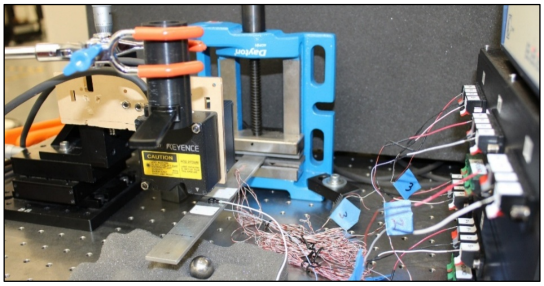
BODIE TECHNOLOGY, INC.

The Noisy Data Experts™

Improving High-G Shock Measurements: A Practical Case Study for Physical Testing and/or Numerical Simulation

Ted Diehl, PhD, Bodie Technology, Inc

95th Shock & Vibration Symposium, 2025



Goals of Our Severe-Shock Case Study

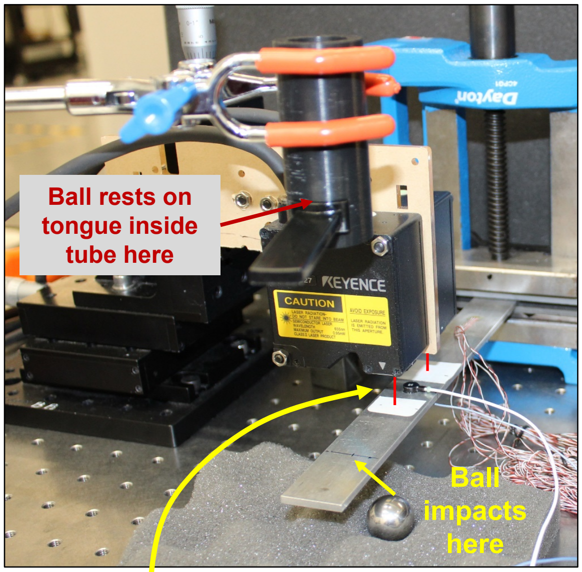
- **Create a shock test that:**
    1. Is severe with high G accelerations and significant frequency content.
    2. Can be created and performed relatively easily provided you have appropriate sensors and DAQ. Does not require Hopkinson Bar nor explosives!
    3. Could be numerically simulated to help both your Simulation and Test teams get on the same page.
    4. Will utilize multiple types of sensors and sensing technology.
        - Severe-shock potentially causes one or more sensors to exhibit distortion.
        - Protocol could be modified to test long cable run issues if desired.
    5. Has measurement results which can be checked in such a manner as to be self-evidently plausible or implausible.
- This study is from an actual real-world development test. The measurements in this study will not be flawless. Actions will be needed to improve the measurements.

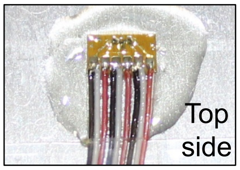
This presentation is a highly condensed version of a 52-slide workshop from the class *Working With Physical Measurements from Severe Mechanical Shock & More*

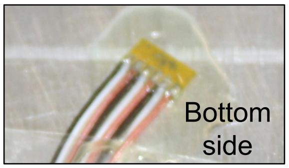
Our Severe-Shock Test Setup Key features:

- Clamped cantilevered aluminum beam.
- Steel ball bearing dropped from alignment tube with releasable tongue to control drop height.
- Piggy-back configuration of two different types of accelerometers, one on top and the other on the bottom side of the beam.
- Two laser displacement sensors located “around accels” should bound the transient response measured by the accels.
    - These lasers are most accurate with displacement and are least with accel.
    - If we can get both the Accel sensors and Lasers to agree ⇒ confidence!
- Strain Gages for additional learnings (not discussed).

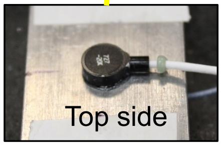
Steel Ball Impacting an Aluminum Cantilever Beam

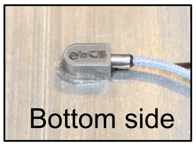






Rotated 45*deg.

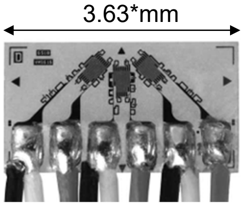




For Reader’s Reference

Test Setup Details

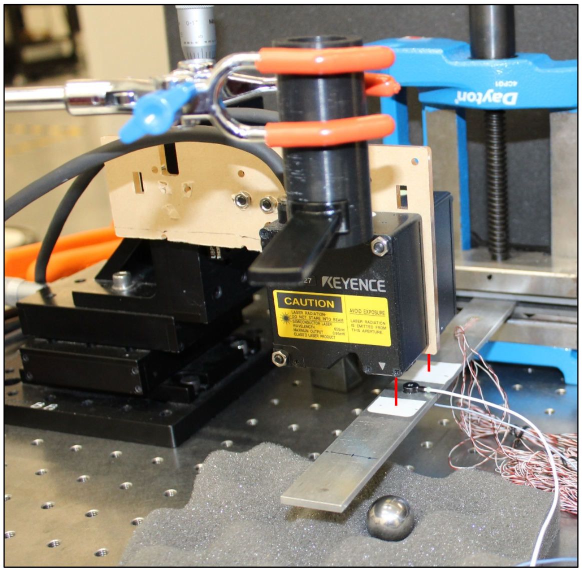
- 2024-T4 Aluminum Beam: [3.1, 25.4, 241.3]*mm, Micro-Measurements part# MMF327764 EWB-2.
- Steel Ball: 19.06*mm diameter, 28.65*gm.
    - (Optional) Include felt or foam padding at impact location to blunt impact.
- Accels:
    - **Endevco 727-20K**: undamped PR adhesive-mounted accel (range: 20*kG, 0 to 50*kHz, fn_typical: 350*kHz)
    - **PCB 352A92-20K**: damping unstated, IEPE adhesive-mounted accel (range: 20*kG, 1.2 to 10,000*Hz, fn > 100*kHz)
- Laser Displacement sensors (quantity 2):
    - **Keyence LK-H027**: +/- 2.5*mm range at a 10*us output sampling increment. Keyence output sampling increment setting for test was 10*us ⇒ fs = 100*kHz & fNyq = 50*kHz.
- Strain Gages (quantity 2, rectangular 45 rosettes)
    - **Micro-Measurements C5K-06-S5198-350-39F**

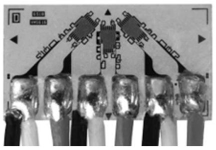


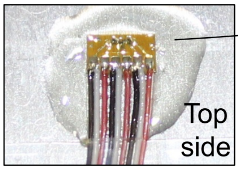
Key Test Dimensions

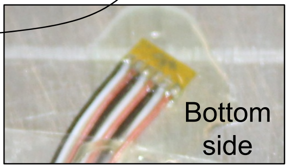
Note: mounting distances are measured from clamp.

- Laser Displacement sensor mounting: [101.5, 139.5]*mm
- Accelerometer mounting: 122*mm
- Strain gage mounting: 30*mm
- Ball impact location from clamp: 183*mm
- Ball drop height: 100*mm
- Relative to strain gages:
  Bottom side is rotated 45*deg so that one leg is aligned transverse to show anticlastic curvature strain. Computed principal strains of both Top and Bottom should match.







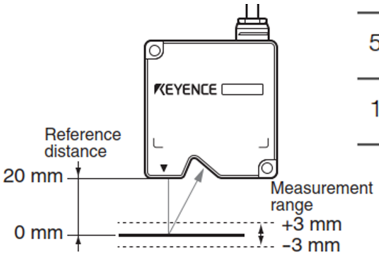


Rotated 45*deg.

Additional Details on Keyence Laser Sensors

- Ref: Keyence User Manual, "High-speed, High-accuracy Laser Displacement Sensors, LK-G5000 Series", Keyence document # 96M12277, pp 1-12.
  - For sensor head: LK-H027, measurement range for diffuse reflection:
    - Note: "Range setting" is the Keyence DAC (Digital to Analog Converter) output sampling increment.

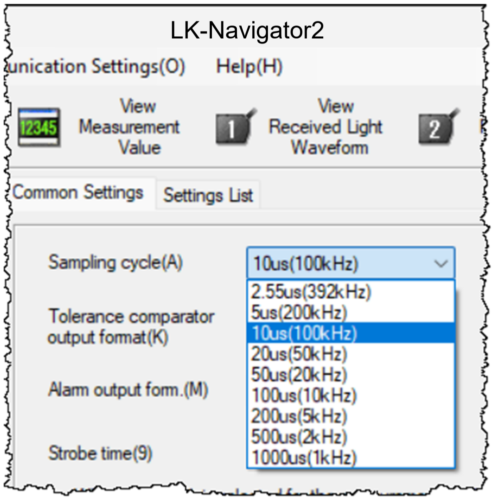
Our tests utilized the 10*us range.



LK-H02x

Range setting	Center
2.55 μs	±0.3 mm (±0.2 mm) **
5 μs	±1.2 mm (±1.0 mm)
10 μs	±2.5 mm (±2.2 mm)

** Values in parentheses are for specular reflection mounting.



Sampling cycle(A) 10us(100kHz)
2.55us(392kHz)
5us(200kHz)
10us(100kHz)
20us(50kHz)
50us(20kHz)
100us(10kHz)
200us(5kHz)
500us(2kHz)
1000us(1kHz)

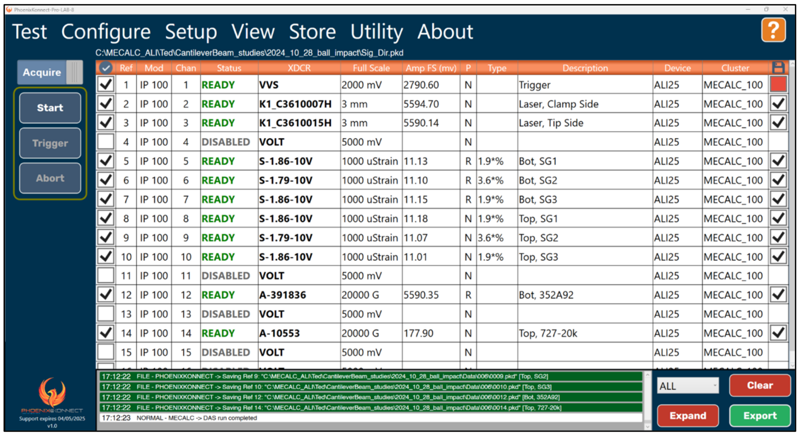
Tolerance comparator output format(K)

Alarm output form.(M)

Strobe time(9)

DAQ Info

- DAQ System
  - ***PhoenixKonnect*** software controlling a ***MECALC*** QuantusSeries w/ ALI25 cards.
    - Delta-Sigma design with 8x oversampling, excellent AA protection, 5*MSa/s, 24-bit, max slew rate > 50*V/us.
    - System description and spec sheet found at https://phoenixkonnect.com
  - For case study, we used sampling rate = 2.5*MSa/s (system capable of 5*MSa/s).
  - Data post processed by ***Kornucopia® ML™*** (workshop: *Severe-Shock Case Study*)



C:\MECALC_ALI\Ted\CantileverBeam_studies\2024_10_28_ball_impact\Sig_Dir.pkd

☑	Ref	Mod	Chan	Status	XDCR	Full Scale	Amp FS (mv)	P	Type	Description	Device	Cluster	
☑	1	IP 100	1	READY	VVS	2000 mV	2790.60	N		Trigger	ALI25	MECALC_100	🟥
☑	2	IP 100	2	READY	K1_C3610007H	3 mm	5594.70	N		Laser, Clamp Side	ALI25	MECALC_100	☑
☑	3	IP 100	3	READY	K1_C3610015H	3 mm	5590.14	N		Laser, Tip Side	ALI25	MECALC_100	☑
☐	4	IP 100	4	DISABLED	VOLT	5000 mV		N			ALI25	MECALC_100	
☑	5	IP 100	5	READY	S-1.86-10V	1000 uStrain	11.13	R	1.9*%	Bot, SG1	ALI25	MECALC_100	☑
☑	6	IP 100	6	READY	S-1.79-10V	1000 uStrain	11.10	R	3.6*%	Bot, SG2	ALI25	MECALC_100	☑
☑	7	IP 100	7	READY	S-1.86-10V	1000 uStrain	11.15	R	1.9*%	Bot, SG3	ALI25	MECALC_100	☑
☑	8	IP 100	8	READY	S-1.86-10V	1000 uStrain	11.18	N	1.9*%	Top, SG1	ALI25	MECALC_100	☑
☑	9	IP 100	9	READY	S-1.79-10V	1000 uStrain	11.07	N	3.6*%	Top, SG2	ALI25	MECALC_100	☑
☑	10	IP 100	10	READY	S-1.86-10V	1000 uStrain	11.01	N	1.9*%	Top, SG3	ALI25	MECALC_100	☑
☐	11	IP 100	11	DISABLED	VOLT	5000 mV		N			ALI25	MECALC_100	
☑	12	IP 100	12	READY	A-391836	20000 G	5590.35	R		Bot, 352A92	ALI25	MECALC_100	☑
☐	13	IP 100	13	DISABLED	VOLT	5000 mV		N			ALI25	MECALC_100	
☑	14	IP 100	14	READY	A-10553	20000 G	177.90	N		Top, 727-20k	ALI25	MECALC_100	☑
☐	15	IP 100	15	DISABLED	VOLT	5000 mV		N			ALI25	MECALC_100	

```
17:12:22  FILE - PHOENIXKONNECT -> Saving Ref 9: "C:\MECALC_ALI\Ted\CantileverBeam_studies\2024_10_28_ball_impact\Data\006\0009.pkd" [Top, SG2]
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17:12:23  NORMAL - MECALC -> DAS run completed
```

Note: sensors on the bottom side of the beam have their polarity reversed (multiply amplitude by -1) to make comparisons with top-side sensors easier.

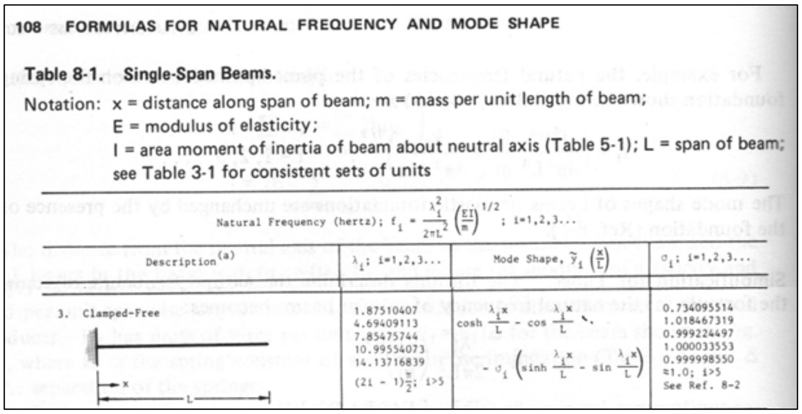
Some Analytical Estimates

- Formulae from: Blevins, "*Formulas for Natural Frequency and Mode Shape*," Krieger Publishing, 1984, pp 108 and 158.
- Computed natural frequency and natural period estimates :

with Ball Mass [Hz]	no Ball Mass [Hz]
32.36	51.06

with Ball Mass [ms]	no Ball Mass [ms]
30.90	19.58

Note: These frequencies are below 100*Hz. But metal-to-metal impact is likely to generate >100*kHz content. Let's see what happens!



108 FORMULAS FOR NATURAL FREQUENCY AND MODE SHAPE

Table 8-1. Single-Span Beams.

Notation: x = distance along span of beam; m = mass per unit length of beam;
E = modulus of elasticity;
I = area moment of inertia of beam about neutral axis (Table 5-1); L = span of beam;
see Table 3-1 for consistent sets of units

Natural Frequency (hertz); $f_i = \frac{\lambda_i^2}{2\pi L^2}\left(\frac{EI}{m}\right)^{1/2}$; i=1,2,3...

Description[(a)]	λ_i; i=1,2,3...	Mode Shape, $\tilde{y}_i\left(\frac{x}{L}\right)$	σ_i; i=1,2,3...
3. Clamped-Free	1.87510407 4.69409113 7.85475744 10.99554073 14.13716839 $(2i-1)\frac{\pi}{2}$; i>5	$\cosh\frac{\lambda_i x}{L} - \cos\frac{\lambda_i x}{L} - \sigma_i\left(\sinh\frac{\lambda_i x}{L} - \sin\frac{\lambda_i x}{L}\right)$	0.734095514 1.018467319 0.999224497 1.000033553 0.999998550 ≈1.0; i>5 See Ref. 8-2

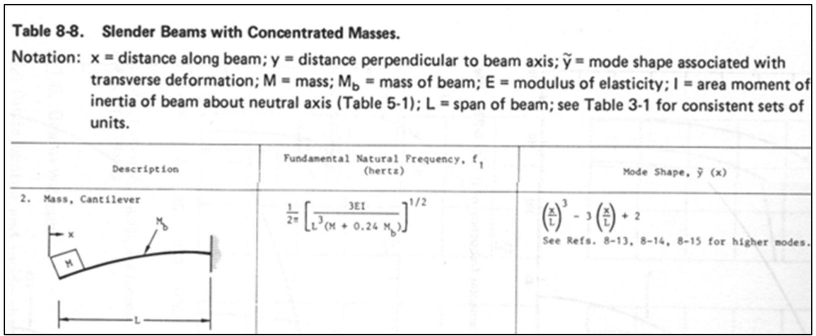


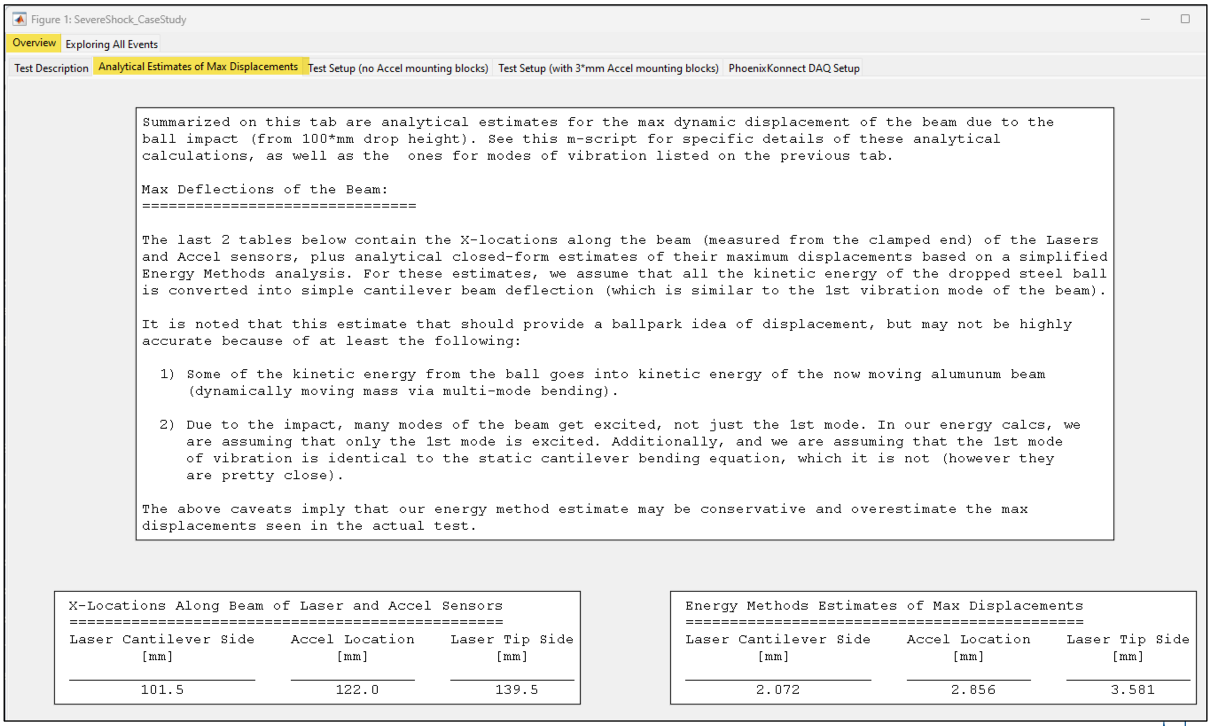
Table 8-8. Slender Beams with Concentrated Masses.

Notation: x = distance along beam; y = distance perpendicular to beam axis; $\tilde{y}$ = mode shape associated with transverse deformation; M = mass; M_b = mass of beam; E = modulus of elasticity; I = area moment of inertia of beam about neutral axis (Table 5-1); L = span of beam; see Table 3-1 for consistent sets of units.

Description	Fundamental Natural Frequency, f_1 (hertz)	Mode Shape, $\tilde{y}$ (x)
2. Mass, Cantilever	$\frac{1}{2\pi}\left[\frac{3EI}{L^3(M + 0.24 M_b)}\right]^{1/2}$	$\left(\frac{x}{L}\right)^3 - 3\left(\frac{x}{L}\right) + 2$ See Refs. 8-13, 8-14, 8-15 for higher modes.

Energy Methods Estimates of Expected Max Displacements

Unfortunately, these estimates were computed AFTER all the testing was performed.



```
Summarized on this tab are analytical estimates for the max dynamic displacement of the beam due to the
ball impact (from 100*mm drop height). See this m-script for specific details of these analytical
calculations, as well as the  ones for modes of vibration listed on the previous tab.

Max Deflections of the Beam:
===============================

The last 2 tables below contain the X-locations along the beam (measured from the clamped end) of the Lasers
and Accel sensors, plus analytical closed-form estimates of their maximum displacements based on a simplified
Energy Methods analysis. For these estimates, we assume that all the kinetic energy of the dropped steel ball
is converted into simple cantilever beam deflection (which is similar to the 1st vibration mode of the beam).

It is noted that this estimate that should provide a ballpark idea of displacement, but may not be highly
accurate because of at least the following:

  1) Some of the kinetic energy from the ball goes into kinetic energy of the now moving alumunum beam
     (dynamically moving mass via multi-mode bending).

  2) Due to the impact, many modes of the beam get excited, not just the 1st mode. In our energy calcs, we
     are assuming that only the 1st mode is excited. Additionally, and we are assuming that the 1st mode
     of vibration is identical to the static cantilever bending equation, which it is not (however they
     are pretty close).

The above caveats imply that our energy method estimate may be conservative and overestimate the max
displacements seen in the actual test.
```

```
X-Locations Along Beam of Laser and Accel Sensors
=================================================
Laser Cantilever Side    Accel Location    Laser Tip Side
         [mm]                 [mm]              [mm]
_____________________    ______________    ______________

        101.5                122.0             139.5
```

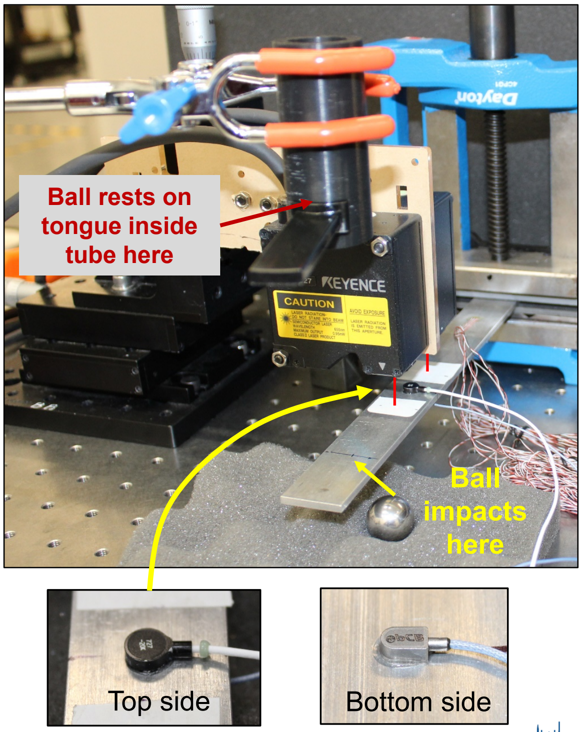
```
Energy Methods Estimates of Max Displacements
=============================================
Laser Cantilever Side    Accel Location    Laser Tip Side
         [mm]                 [mm]              [mm]
_____________________    ______________    ______________

        2.072                2.856             3.581
```

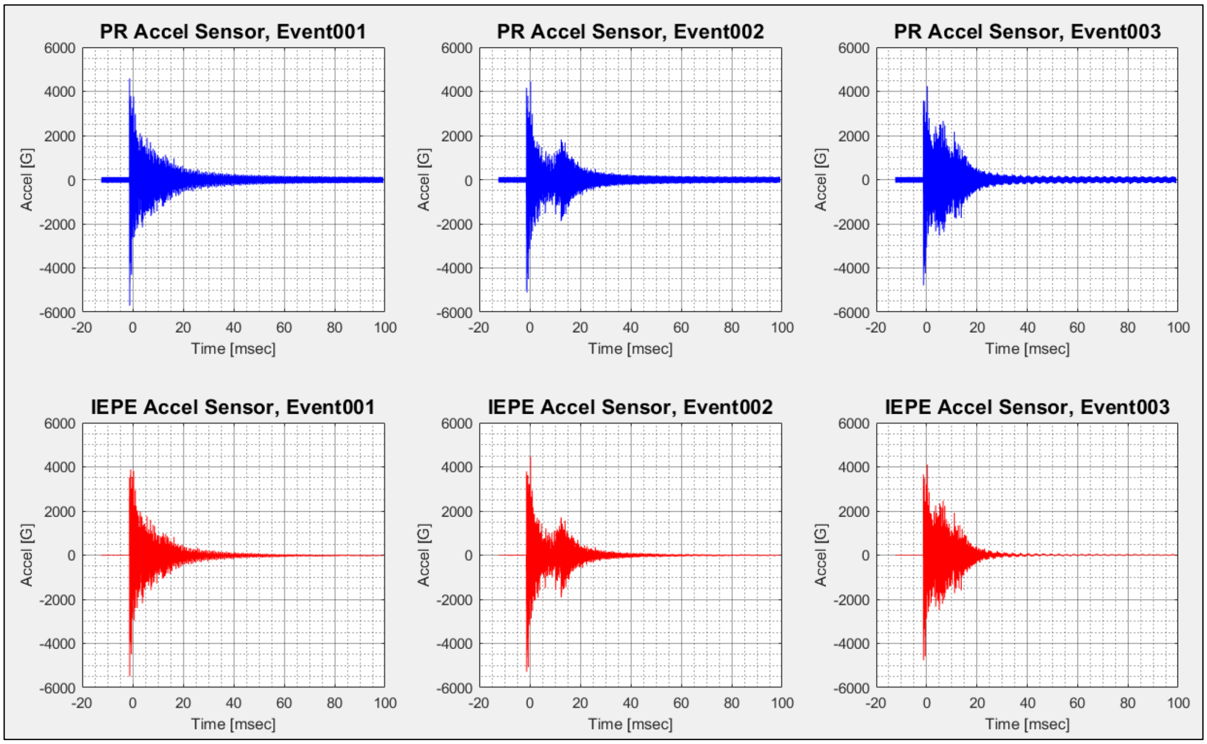
Test Events 001 – 003

- A total of 6 Test Events were performed (001 – 006).
    - We will initially focus on the first 3 Test Events (001 – 003).
- The two accelerometers are adhered with cyanoacrylate directly to the aluminum beam.
- Steel ball dropped from 100*mm directly onto beam as denoted.
    - **Metal-on-metal impact ⇒ severe shock!**
- We can control severity of shock and its frequency content by:
    - changing drop height.
    - changing locations relative to beam clamp.
    - adding felt pad or similar at impact location.

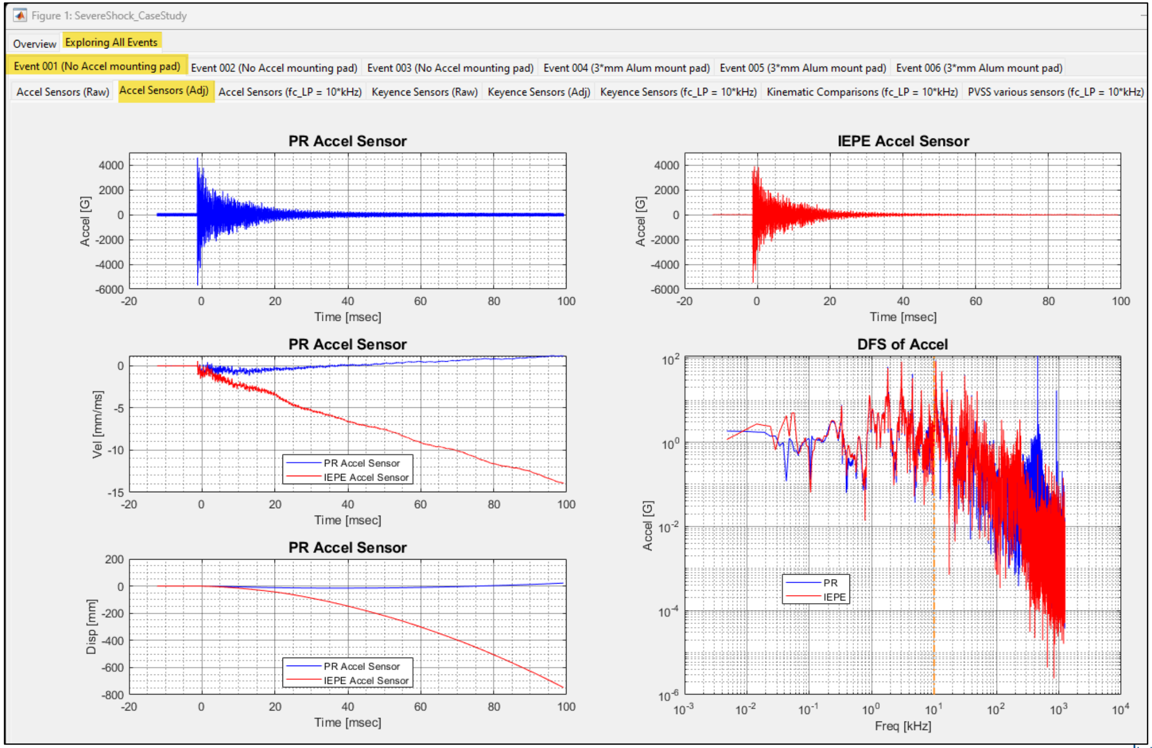
Steel Ball Impacting an Aluminum Cantilever Beam



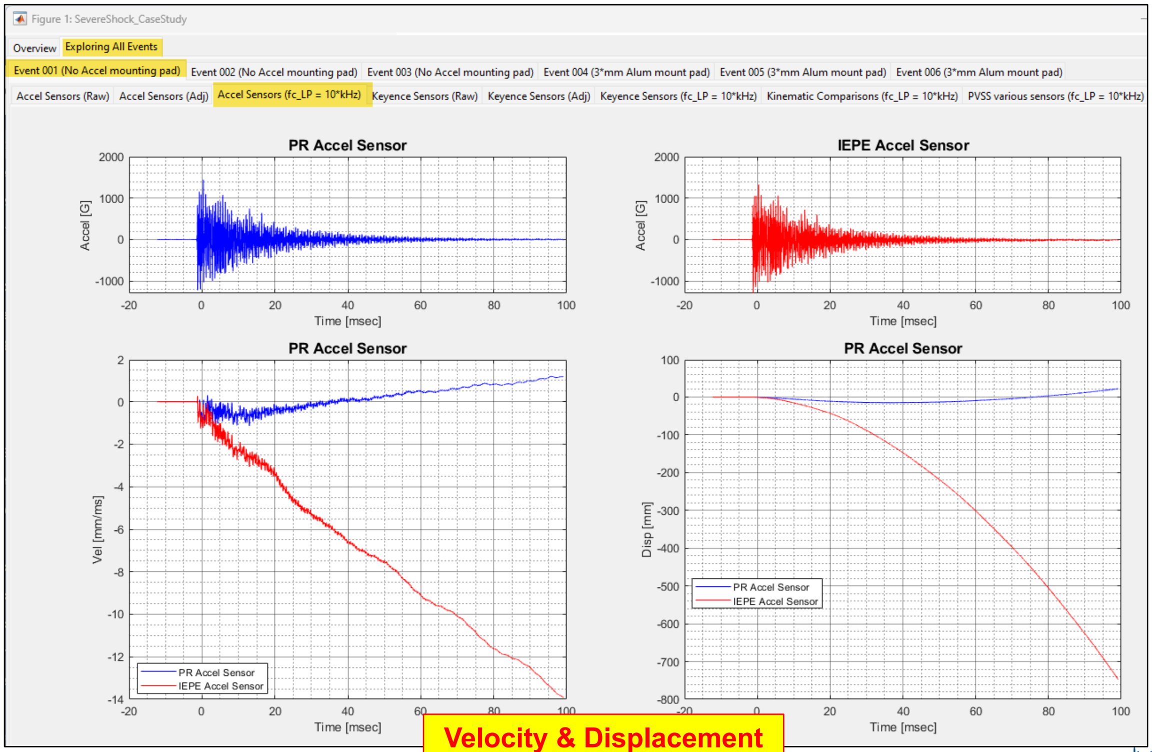
Raw Accelerometer Measurements – Are these OK?



Event001 – DC Bias Adjusted, DFS, and Integrations to Velocity & Displacement

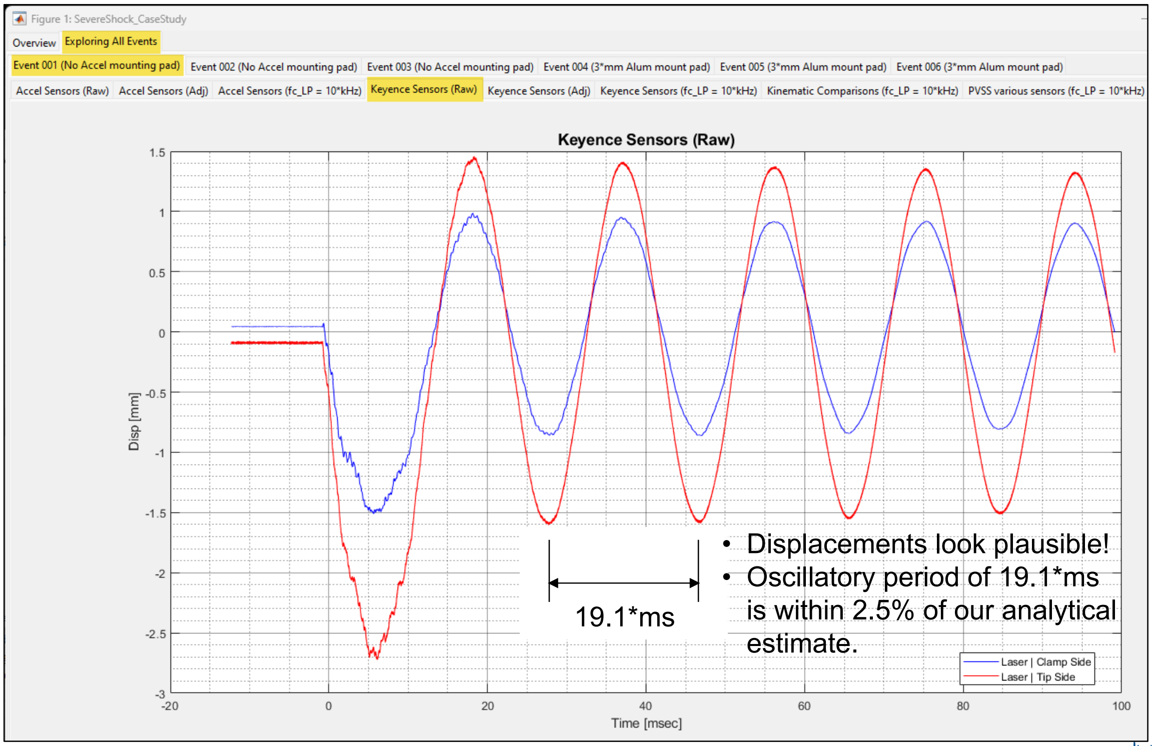


Event001 – After fc_LP = 10*kHz (remove sensor resonance)



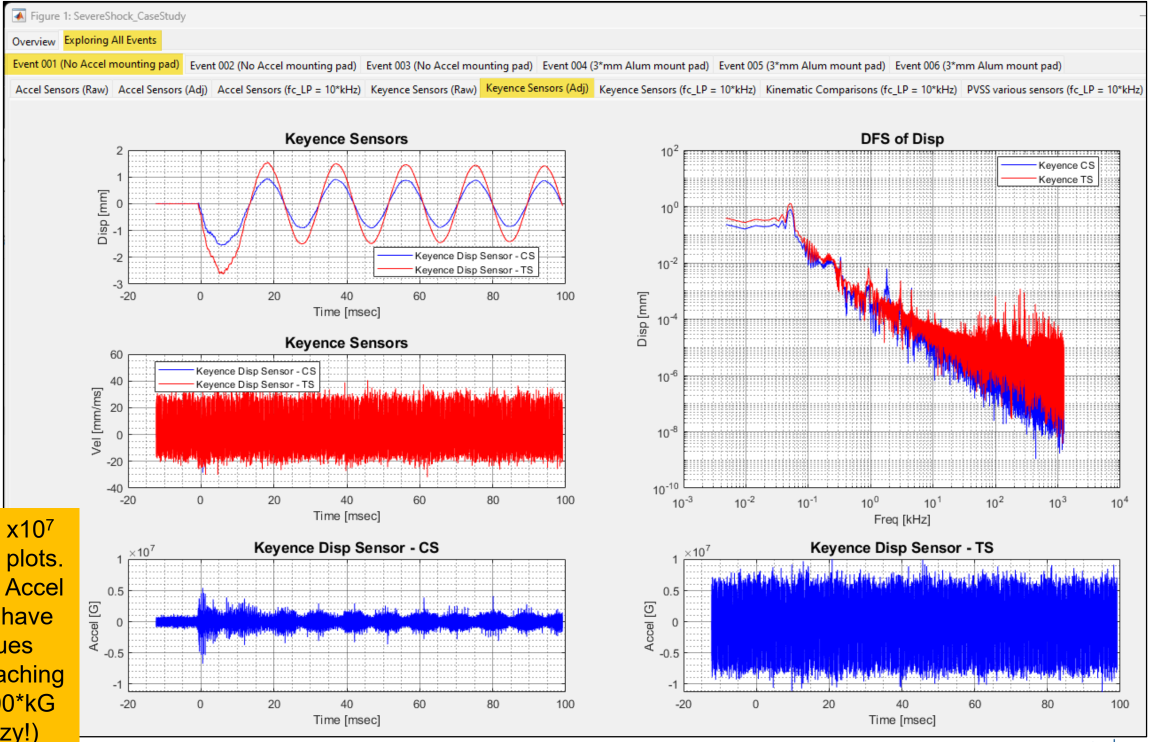
Velocity & Displacement still implausible!

Event001 – Keyence Raw Laser Displacement Sensors



- Displacements look plausible!
- Oscillatory period of 19.1*ms is within 2.5% of our analytical estimate.

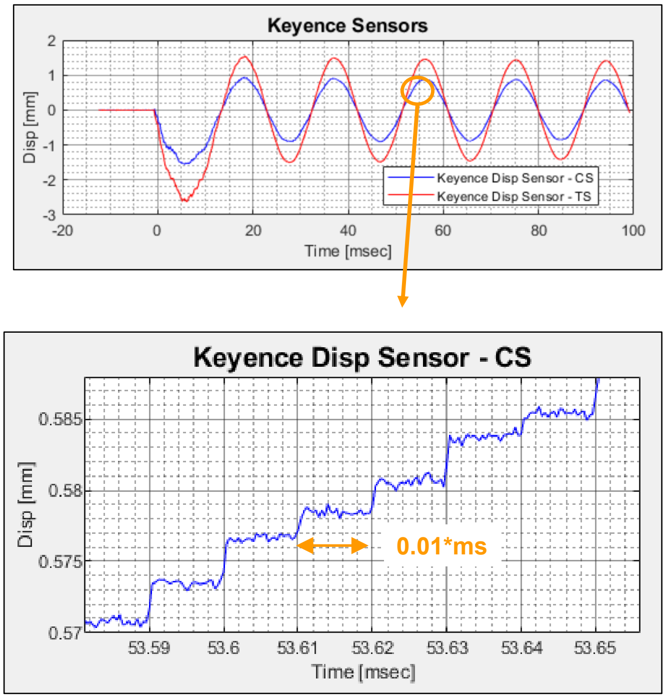
Event001 – DC Adjusted Lasers, DFS, and Derivatives to Velocity & Accel



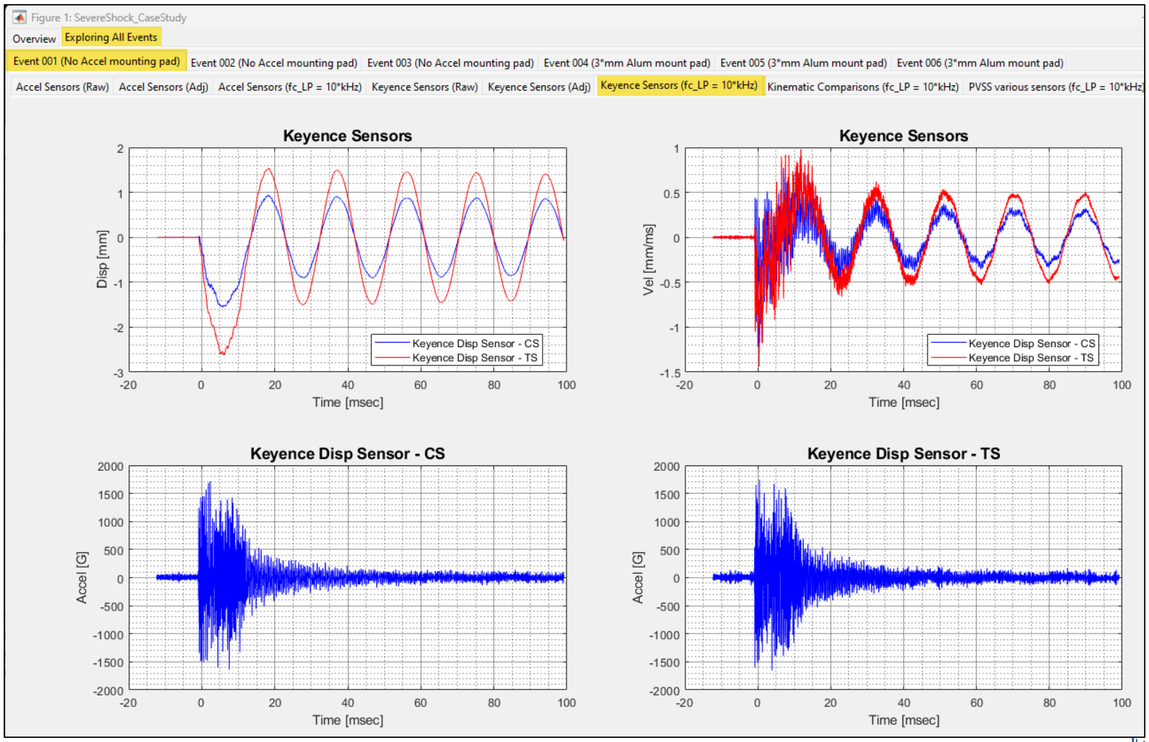
Note: $\times 10^7$ on the plots. These Accel plots have values approaching 10,000*kG (crazy!)

Explaining The Cause of the Crazy Velocity and Accel Computations from Measured Laser Displacements

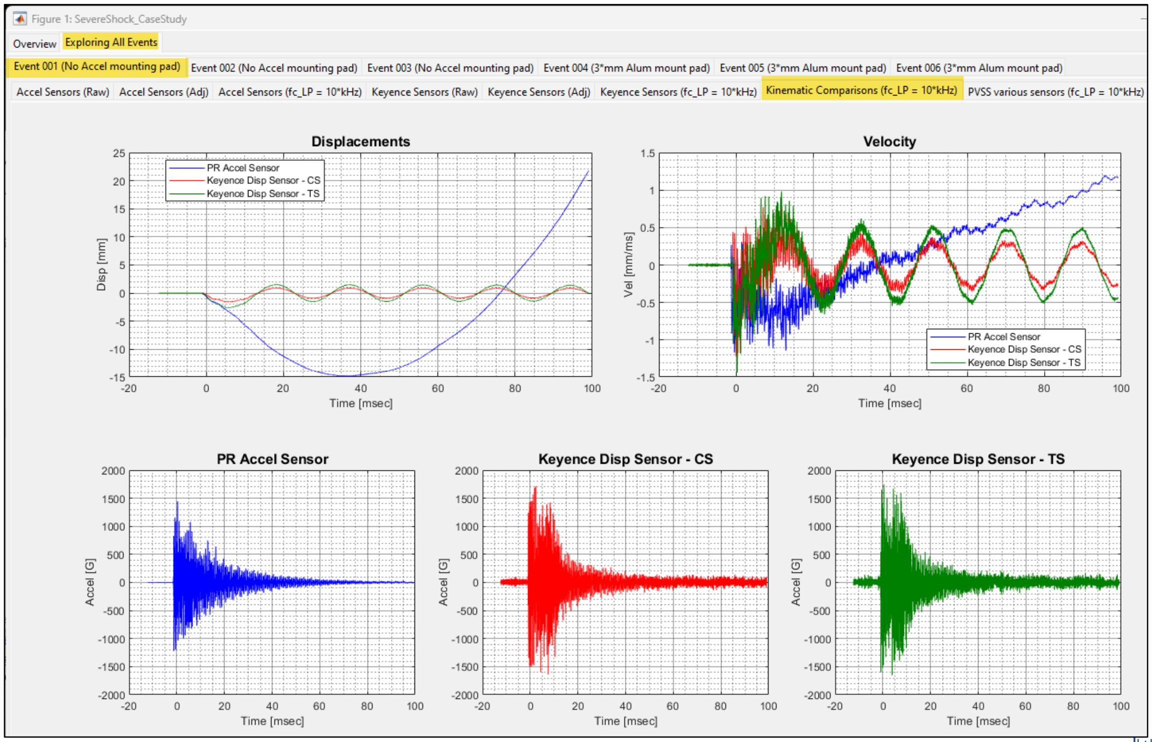
- Zooming in closely on the Laser Disp data (clamp-side, CS) shows the cause of the crazy derivative calcs for Velocity and Accel.
  - The data appears like *stair steps*.
  - This is caused by the very high sampling DAQ (2.5*MSa/s) collecting data from the Laser that has in its Signal Conditioner a DAC (Digital to Analog Converter) with a sampling rate of 10*us = 0.01*ms.
- The solution is to LP filter the displacement data to a value sufficiently below 1/(10*us) = 100*kHz.
  - We will use the same decimation and LP filter we applied to the Accel sensors, namely fc_LP = 10*kHz, but apply it to Laser Disp and then differentiate.



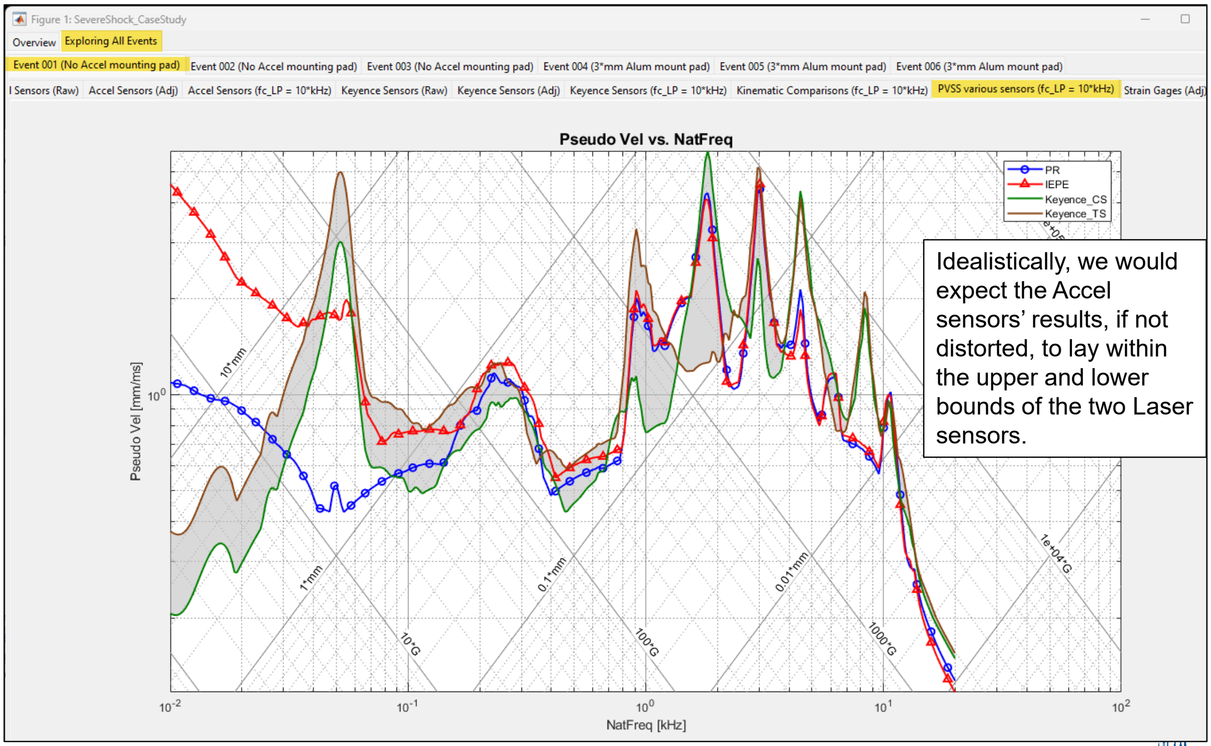
Event001 – Laser Results After fc_LP = 10*kHz Are Now Plausible (Displacement, Velocity & Acceleration)



Event001 – Comparing the PR Accel to the Laser Sensors



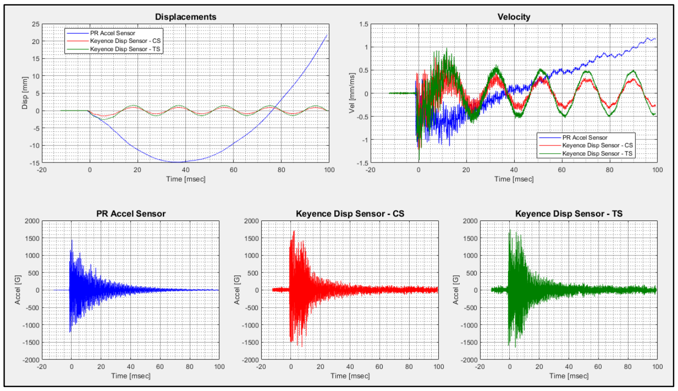
Event001 – PVSS Comparisons – Large Issues Below 100*Hz for the two Accel Sensors (PR & IEPE)

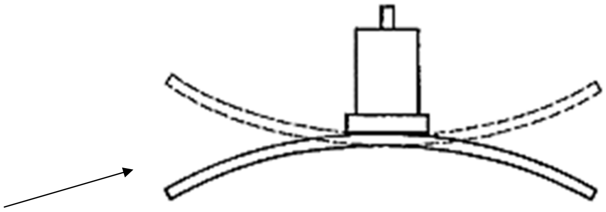


Idealistically, we would expect the Accel sensors' results, if not distorted, to lay within the upper and lower bounds of the two Laser sensors.

Event001 – Comparing the PR Accel to the Laser Sensors

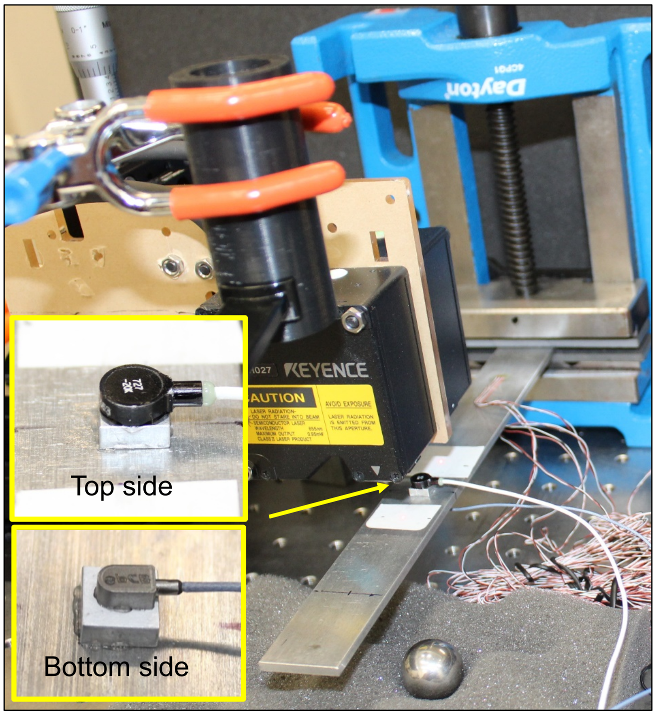
- Accelerations look modestly similar, but there is some clear differences between the PR Accel and the Lasers.
- Displacements computed from the PR sensor are not credible at all.
- The Velocity computed from the PR Accel shows evidence of a strong zero-shift-like distortion.
- What could be causing the difficulties with the Accel sensors (both the PR and IEPE)?
  - Clues:
    - Shock is very severe (metal-on-metal impact).
    - Sensors are adhered on a beam the is likely exhibiting significant bending strain.



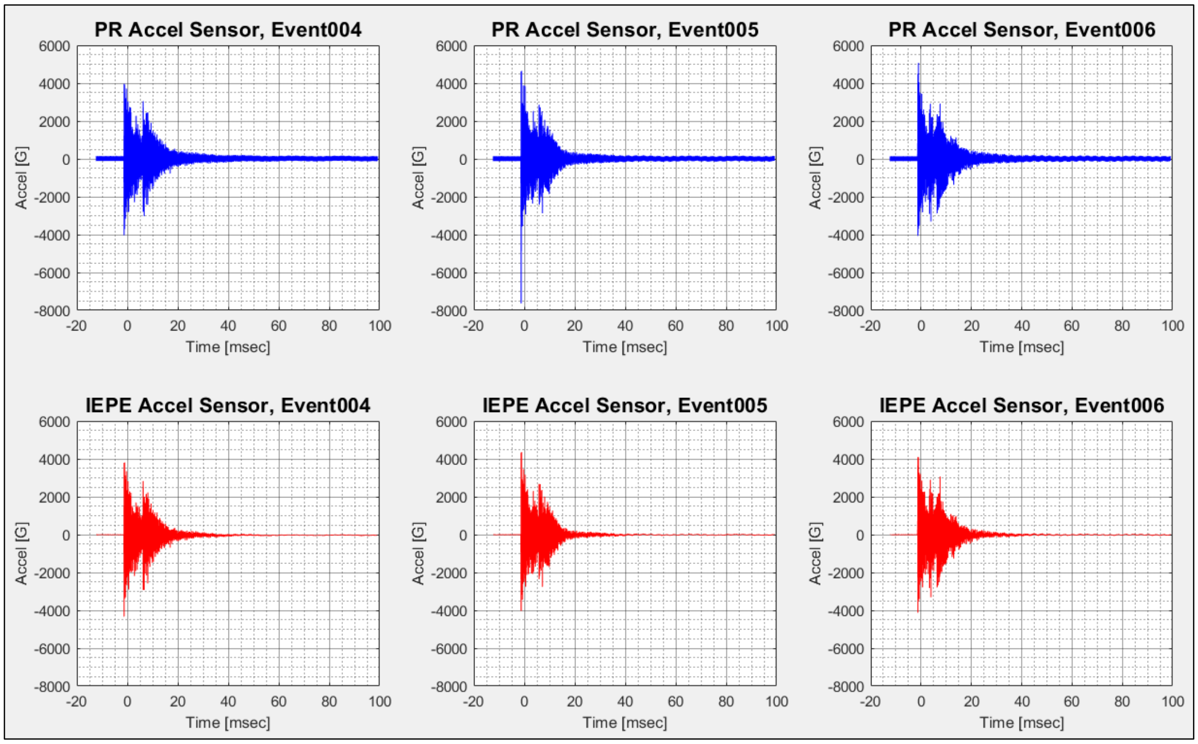


Address Base-Strain By a "Mechanical Fix"

- Using *Saint-Venant's Principle*, we find that adding a small mounting block significantly inhibits the beam's surface strain from getting to the sensor's case, resulting in an improved acceleration measurement including integration checks.
    - Mounting blocks are 3*mm thick Aluminum, adhered to both the beam and the Accel sensors with cyanoacrylate.
- Test Events 004 – 006 utilized the mounting block approach depicted to the right.
    - We will quickly look at the raw accels for all 3 Events and then for brevity we will explore the results further for Test Event 005.



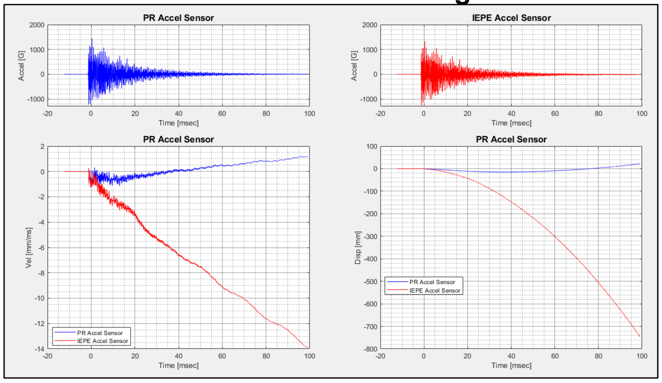
Raw Accelerometer Measurements – Are these OK?



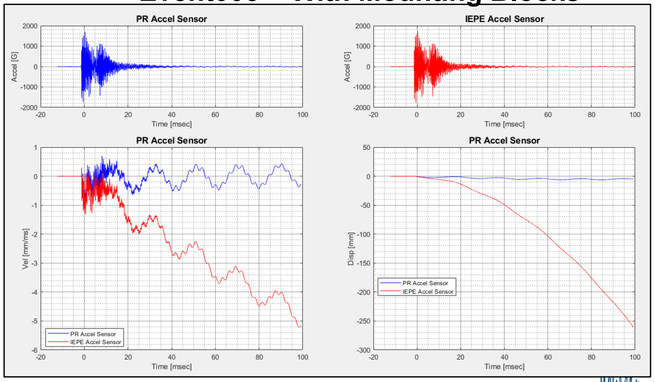
Event005 – W/ Mounting Blocks, fc_LP = 10*kHz

- To help see the amount of improvement, top plot is from Event001 (no mounting blocks) and bottom plot is from Event005 (with mounting blocks).
    - A clear improvement in Velocity and Displacement.
- The PR Accel looks very good now, not perfect, but fairly plausible.
    - The IEPE still shows drifting in the Velocity and Displacement, but it is improved from before.
    - Looking closely at the beginning of the IEPE Velocity you can also see what appears to be an immediate negative shift in the Velocity.
        - Perhaps this is caused by stress on the sensing element from severe metal-on-metal shock ???

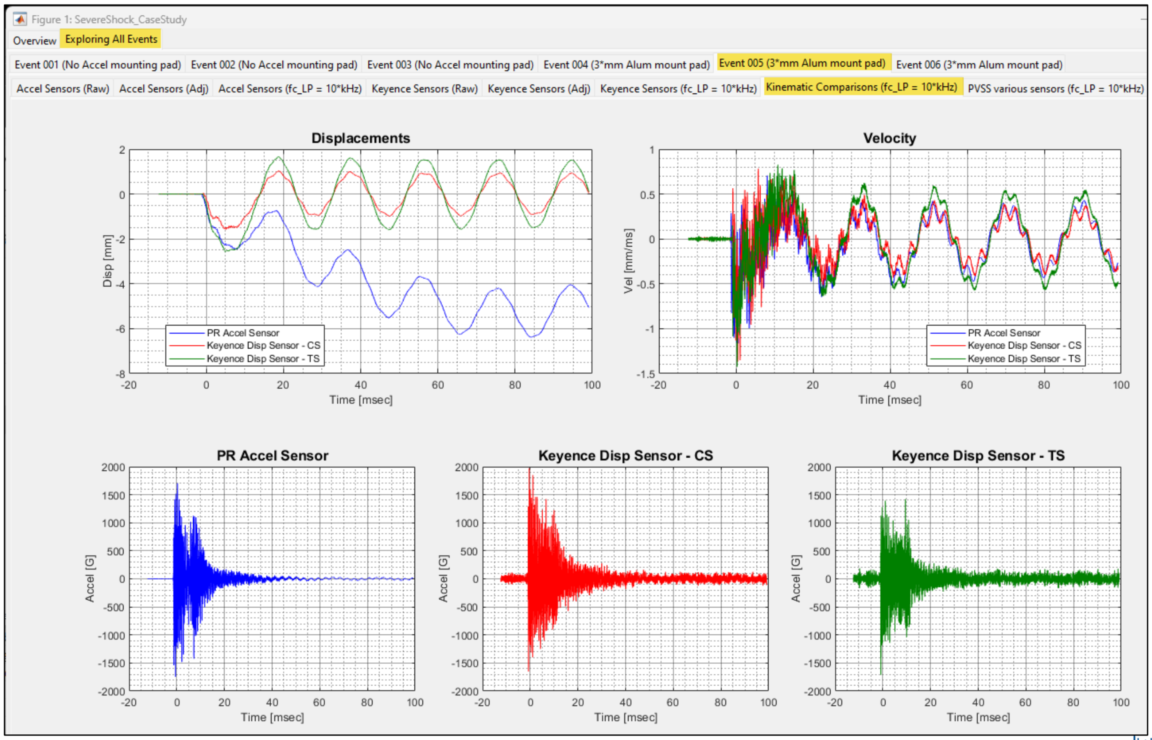
Event001 – No Mounting Blocks



Event005 – With Mounting Blocks



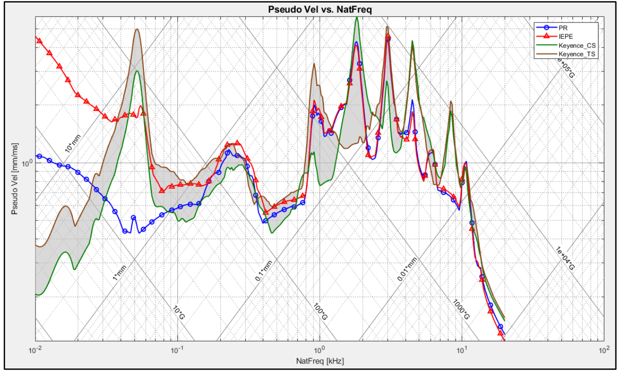
Event005 – Comparing the PR Accel to the Laser Sensors



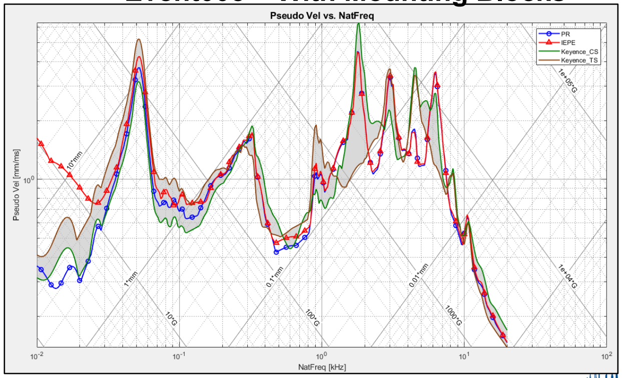
PVSS Shows Clear Improvement for BOTH PR & IEPE Accels

- Looking at the PVSS assessments we can see that BOTH the PR and IEPE Accel measurements are significantly improved by the use of the mounting blocks to mitigate base-strain distortions.
    - With this improvement, the IEPE sensor still shows an issue at very low natural frequencies though. This is likely due to the zero-shift-like response seen in its Velocity calculations (noted previously).
- Also, both the PR and IEPE sensors exhibit nearly identical responses above 40*Hz. Their responses in this freq range show some differences to the Lasers' responses.

Event001 – No Mounting Blocks



Event005 – With Mounting Blocks

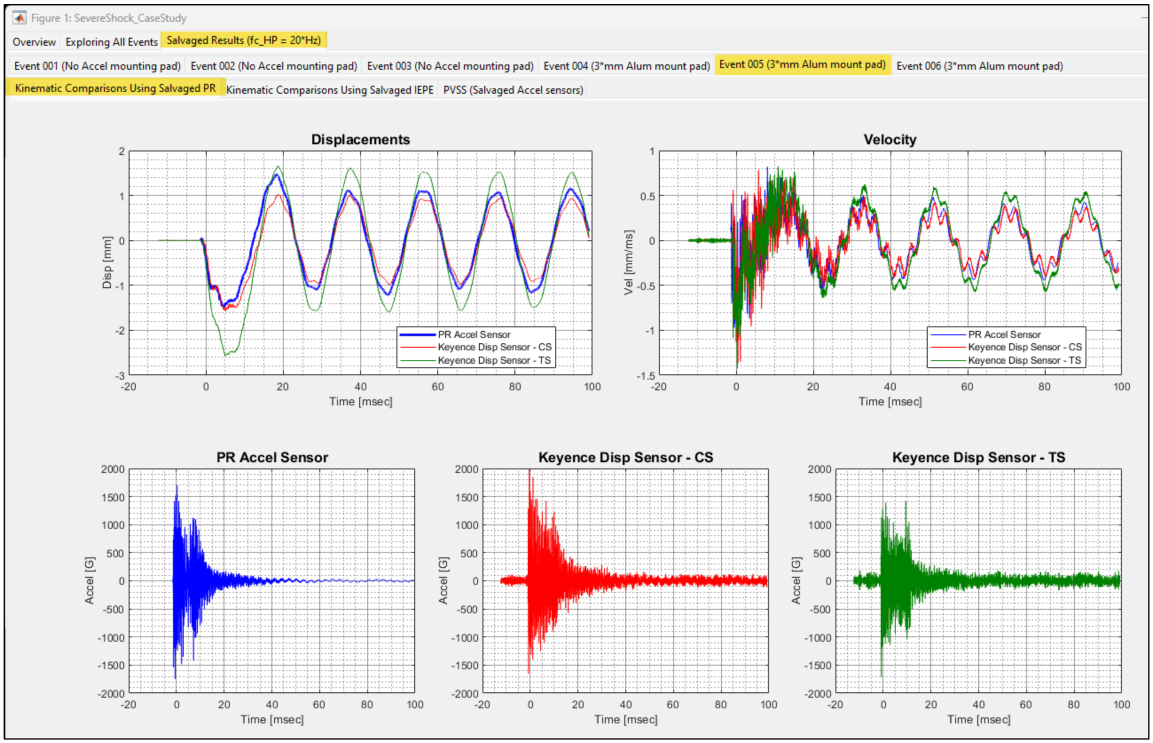


For Reader's Reference

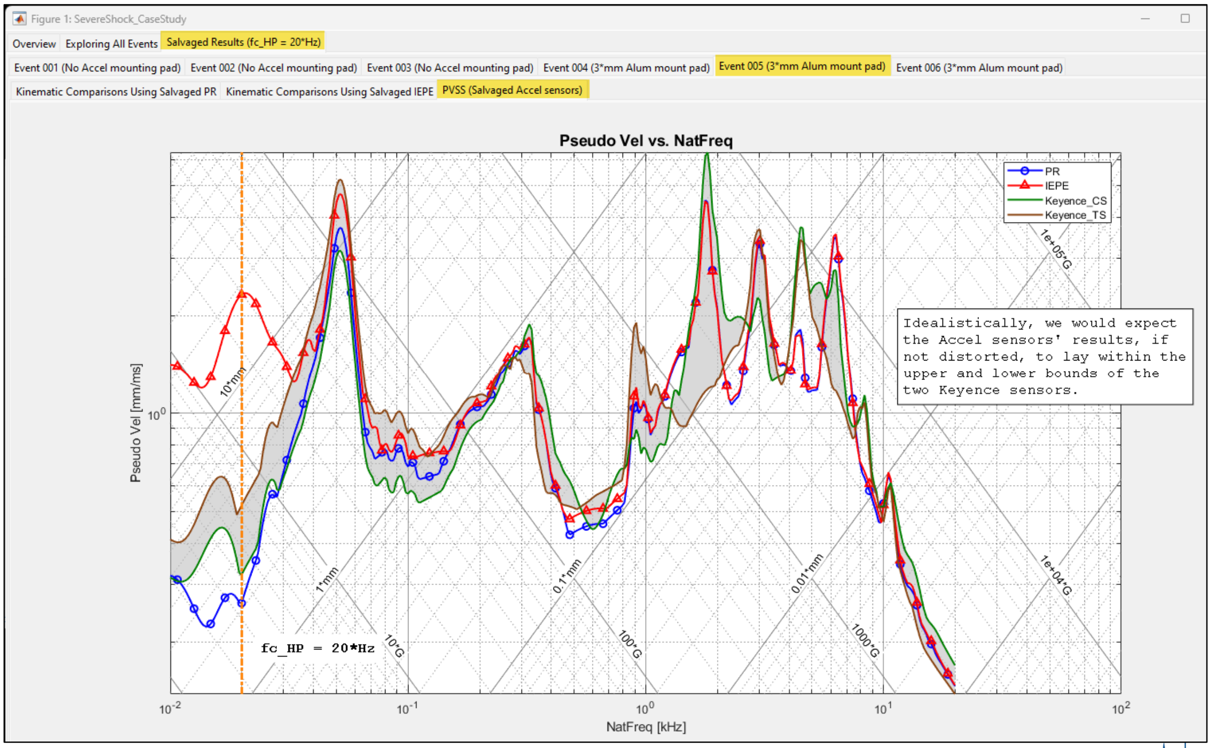
Further Salvaging / Correcting the Accel Sensors

- Our last effort for improvement – can we apply salvaging techniques to the measured Accel sensor data to further improve our results?
    - We will demonstrate results using a HP filtering approach:
        1. Start with the DC-adjusted Accel data after decimation & LP filtering (10*kHz), trimmed to the *"start of the action".*
        2. Compute HP filter coefficients.
            - Perform quick study to determine the lowest fc_HP that works. For our study we found fc_HP = 20*Hz worked best.
        3. Apply HP filter to the Displacement vs Time curve using assumed start condition of a flipped mirror. This yields the salvaged Displacement data.
        4. Recompute other kinematic quantities (Velocity and Acceleration) from the salvaged Displacement.
        5. Recompute PVSS from the now salvaged sensor data.
    - Compare the Salvaged results to the original Laser results (no salvaging).
- The full study (Kornucopia m-file `SevereShock_CaseStudy.m` and its related `FIG` and `HTML` files) explores applying salvaging to ALL six Test Events, both Accel sensors (PR & IEPE).
    - For brevity, only Events 005 and 001 will be presented here.

Event005 – Salvaged PR Accel Compared to the Lasers



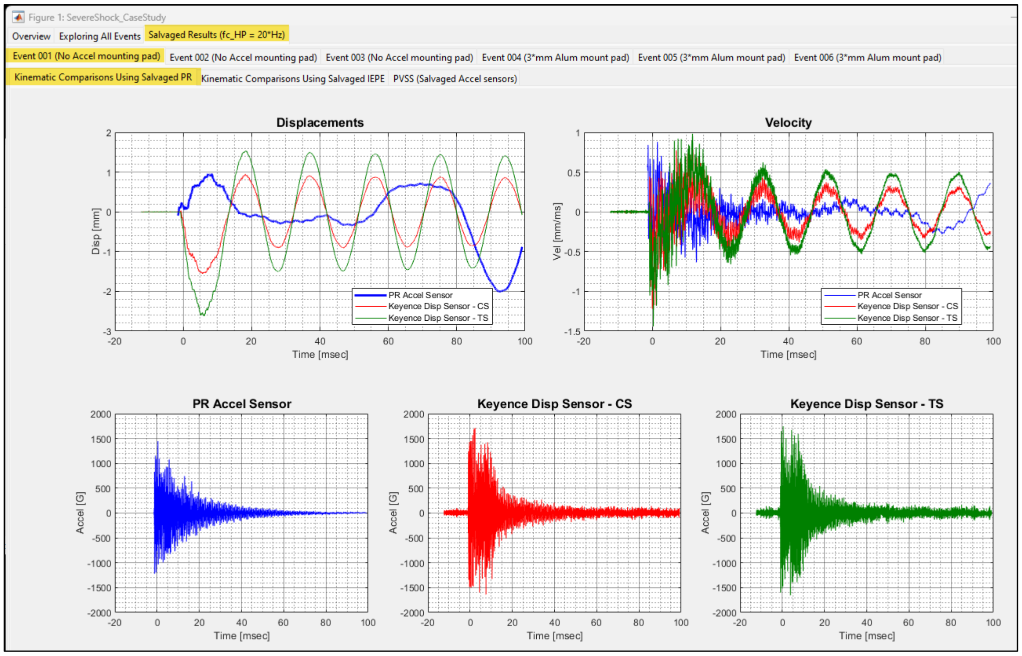
Event005 – PVSS of Salvaged Accels Compared to Lasers



Idealistically, we would expect the Accel sensors' results, if not distorted, to lay within the upper and lower bounds of the two Keyence sensors.

Event001 – Salvaged PR Accel Compared to the Lasers

Attempts to salvage test Event001 (with base-strain distortion) fail because the distortions lie in the same band as the beam's response.



Key Learnings

- **Accurately measuring severe shock is challenging but can be done successfully!**
- Whenever possible, do studies using different sensing technology to help understand capabilities and debug issues/challenges.
  - Adding HS Video to any future extensions of this study would be helpful.
- Ensure to read the sensor and DAS component spec sheets thoroughly BEFORE doing the Tests.
  - For the Keyence Laser, whose stated amplitude range was slightly exceeded in the tests, using a purposeful positive initial offset of 0.3*mm would have kept the sensor within its ± 2.5*mm range (our tests slightly exceeded that).
- If possible, perform any analytical or simulation calculations BEFORE the tests to help inform test set-up (amplitude and frequency ranges) and sensor selection.
- Try to have post processing scripts available BEFORE running the tests so that data quality checks can be assessed after EACH Test Event. This way you can catch problems and address them so future Test Events are as accurate as possible.
- Base-strain distortion can, in the right conditions, be significant with adhesively-mounted sensors. Utilizing mounting blocks is a viable approach to minimize the problem.
- **Performing well-controlled severe shock studies is an excellent way for you and your team to improve your testing (and simulation) capabilities.**