Measurement of Force in IED Vehicle Interactions

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Abstract High-rate vertical acceleration and resulting force measurements from underbody blast events are routinely being replicated in laboratory environments. A knowledge of the input force time history requires acceleration time history data of the rig structure designed to measure force for mass compensation computations. These mass compensation computations are difficult to perform, however, as a function of accelerometer resonance and the accelerometer's propensity to express modes in the load-measuring structure. One needs to apply a filter to such accelerometer data, but at this time there is no standard methodology for deriving an appropriate filter. Current researchers trying to measure input forces either do not report the filter frequencies used in mass compensation computations or use current standards derived for different applications than what the experiment may entail. The hypothesis of this study is that, with load cells of appropriate response characteristics, one can infer an optimized filter for acceleration time histories used in mass compensation computations. The proposed methodology applies a number of filters to acceleration data, then computes the standard deviation of mass cancelled data with no specimen present, and defines the best fit acceleration data as those with the minimum standard deviation after mass compensation has been performed.

Keywords Mass compensation, underbody blast, vertical loading, high-rate loading

I. INTRODUCTION

When studying the response characteristics of Post Mortem Human Surrogates (PMHSs) exposed to vertical high amplitude and short duration forces in the Society of Automotive Engineers' –Z direction (SAE-Z, inferior to superior), like those seen in underbody blast environments, a knowledge of the input force time history can prove useful in drawing conclusions about such factors as fracture time, specimen response and anthropomorphic test device (ATD) response. Measuring input loads imparted into test specimens necessitates a knowledge of the acceleration time history of the instrumentation and test structure needed to make such load measurements. As a function of accelerating load-measuring instrumentation and load-measuring structures, a force time history is observed by instrumentation, and it is this force time history that needs to be removed from overall force observations; the force to be removed is derived by multiplying the mass of the measuring instrumentation and corresponding measurement structures by the acceleration they undergo--mass compensation.

Current literature investigating the consequences of vertical loading on PMHSs primarily incorporate filter guidelines from the SAE Instrumentation for Impact Test document for mass compensation computations, or do not report filter types applied to acceleration data for mass compensation [1-5]. SAE Channel Frequency Class (CFC) filter frequency cutoff values have a range of frequencies designed for a variety of measurements; for example, spine accelerations in an ATD are to be filtered with a CFC 180 filter which has a frequency cutoff value of 300 Hz [6]. These filter cutoff values are specific to vehicle structures and ATD instrumentation, and may not be applicable to the variety of testing conditions in which they are being applied.

In studies by Yoganandan et al. [1-2], PMHS lower extremities are impacted by a massed pendulum, and mass compensation of a load cell plate structure is computed with no filter recommendations reported. In a study by Kitagawa et al. [3], PMHS lower extremities are impacted by a massed pendulum with a load cell accelerometer combination affixed to the striking portion of the pendulum, and accelerometer data for mass compensation

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are filtered with a CFC of 1000 (1650 Hz low pass filter (LPF)). In a study by Funk et al. [4], PMHS lower extremities are impacted by a linear impactor or compound pendulum, and mass compensation computations are performed after accelerometer data are filtered with a CFC of 180 (300 Hz LPF). Lower extremity injuries studied by Henderson et al. [5] utilize a drop tower assemblage to impact a potted lower leg, and acceleration data are filtered with a CFC or 1000 (1650 Hz LPF) for mass compensation computations.

The Center for Applied Biomechanics' linear impactor is designed to deliver high amplitude and short duration force time histories, the same as those seen in underbody blast events, via the translation of a platen assemblage with a restricted stroke length into specimens constrained by a number of different boundary conditions, as called for by a specific experiment, with energy delivered to the platen via a pneumatically-driven mass. When the pneumatically-driven mass strikes the platen, accelerometers can go into resonance and express localized modes of the load-measuring structure, making mass compensation of the structure-induced force difficult. The purpose of this research is to develop a methodology to appropriately filter acceleration data used in mass compensation, therefore allowing researchers to measure input loads during simulated underbody blast experiments.

The hypothesis of this study is that with load cells of appropriate response characteristics one can infer an optimized filter for acceleration time histories, and use those acceleration time history data in mass compensation computations.

II. METHODS

Test specimens are placed between the top platen and carriage sled (see fig. 1). A prescribed gap of 2.54 cm is created on the guide rails at the bearing block/polyurethane decelerator interface; this gap allows for unimpeded translation of the seat platen/top platen structure during this distance. A pneumatically-driven linear impactor strikes the seat platen via several pulse shaping layers consisting of 80-60 durometer polyurethane. When the linear impactor strikes the seat platen, the seat platen/top platen structure translates via the two guide rails affixed to stationary bearing blocks. The carriage sled is a non-fixed boundary condition and is also allowed to translate during experimentation along two tracks and four bearings.

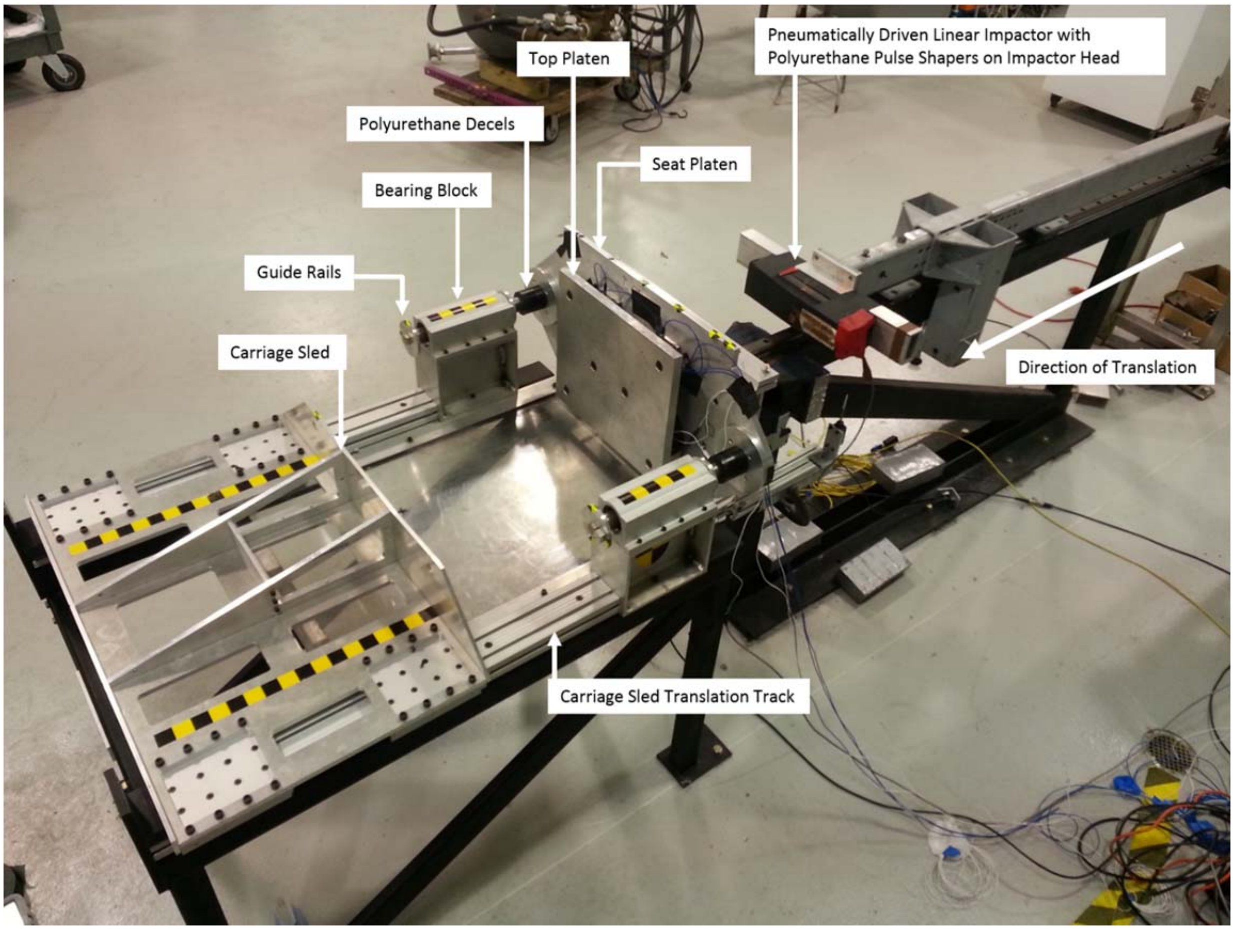

Fig. 1. Image of linear impactor system; the direction of translation for all components is from right to left.

Between the seat platen and top platen are three single-axis piezoelectric impact style load cells, model number 200C50 (PCB Piezotronics, Depew, NY). The top platen is hand tightened to yield as small a precompression as possible while keeping it securely affixed to the seat platen. These load cells have a compression capacity of 222.4 kN, a response frequency of 30 kHz, and consist of a load cell and convex impact cap. The load cells are specifically chosen due to anticipated uneven loading of the cell surfaces during experimentation. As a function of the striking energy delivered by the linear impactor, modes develop in the two-platen structure resulting in a non-parallel interface. These modes can induce concentrated stress points on flat load cells, potentially damaging them, and/or induce a large moment on such load cells yielding inaccurate measurements. With the presence of a convex impact cap, stress concentrations can be distributed and moments on the load cell can be avoided as misalignments between the load application direction and the centerline of the load cell occur.

Affixed to the top platen are three linear piezoresistive accelerometers model number 7270A (Meggit Sensoring Systems, Irvine, CA). Accelerometer 1 is located 5.08 cm above load cell 1, about its center line; accelerometer 2 is located 5.08 cm below load cell 2, about its center line; and the corner accelerometer is located at the very right corner of the top platen. Accelerometers are mounted to the facet of the top platen that faces the load cells, and are deliberately affixed to the top platen in locations that exhibit varying amounts of support structure, with accelerometers 1 and 2 located near bolt anchorage and load cell points, and the corner accelerometer at the least-supported point on the top platen where only a single bolt facilitates contact (see fig. 2).

These accelerometers have a 6000 g capacity and a nominal mounted resonance frequency of 180 kHz. The accelerometers are used to compute the force incurred upon the three piezoelectric load cells as a function of accelerating the load cell/platen structure via the formula below:

$$F = ma \quad (1)$$

where F is force (N), m is mass (kg), and a is acceleration (m/s/s).

The mass used for force calculations consists of the top platen, top platen hardware and the total mass of the load cells--7.81 kg. Bolt hardware is not threaded into any surface and is secured in place with nuts on the back end of the seat platen; this prevents any load from being shunted past the load cell array.

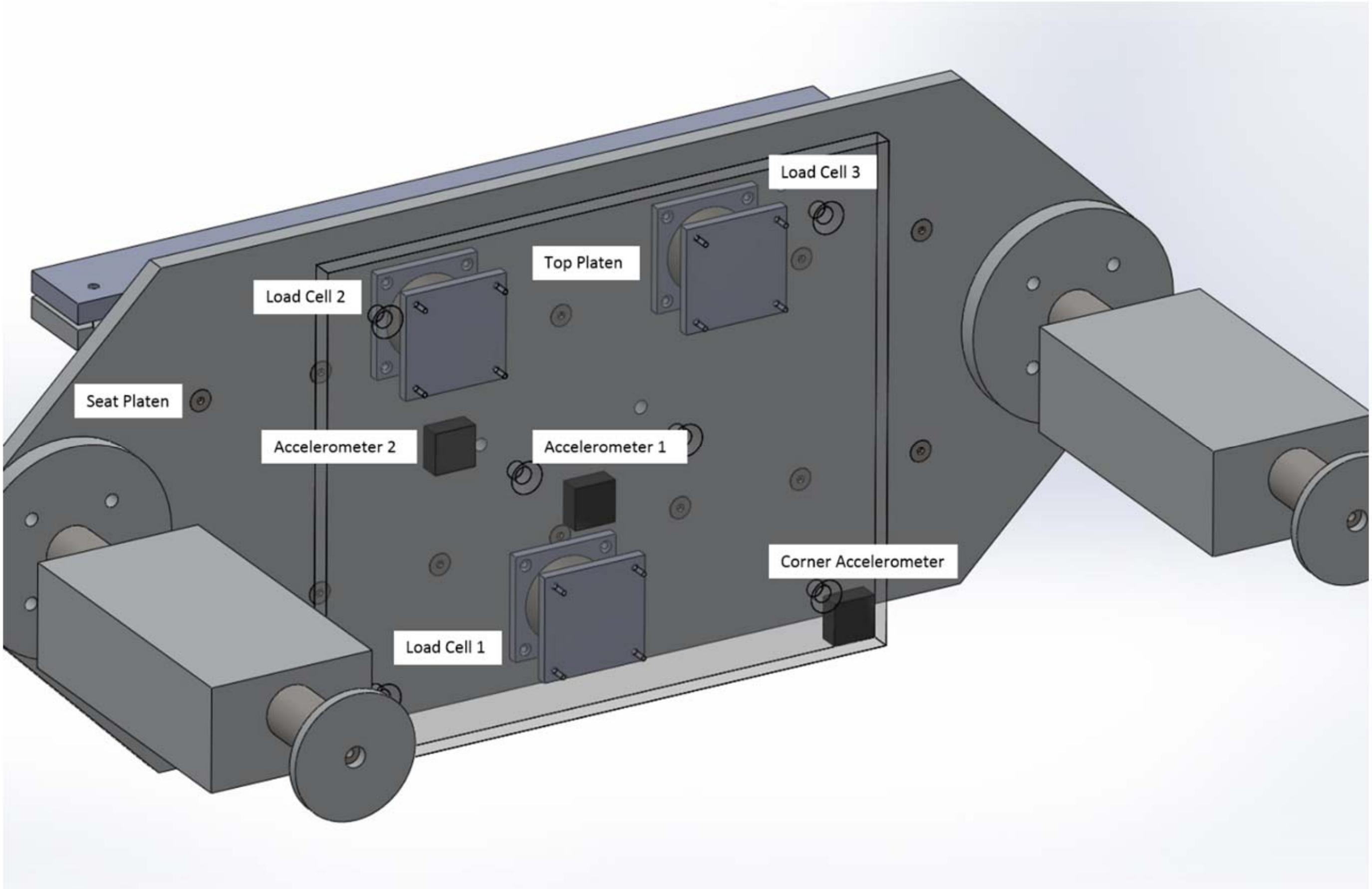

Fig. 2. A close-up image of the seat platen/load cell/ top platen assemblage, showing the load measuring structure.

Data are collected on a Synergy 7027 unit (Hi-Techniques, Inc., Madison, WI) at 1 MHz with an anti-aliasing filter of 200 kHz. Sampling at a specific frequency does not mean one can resolve that particular frequency; a single sample point taken at 1 MHz increments cannot describe a frequency period of 1 MHz, meaning that only frequencies much below the sampling frequency can be resolved accurately. Filtering of acceleration data consists of using the load cell sum data as the metric for accuracy; due to the construction of the load measuring structure, an assumption is made that all combined loading it may induce upon itself during a loading event is focused through the three load cell points, yielding a load over time history of the entire top platen. Spectrogram plots were derived to check for load cell content at 30 kHz (the load cell's response frequency). Spectrogram plots of both individual load cells and load cell sums were generated to verify that load cell content is not approaching the cell's stated response frequency.

Accelerometers needed to perform mass compensation calculations express localized acceleration time histories as a function of the modes that the load-measuring structure expresses. Single accelerometers and averaging multiple accelerometers are studied to approximate the global acceleration of the load-measuring structure. The selection criteria for an appropriate filter is chosen as a function of the filter's capacity to attenuate acceleration multiplied by mass data to best match load cell data during experimentation, with nothing present atop the top platen. Best matched acceleration multiplied by mass data are defined as the minimum standard deviation of load data after mass compensation of the load region of interest has been computed. Mass compensation is performed by subtracting filtered acceleration multiplied by mass data from load cell data if filtered acceleration multiplied by mass data are below zero, indicating acceleration (compression), and preserving the load cell data when acceleration is above zero, indicating deceleration (tension). Because the load cells are not coupled to the top platen to measure tension, deceleration measurements indicated by accelerometer(s) measure as zero load on the load cells; thus these otherwise tension data are disregarded in mass compensation.

An iterative process with frequency steps of 50 Hz resolution from 50 to 20k Hz applies a series of 4-pole zero-phase Butterworth filters to acceleration data and performs the aforementioned computations to produce a filter that minimizes the standard deviation of load cell data after mass compensation from structure-induced forces has been computed.

To test the effects of different input conditions on the load-measuring structure, the load cell platen structure is impacted by the pneumatic linear impactor at two input conditions--172.37 kPa and 241.32 kPa--with no specimen atop the top platen and three repeat tests apiece. To test the effects of a specimen present atop the top platen, the load imparted into a 25.09 kg rigid body placed between the top platen and carriage sled is computed at the 172.37 kPa input condition, and an identical test is performed except with 5.08 cm of 30 durometer Sorbothane® (Sorbothane, Inc., Kent, OH) placed between the rigid body and the top platen.

III. RESULTS

Tables 1 and 2 present a summary of ideal low pass filter frequencies computed to best fit acceleration multiplied by mass data to load cell data. These filters are designed to reflect the minimum standard deviation of resulting data after mass compensation has taken place with no specimen atop the top platen. The data represent three tests performed at two different input conditions as a function of rig input pressure.

Table 1
172.37 kPa Input Condition

Sensor Configuration	Filter Frequency: Tests 1,2, and 3			Mean and Standard Deviation: Tests 1,2, and 3		
Two Accelerometer Avg. Accelerometers 1 and 2	900	900	900	M=-54.79 SD=332.99	M=-61.54 SD=303.53	M=-40.30 SD=329.62
Accelerometer 1	750	800	750	M=-99.52 SD=471.74	M=-101.24 SD=439.41	M=-70.25 SD=466.76
Accelerometer 2	1000	1000	1000	M=7.9 SD=399.71	M=0.85 SD=349.76	M=19.68 SD=395.37
Corner Accelerometer	500	500	500	M=-56.24 SD=668.69	M=-59.82 SD=648.33	M=-29.36 SD=660.75

Table 2
241.32 kPa Input Condition

Sensor Configuration	Filter Frequency Tests: 1,2, and 3			Mean and Standard Deviation: Tests 1,2, and 3		
Two Accelerometer Avg. Accelerometers 1 and 2	1000	950	950	M=-280.19 SD=508.23	M=-123.78 SD=529.61	M=-315.38 SD=530.13
Accelerometer 1	750	650	600	M=-362.08 SD=739.02	M=-203.56 SD=701.25	M=-385.28 SD=730.00
Accelerometer 2	1050	1250	1000	M=-197.40 SD=663.40	M=-65.18 SD=563.80	M=-231.36 SD=625.08
Corner Accelerometer	450	450	150	M=-285.36 SD=1082.68	M=-124.43 SD=970.03	M=-318.71 SD=1079.15

Tables 3 and 4 show the differences between mean filter frequencies. An f-Test is conducted for each combination of sensor configurations for a check of equal or unequal variance between each sensor configuration; the appropriate t-Test is then conducted as a function of the equivalence of the variance between each sensor comparison combination. For the 172.37 kPa input condition only accelerometer 1 garners a difference in computed frequencies (i.e. has any standard deviation); the sample mean of accelerometer 1's frequencies are different than those of the other accelerometer configurations.

Table 3
Comparison of Accelerometer 1's Filter Mean and Different Sensor Configurations
172.37 kPA Input Condition, No Test Specimen

Sensor Configuration	t-test significance
Two Accelerometer Avg.	t(4)=-8; P<0.05
Accelerometer 2	t(4)=-14; P<0.05
Corner Accelerometer	t(2)=16; P<0.05

Positive t statistics indicate the mean of accelerometer 1 is larger than that of the sensor configuration it is being compared to, and vice versa for t statistics that are negative.

Table 4
Comparison of Filter Means for Different Sensor Configurations
241.32 kPA Input Condition, No Test Specimen

Sensor Configuration 1	Sensor Configuration 2	t-test significance
Two Accelerometer Avg.	Accelerometer 1	t(4)=6.36; P<0.05
Two Accelerometer Avg.	Accelerometer 2	t(2)=-1.70; P>0.05
Two Accelerometer Avg.	Corner Accelerometer	t(2)=6.08; P<0.05
Accelerometer 1	Accelerometer 2	t(4)=-4.91; P<0.05
Accelerometer 1	Corner Accelerometer	t(4)=2.89 P<0.05
Accelerometer 2	Corner Accelerometer	t(4)=5.96 P<0.05

Positive t statistics indicate the mean of configuration 1 is larger than the mean of configuration 2, and vice versa for t statistics with a negative value. The means of computed filter frequencies for the two accelerometer average and accelerometer 2 comparison are not statistically different.

In Table 5 computed filter frequencies are compared to each other between the two different load applications to detect differences between the mean of frequencies; again, an f-Test is conducted for each comparison to determine the equivalence of the variance, as to apply the appropriate t-test.

Table 5
Sensor Configuration Filter Mean Comparisons for Both Input Conditions

Sensor Configuration 172.37 kPa	Sensor Configuration 241.32 kPa	t-test significance
Two Accelerometer Avg.	Two Accelerometer Avg.	t(2)=4; P>0.05
Accelerometer 1	Accelerometer 1	t(4)=-2.12; P>0.05
Accelerometer 2	Accelerometer 2	t(2)=1.31; P>0.05
Corner Accelerometer	Corner Accelerometer	t(2)=-1.5; P>0.05

Data indicate there are no statistical differences between means of identical accelerometer configurations as a function of changing input conditions.

Figures 3 through 5 show a representative sample of load data compared to accelerometer multiplied by mass data filtered at computed filter cutoff values with no specimen present. Figures 6 and 7 are load time histories garnered from tests with a rigid specimen placed between the platen and carriage; figure 6 has no compliant interface between specimen and top platen, while figure 7 has a 5.08 cm 30 durometer Sorbothane® interface between specimen and top platen. Where different filters are computed for identical testing conditions, filters are averaged over all three filters. Each figure includes the average of accelerometer 1 and 2 multiplied by the mass of the load-measuring fixture, either unfiltered or filtered, and the sum of all three load cells; filters are applied to accelerometer data only, and are 4-pole Butterworth low-pass zero-phase filters.

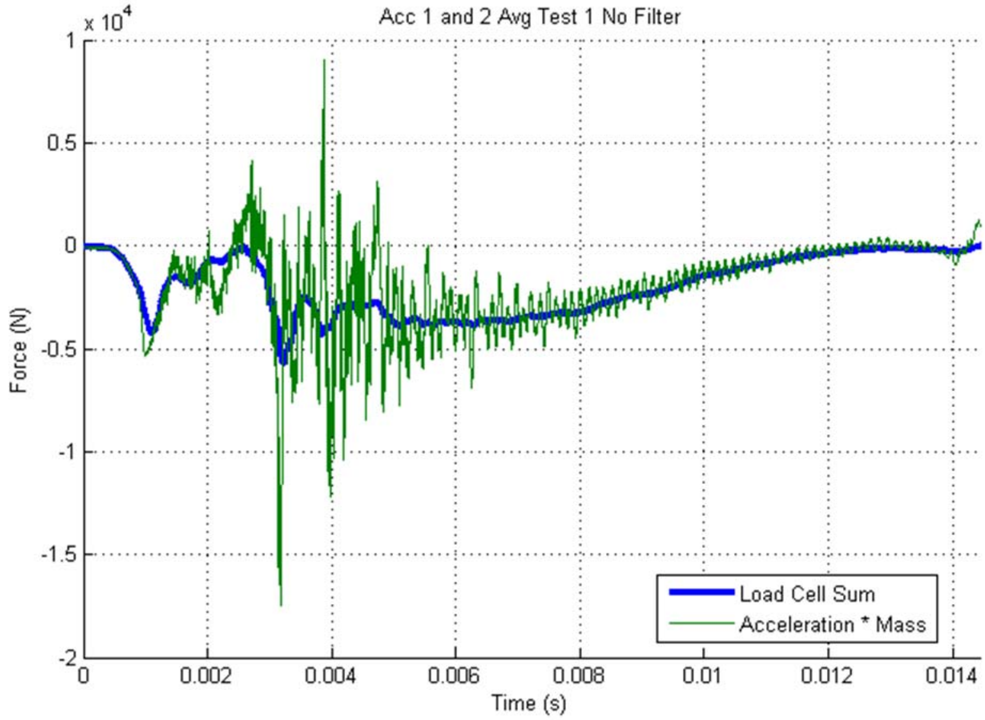

Fig. 3. A comparison of unfiltered acceleration and load cell data; 172.37 kPa. No specimen present.

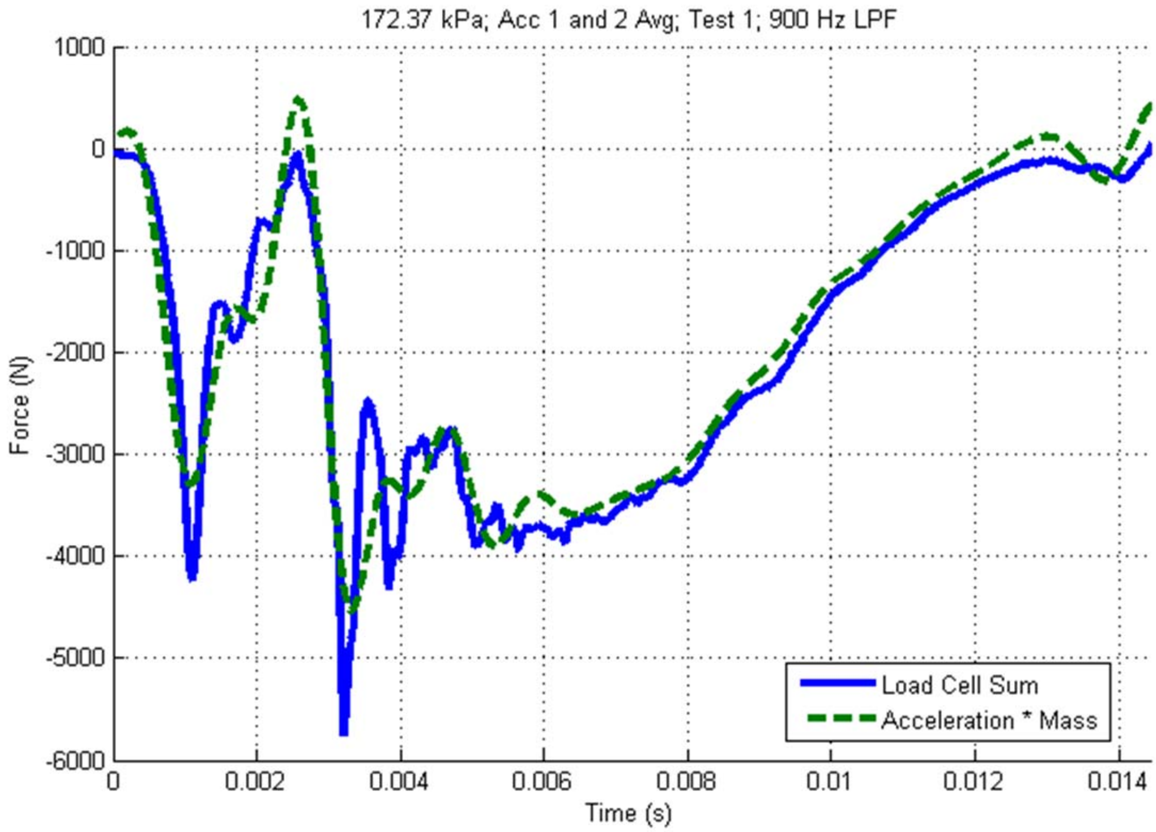

Fig. 4. A comparison of filtered acceleration data and load cell data. No specimen present.

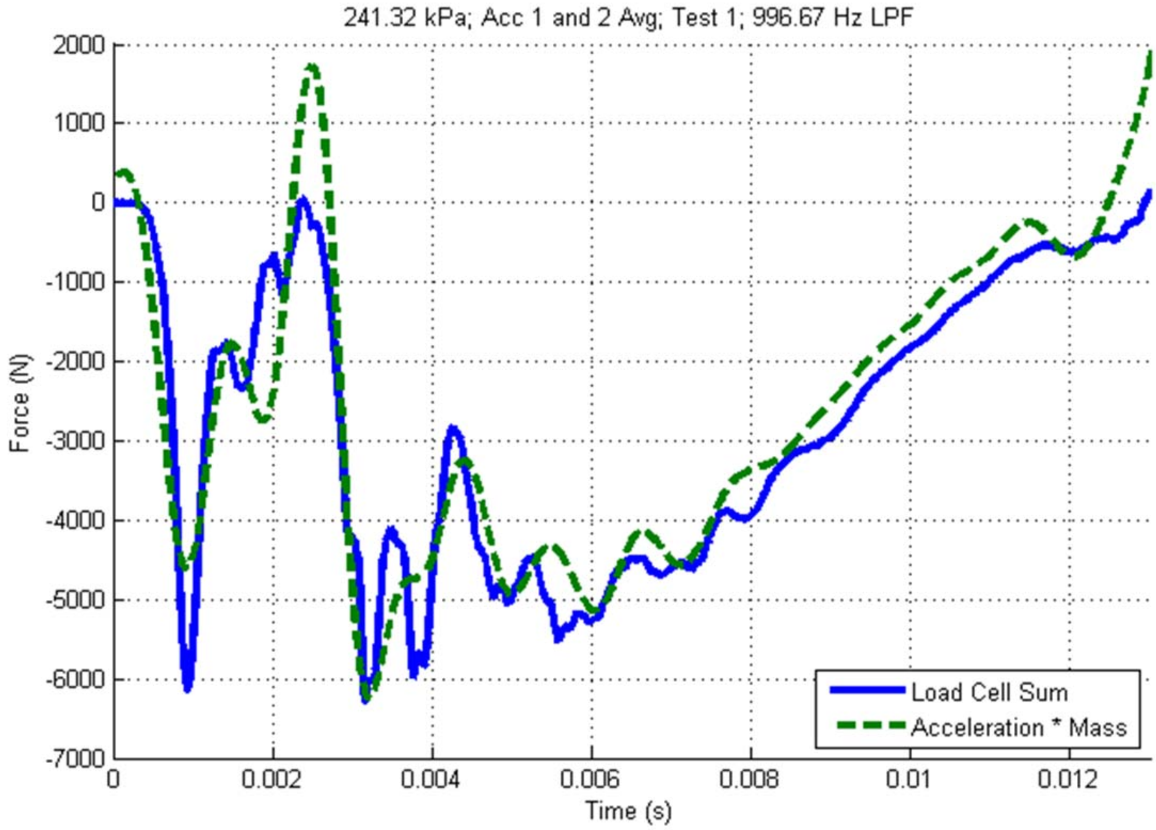

Fig. 5. A comparison of filtered acceleration data and load cell data. No specimen present.

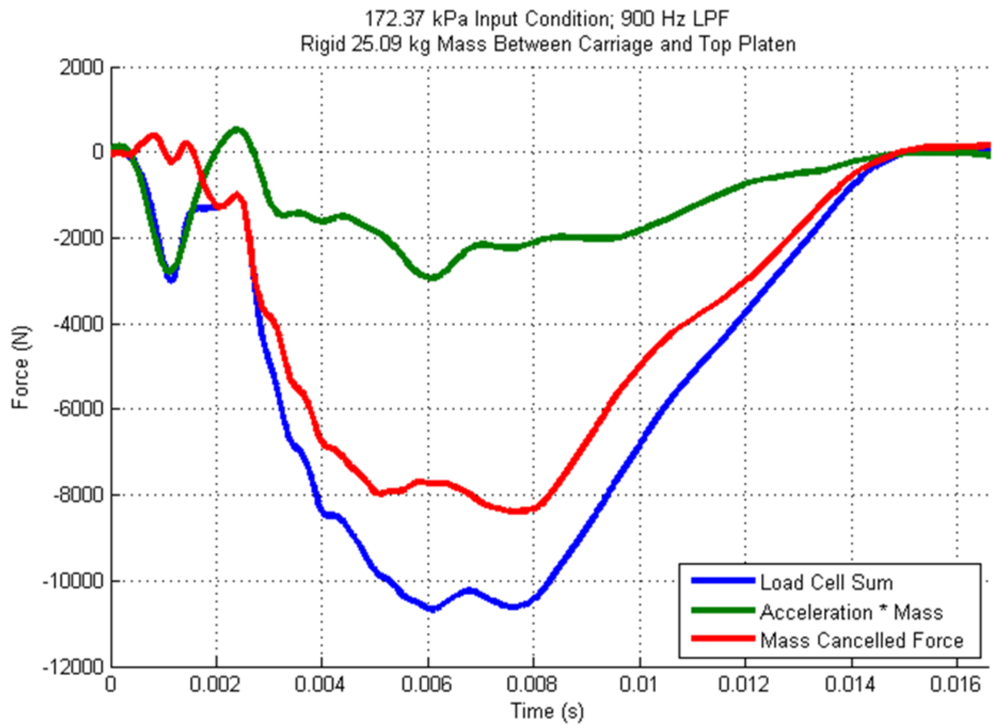

Fig. 6. A comparison of filtered acceleration data, load cell data and the resulting force after mass compensation with rigid specimen present.

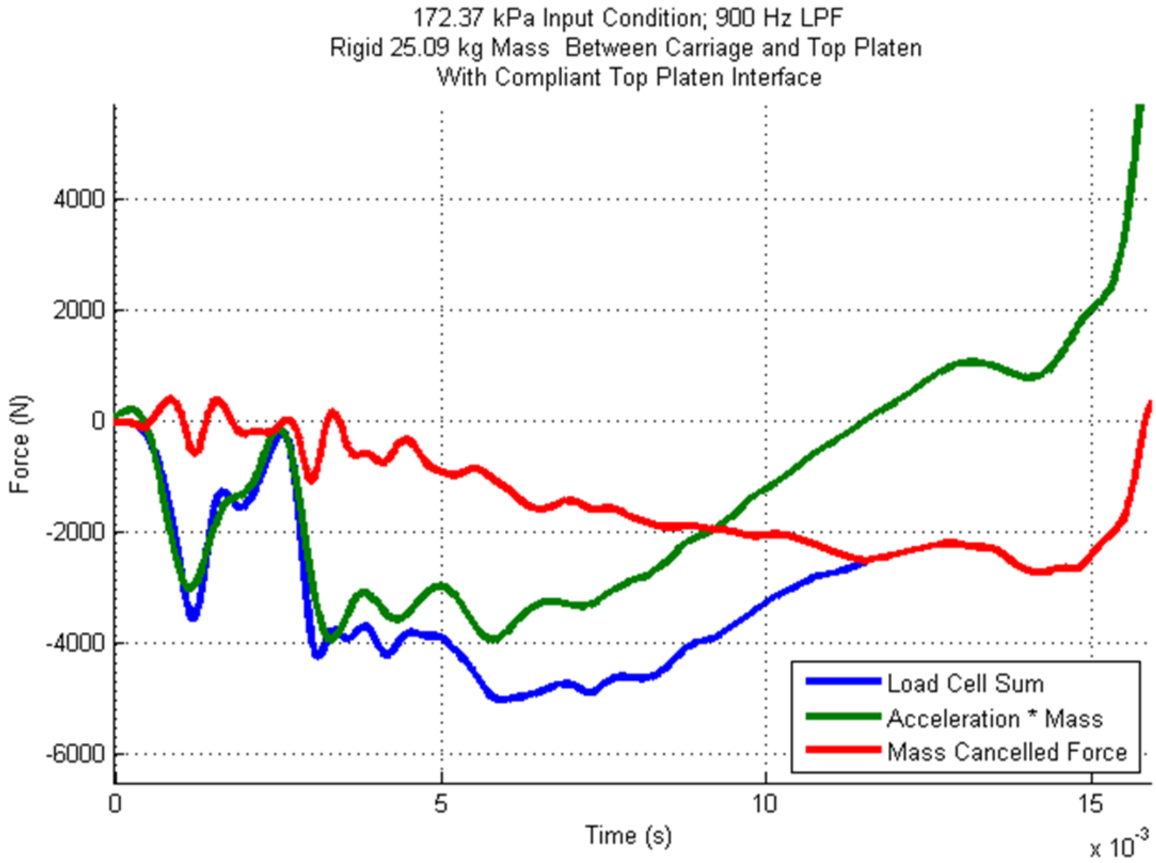

Fig. 7. A comparison of filtered acceleration data, load cell data and the resulting force after mass compensation. 5.08 cm of 30 durometer Sorbothane® is in series with the top platen/rigid specimen interface.

IV. Discussion

Idealized computed filter cutoff values for accelerometer configurations appear to be in agreement with each other over different loading conditions; there exists no statistical difference between the means of filter sets in identical sensor configurations via the two loading conditions of 172.35 kPa and 241.32 kPa. Additional tests need to be performed at these two input conditions as well as higher and lower input conditions for both greater statistical power and to observe deviations from hypothesized trends. Additional filter metric parameters incorporated into the optimization process may yield smaller standard deviations of data after mass compensations have been performed in non-specimen experiments. Future optimization processes will include such variables as varying pole numbers, different filter types--Butterworth, Chebyshev and Elliptic, and notch filters at varying frequencies.

Corner Accelerometer multiplied by mass data appears to yield the poorest approximation of force data for non-specimen tests. Corner accelerometer data require a significantly smaller filter cutoff value when compared to other sensor configurations and, within the 241.32 kPa input condition, the corner accelerometer standard deviations are statistically different from all other accelerometer configurations. Positive t statistics indicate the corner accelerometer mean is larger than that of the sensor configuration (see table 6).

Table 6
Corner Accelerometer Standard Deviation Comparisons for 241.32 kPa PSI Input Condition

Sensor Configuration	t-test significance
Two Accelerometer Avg.	t(2)=13.84; P<0.05
Accelerometer 1	t(4)=8.28; P<0.05
Accelerometer 2	t(4)=9.07; P<0.05

Additionally, filtered data from the Corner Accelerometer multiplied by mass data visually appear to be a poorer approximation of load cell data when compared to other sensor configurations (see fig. 8).

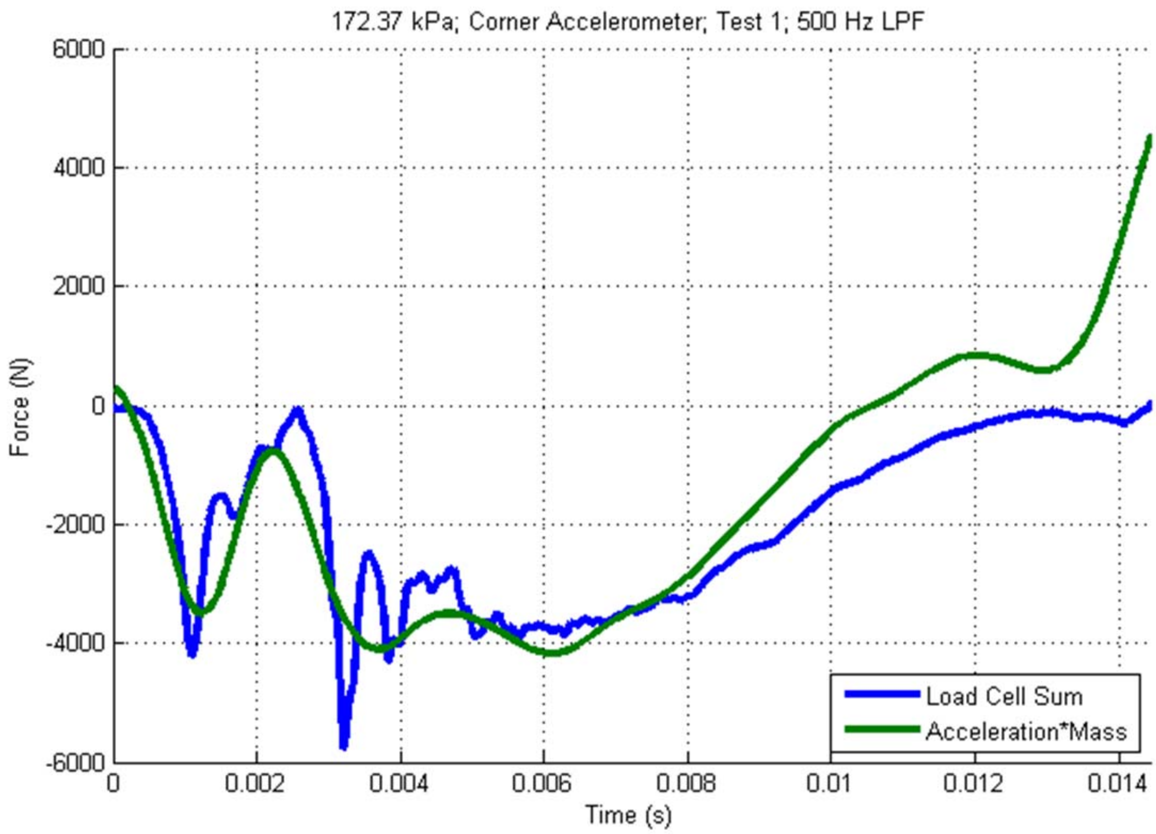

Fig. 8. A comparison of filtered corner accelerometer data and load cell data. A 500 Hz 4-pole zero-phase Butterworth LPF is applied to accelerometer data only. No specimen present.

Regarding the mean differences of filter cutoff data in the 241.32 kPa loading condition, there seems generally to be a statistically significant difference between sensor configurations, with the exception being a comparison between the two-accelerometer average (accelerometers 1 and 2) and accelerometer 2. This indicates that there are more appropriate locations for accelerometers on the top platen structure than others, which is also reinforced as a function of the results from the corner accelerometer analysis. Future studies will also investigate acceleration data via accelerometers coupled to load cells.

Peaks of the acceleration multiplied by mass time history are attenuated by the filter choice to maintain the minimum standard deviation of mass cancelled data. To preserve initial peaks in the acceleration profile while maintaining a minimum standard deviation, averaging multiple accelerometers may be necessary. With this limited dataset, however, it is difficult to say whether or not averaging accelerometers is advantageous. Within the 172.37 kPa input condition data set there is no statistical difference between the standard deviation of mass cancelled data between accelerometer 2 and the averaging of accelerometers 1 and 2--t(4)=2.03; P>0.05.

Additional testing also needs to be conducted at larger loading conditions to observe the frequency content measured by the load cell array. As loading conditions increase, the frequency content captured by the load cells may eventually near their observation capacity. In such a case more applicable load cells should be chosen for study. The load cells used for this test have a load capacity much larger than needed and also have the lowest of frequency responses in this particular series of load cells purchased from PCB Piezotronics. Load cells with smaller load capacities have progressively higher response frequencies.

When looking at the test data with a specimen present, the response characteristics are what one would expect, with the highest forces being generated at the highest accelerations. The response characteristics with a compliant interface at the rigid body/top platen interface are interesting and demonstrate that potential energy is being stored during experimentation and released well after the top platen has started to decelerate. These data could prove to be useful when studying cadaveric vs. ATD response characteristics. ATD synthetic flesh may store energy and release it in ways that cadaveric flesh cannot. Fracture time, and consequently fracture loads, of cadaveric specimens may also be measureable with this technique, as a fracture is hypothesized to generate a momentary attenuation within force traces.

V. CONCLUSIONS

When imparting high loads into specimens within short durations of time via a linear impactor and platen structure, modes will be induced into the platen structure. These modes obscure the global acceleration time history of the platen structure. When trying to make measurements of total loads imparted into a specimen, one needs to mass cancel the loads that the measuring structure imparts upon itself as a function of the acceleration it undergoes. Variance among data after mass compensation has been computed can be minimized by iteratively applying filters with varying filter frequency cutoff values and computing the standard deviation of the resulting data.

VI. REFERENCES

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