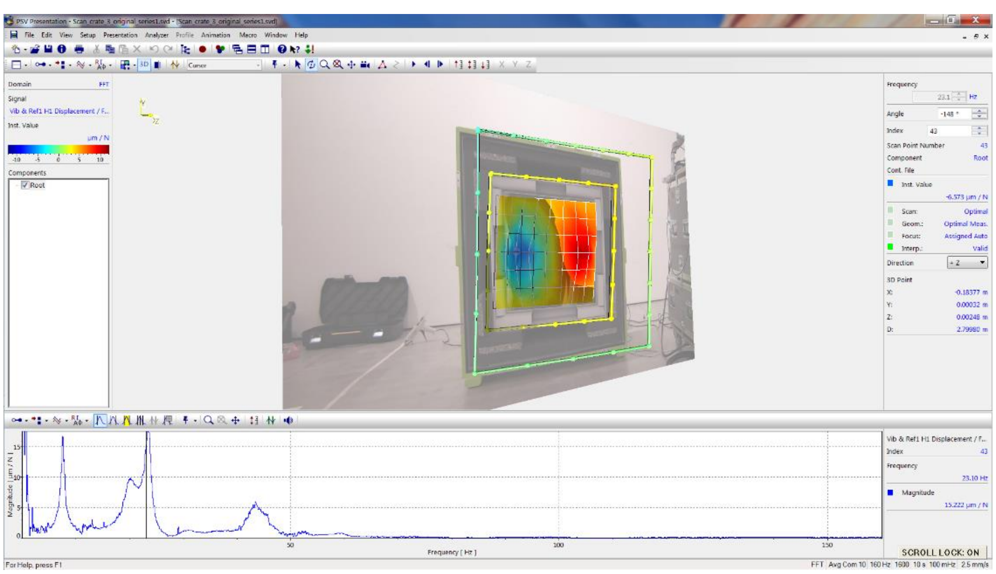
The problem we are trying to solve is how to minimize road-transit transmitted vibrations for canvas paintings in the range of 10 Hz to 50 Hz, which is the range at which canvas paintings have resonant frequencies and undergo the greatest fatigue-related damage. Below 10Hz, paintings tend to move as rigid solids, creating no differential stress within the canvas between restrained edges and unrestrained centers, or between heavily painted, rigid areas and thinly painted, more flexible areas.

Beyond 40 Hz, canvas painting displacements are incredibly small. The higher the sinusoidal frequency, the shorter the distance travelled between accelerations and the lower the velocity of the canvas returning through its neutral point. In these cases, displacements seldom reach a point where they can commonly cause fatigue of remaining chemical and mechanical bonds.

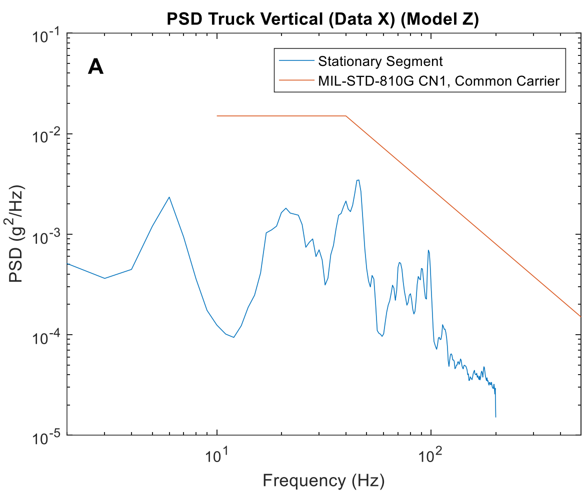
The existing travel paradigm for the transport of paintings suggests that accelerations and displacements in fine art transport trucks are so small, (typically 2 G to 4 G or 19.6 meters/s^2 to 39.2 meters/s^2), that the displacements of canvas paintings inside foam-padded, wooden crates will remain far below the restraining limits of the adhered aged paint, around 4mm for long-term, fatigue damage. Our best performing horizontal foam cushioned wood crate is a good example of why this is not always true.

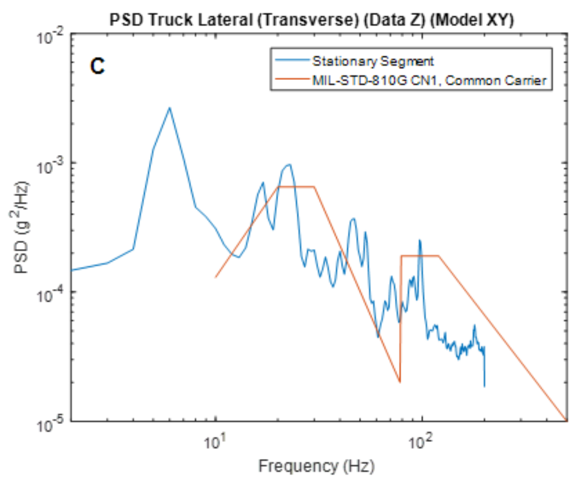
When canvas paintings are vibrated at frequencies near their resonant frequencies for first, second and third modal vibrations (frequently called "drum" modes), they continue to accelerate until the displacement of the canvas reaches the limit of the displacement-constraining materials; in our case, the design paint layers. At 23.4 Hz, and with tiny input accelerations and displacements of the crate and inner box holding the painting (less than 80 mm/s^2 /N and 4um/N, the canvas goes into 2nd harmonic resonance (double drum mode, pictured below) with



the canvas displacement reaching 23.5um/N, or 7.5mm displacement, 58 times the displacement of the outside crate. Typical continuous force from vibration accelerations (F=ma) are about 32 Newtons inside a truck, creating accelerations of about 2.5 meters/s^2 and movement of the crate and inner box of only 130 microns of displacement. The fact that a lined painting can move 7.5mm with such a small input force at a specific vibration frequency is the result of harmonic amplification.

Using a Wohler model for fatigue, 7.5mm would be more than enough canvas movement to break adhesion and cohesion bonds in 20th century oil paint after only five million cycles. At 23.4 cycles per second, the damage threshold is reached in only 60 cumulative hours of motor transport.





The problem is that the crates, cushioning foams and travel boxes transmit, and in some cases amplify vibrations in the region of 10 Hz to 40 Hz. Foams typically only begin to damp vibration frequencies above 140 Hz. A suspension system is required that will hold a canvas paintings in transit while minimizing exposures to vibration frequencies in the critical range of 10 Hz to 40 Hz. Fine art transport trucks generally transmit vibrations well below MIL-STD-810G CN1 of allowable accelerations per Hz in all but the lateral, side to side directions, but transmit vibrations greatest in all directions in the range of 20 to 50 Hz. With the alpha art transit case, we would like to create a suspension container that is tuned to have its natural frequency, (the frequency at which it excites and moves the most), below 10 Hz. In this case, every frequency above 10 Hz should have smaller and smaller accelerations, velocities and displacements. That is to say that we want to minimize the transmissibility above 10 Hz.

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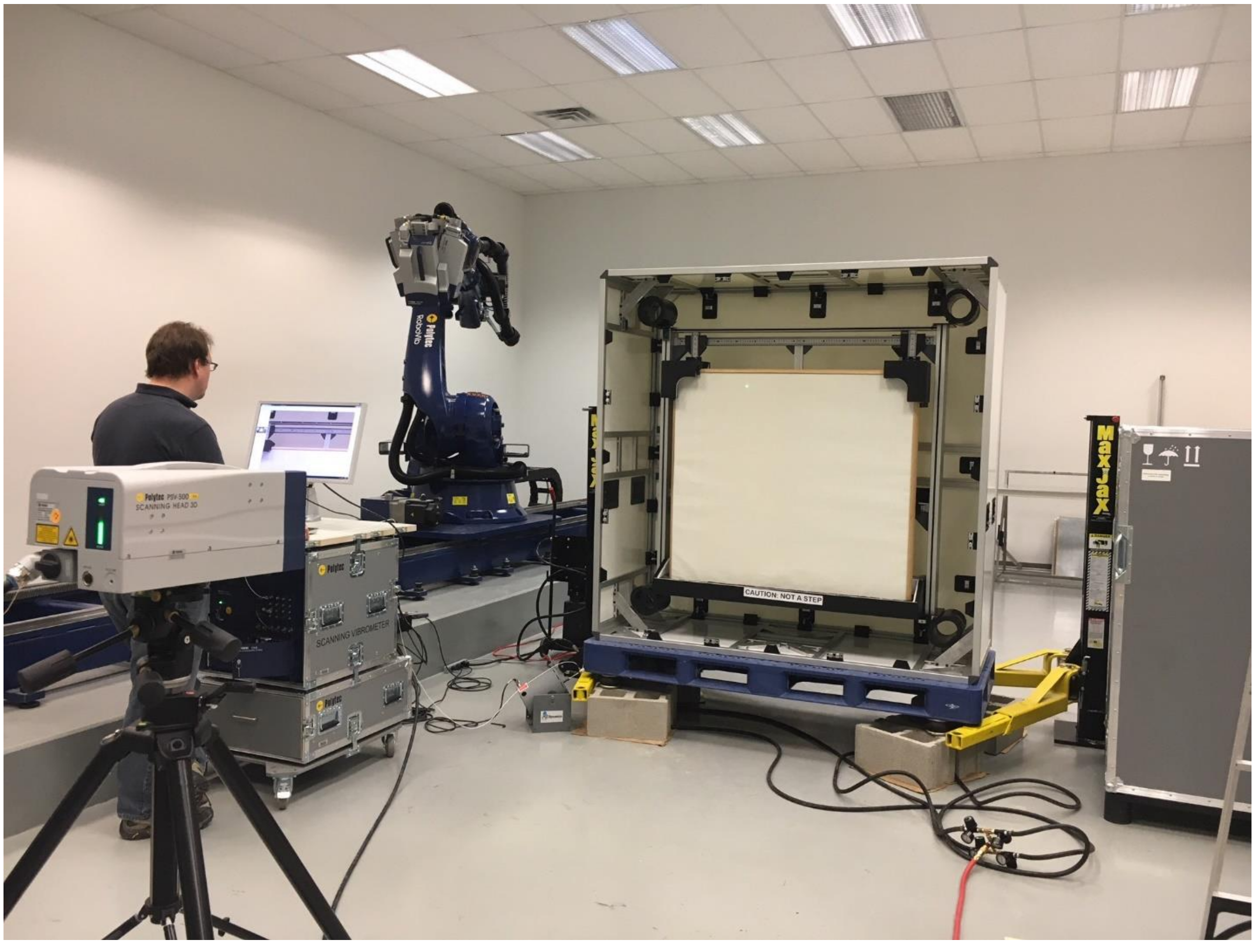

In scanning laser Doppler vibrometer testing at Polytec Inc.'s facility outside Ann Arbor Michigan, the alpha case generally displayed a decreasing curve of transmissibility, as engineered, with four exceptions, at or around 9 Hz, 11.25 Hz, 15 Hz and 18.25 Hz. At the lower edge of the suspension rack and across the top bar, displacements at these four frequencies range between 4 μm/N and 8 μm/N. At the centers of the vertical rails of the suspension rack, the displacements are much smaller, 3 μm/N and less. This indicates that movements of the suspension rack largely rock around the center of the horizontal axis, with the base generally moving more than the top except at 11.25 Hz, when top and bottom movement are roughly equal, at around 6 μm/N. The greatest displacements of the suspension rack are all at the bottom tray of the suspension rack and measure 8.2 μm/N at 9Hz, 8 μm/N at 11.25 Hz, 4.6 μm/N at 15 Hz and 7.5 μm/N 18.25 Hz. This is troubling in that the displacements of the bottom of the suspension rack at these frequencies are in fact greater than the displacements of the corresponding points on the base of the exterior case.

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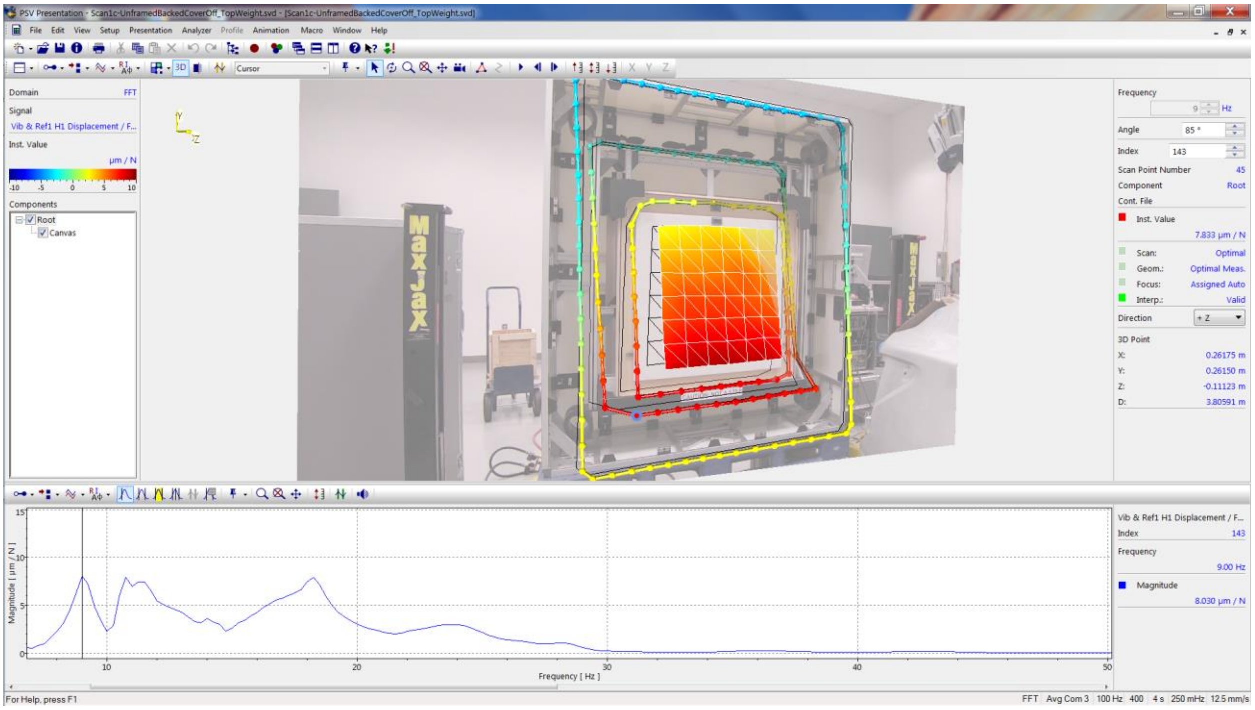
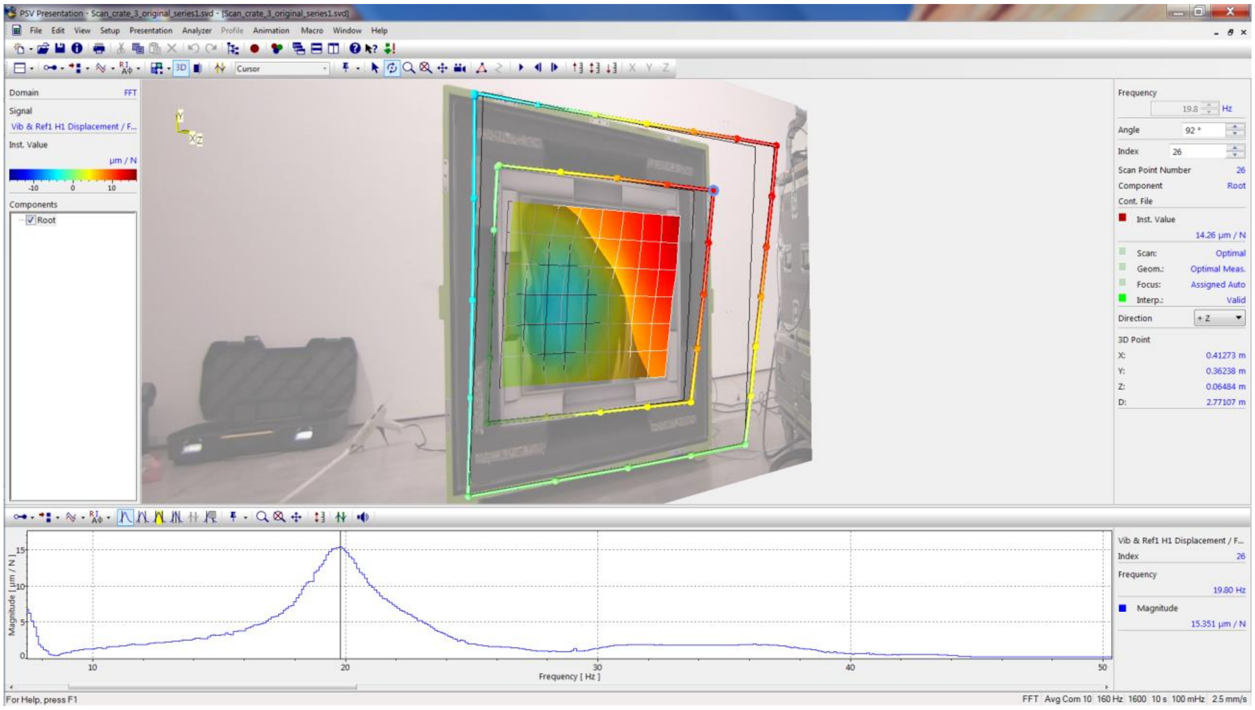


The outer case of the alpha crate shares the resonances of the inner suspension rack at around 9 Hz, 11.25 Hz, 15 Hz and 18.25 Hz. The lower corner of the alpha case exterior where the vibration impulses were applied had a displacement of 13 µm/N at 18.25 Hz. They then rapidly decrease to 6 µm/N at the opposite bottom corner and 3 µm/N or less at the sides and tops of the case.

The extremely good news is that at all the points measured around the inner suspension rack, displacements at frequencies above 18.25 Hz are below 2µm/N, safely below the 5µm/N target. <u>This means that for all paintings with resonant modal frequencies above 18.25 Hz, there are almost no transmitted vibrations</u>.

The vibration transmissibility and damping performance of the alpha suspension rack remains considerably better than our best tested wood crates. In our best horizontal, foam-cushioned, wood crate tested to date, transmission of frequencies of the inner boxes decrease normally from 8 Hz, where the displacements are around 14 µm/N, to the region beginning at around 20 Hz, where they begin to increase rapidly, exceeding 7 µm/N and reaching a peak displacement of 15 µm/N at the highest point of the inner box, directly above the impulse corner.



The 20Hz vibration region is also the natural frequency of the wood outer crate and it is at this frequency that the foam cushions amplify the transmitted vibrations through additive interference. The outer crate and inner travel box remain in phase but the inner box is moving more than the outer box, by as much as 30%. This is what makes wood crates cushioned with foam so dangerous from a continuous road vibration standpoint.

Our typical vertical wood crates have equally poor performance. These crates have resonant frequencies around 12 Hz, 24 Hz and 38 Hz. Typical displacements are around 7 μm/N to 12 μm/N for the outer crate and 8 μm/N to 12 μm/N for the inner travel box.

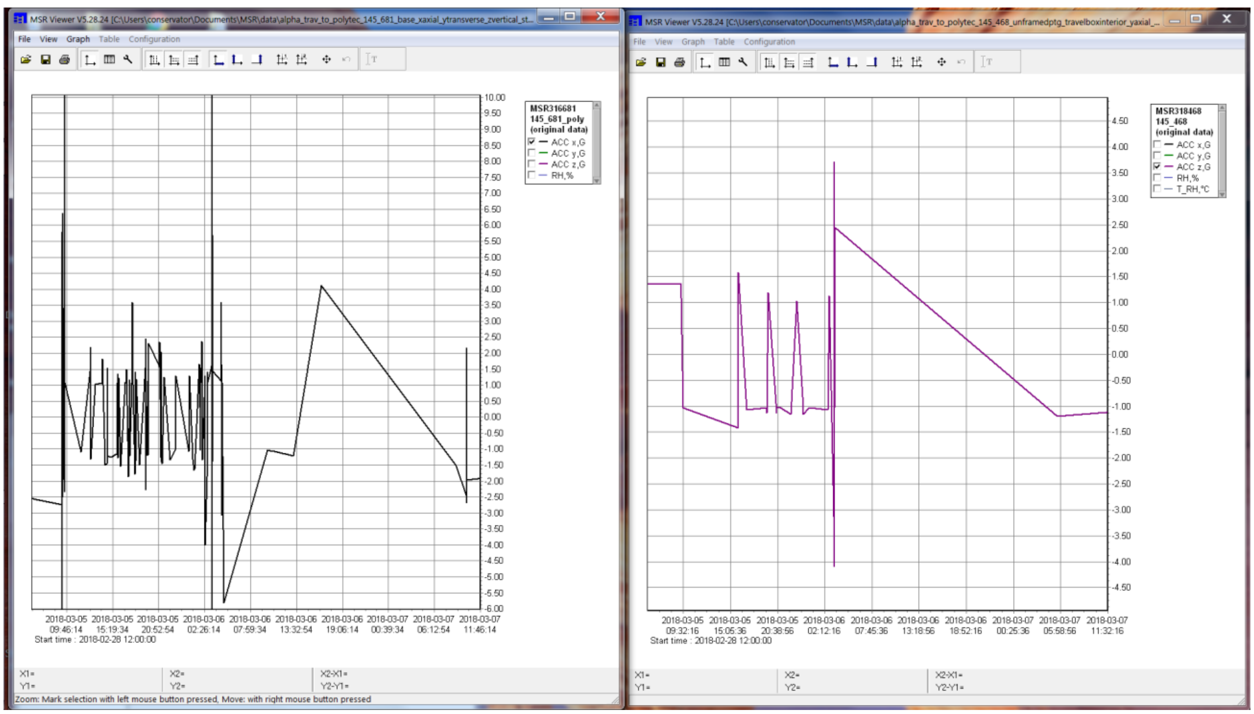
The outer case of the Alpha crate shares the resonances of the inner suspension rack at around 9 Hz, 11.25 Hz, 15 Hz and 18.25 Hz. The lower corner of the Alpha case exterior where the vibration impulses were applied had a displacement of 13 μm/N at 18.25 Hz. They then rapidly decrease to 6 μm/N at the opposite bottom corner and 3 μm/N or less at the sides and tops of the case.

The testing suggested that the resonant frequencies of the outer alpha crate can be further raised by reinforcing the exposed polypropylene honeycomb panel skins by adhering rigid, light-weight paper honeycomb panels on the interior. This further eliminate transmitted and harmonic low vibration frequencies inside the case and improve the 10° C temperature change per hour rate of thermal transmission in cold and hot weather.

The testing further suggested that improving the rigidity of the suspension rack system at the point of corner and base tray adjustment and attachment, as well as the corners and tray elements themselves, improve the performance of the amplified resonant frequencies exhibited by the suspension rack.

The skyped polyethylene foam "fingers" within the tray and corners of the suspension rack marked the enclosed artwork and travel box with black charcoal as a result of vibrations received in transit. Either a non-marking foam should be found or transit should require artwork wrapping.

The accelerometer data used in transit of the alpha case to and from Polytec, Inc., Ann Arbor also revealed important insights into the performance of the suspension system.



Comparing the critical transverse vector shock accelerations of the alpha case base exterior in black, left and the suspension rack in magenta on the right, above, we can note that both the frequency and severity of shocks above 2G were reduced during transit.

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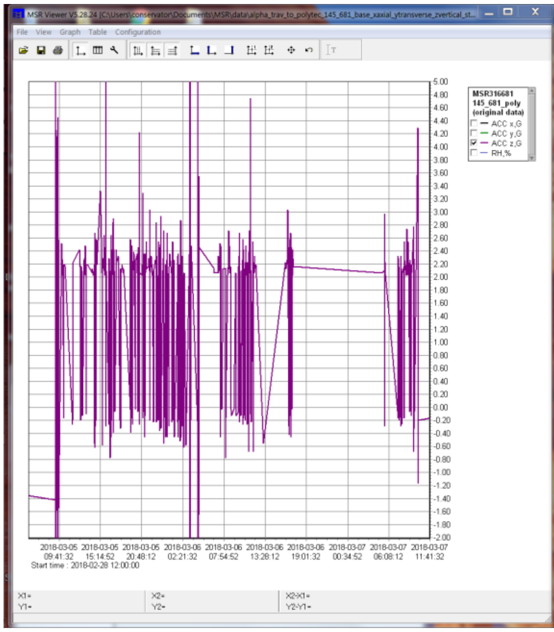
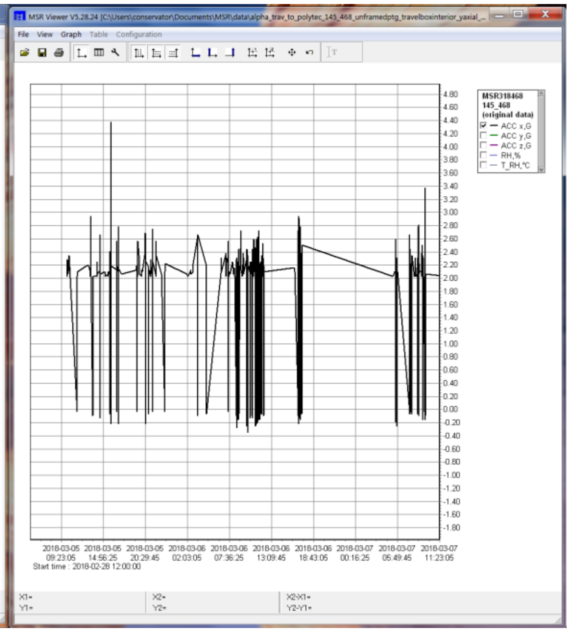

Likewise, comparing the alpha case exterior vertical vector accelerations in transit in magenta, left to the suspension rack in black, on the right, we can note a complete damping of all major shock impulses over 6 G and a significant reduction in all shocks over 2G.

Finally, it is also important to note that in shock and vibration impulses over 0.5 G acceleration, the new alpha suspension system provides an immediate, normal ring-down over about 500 milliseconds. Foam-cushioned crates create a "bounce-back" undamped spring action wherein impulses over 0.5G are first accelerated over several cycles from additive interference of the opposing foams, followed by a slower ring down. A typical ring-down behavior of the suspension system on the facsimile painting following a 4G truck acceleration is pictured below.