MEMS Shock Accelerometer Characterization for High-g Applications

63rd Annual NDIA Fuze Conference
August 4-5, 2020

Presenter: Dr. Adriane G. Moura
Applied Research Associates Inc.

Dr. Alain Beliveau
Applied Research Associates Inc.

Dr. Jacob Dodson
Air Force Research Laboratory

Outline of Topics

- Motivation & Objective
- Background & Approach
- Experimental Setup
- Results
- Conclusions

Motivation

- Accelerometers are essential sensors for measuring and understanding high-g environments
  - Fuze applications
    - Assess environment
    - Provide information for fuze to make decision
  - Testing/instrumentation
    - Measure shock
    - Understand environment

Objective

- Summarize MEMS shock accelerometers high-g performance
  - Dynamic evaluation on Hopkinson bar illustrated with Kulite accelerometer

Accelerometers of interest

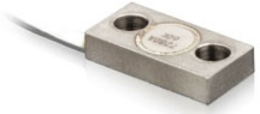
Reference Accelerometer

Endevco (undamped) — 7270A

Sensors under test (SUT)

Traditional High-G

Endevco (damped) — *7280A* — *7280AM4*

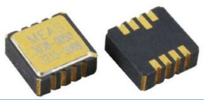


Kulite (damped) — *GMD280* — **60 kg$_n$**

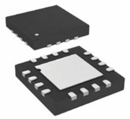
PCB (damped) — *3991A10/11* — *3501A12*

Low Cost High-G

TE Connectivity — *Model 3038* — **6 kg$_n$**

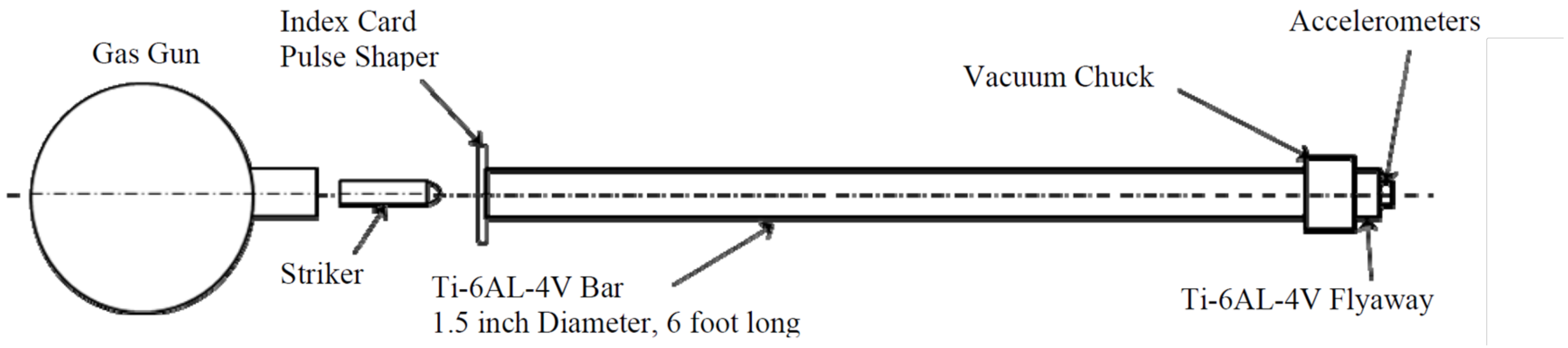


Analog Devices — *ADXL 377* — **200 g$_n$**

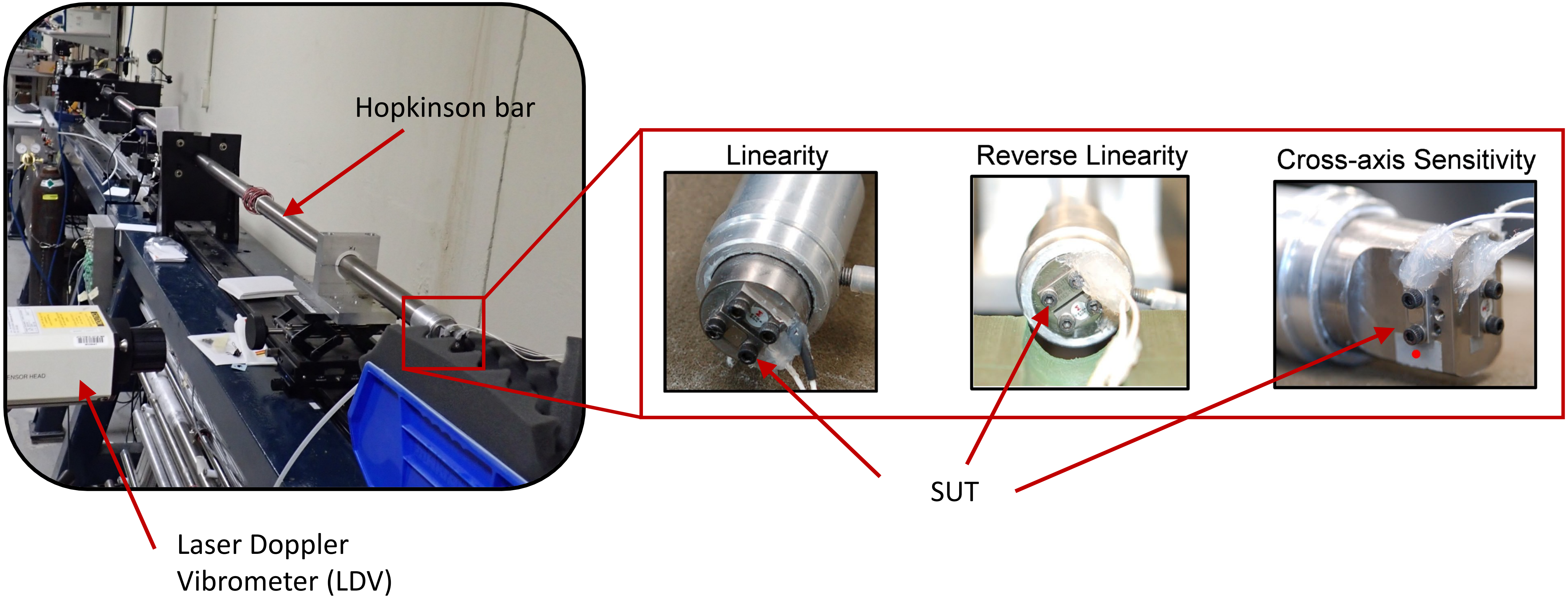


Background and Approach

- Over the years, piezoresistive accelerometers have been preferred in the AFRL Fuzes branch
  - Surface mount
  - Two-hole screw mount
  - Stud mount
- Hopkinson Bar Approach
  - Reference acceleration was obtained from laser vibrometer (up to its limit of 20m/s) or from Endevco 7270A series
  - Accelerometers were tested in their axial and lateral orientation (when applicable)

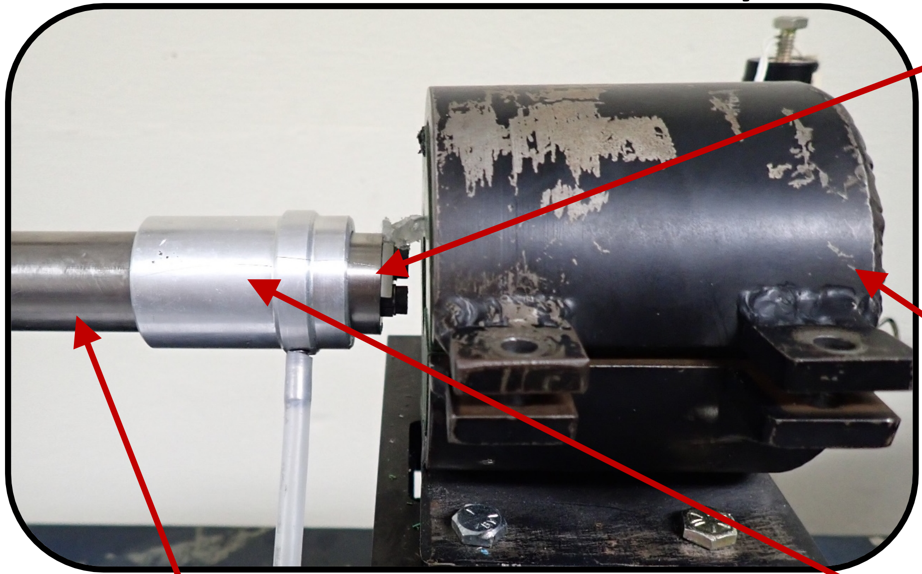


Experimental Setup



Experimental Setup

Forward and Reverse Linearity



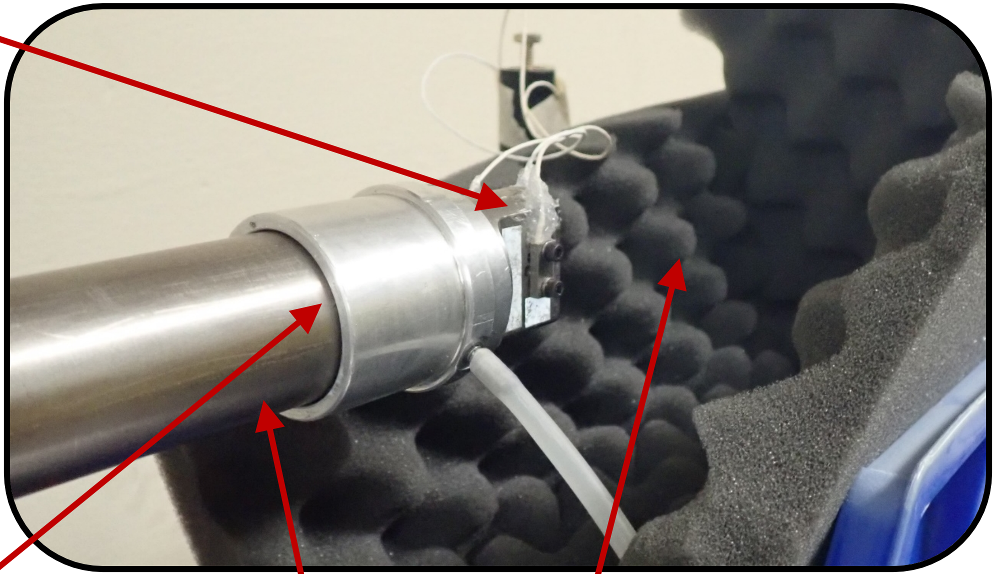
Flyaway

Catcher

1” Titanium
Hopkinson bar

Vacuum collar

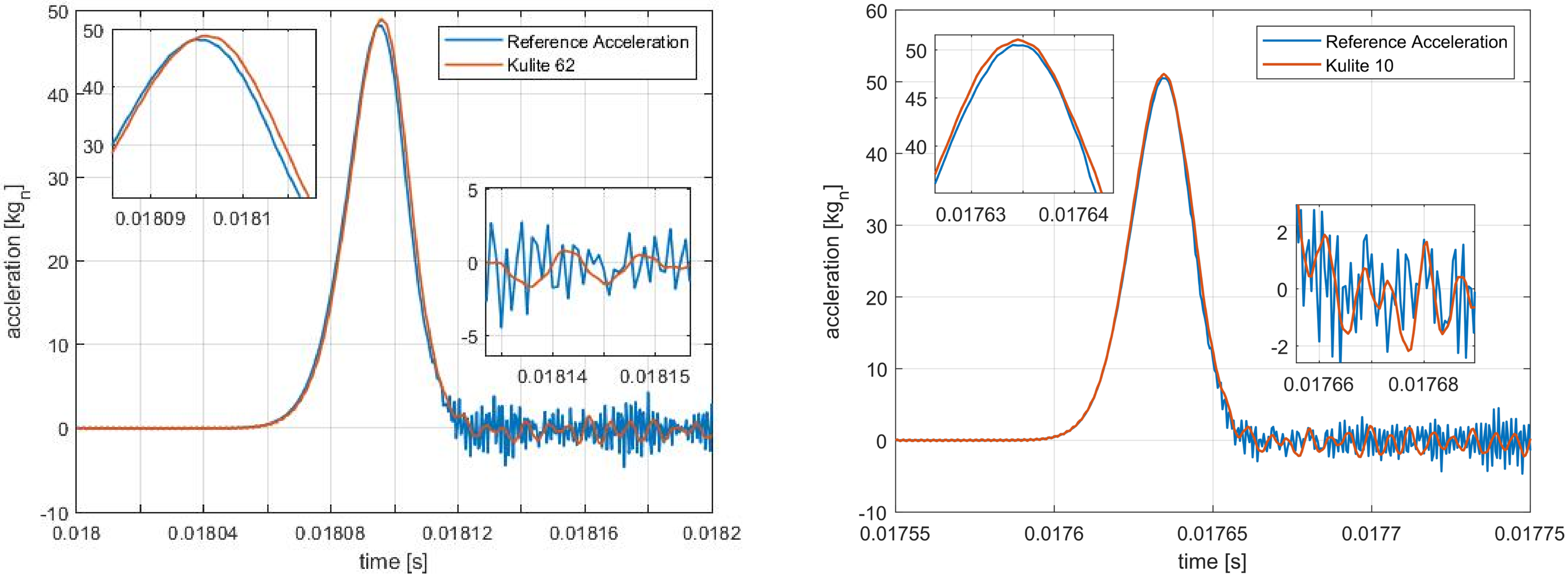
Forward and Reverse Linearity



1.5” Titanium
Hopkinson bar

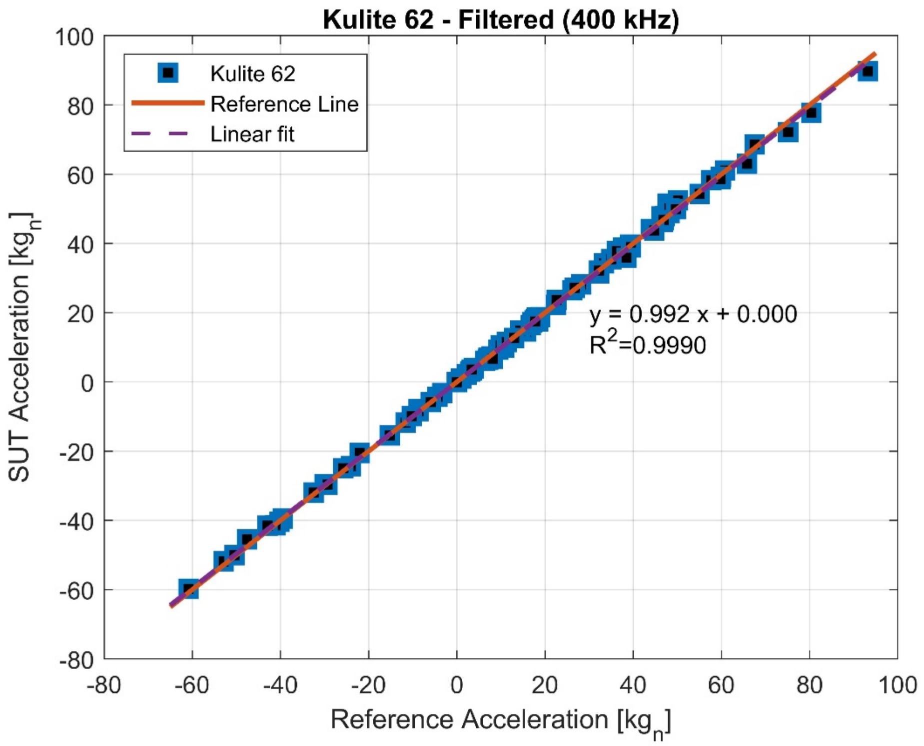
Catcher

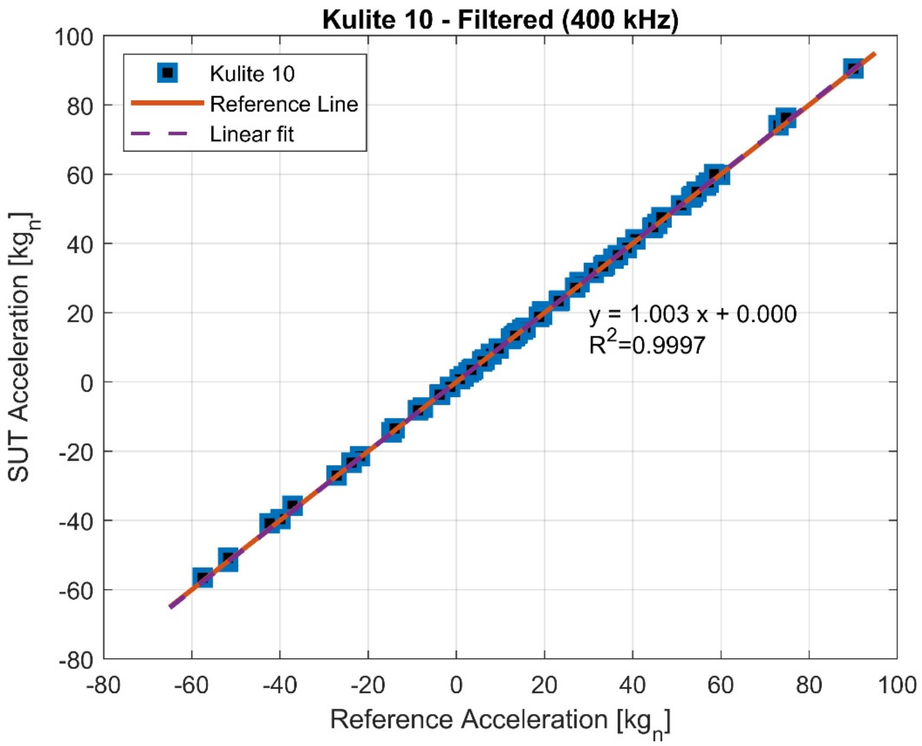
Results – Axial Response Linearity



Kulite accelerometers closely matched the reference accelerometer over the range tested

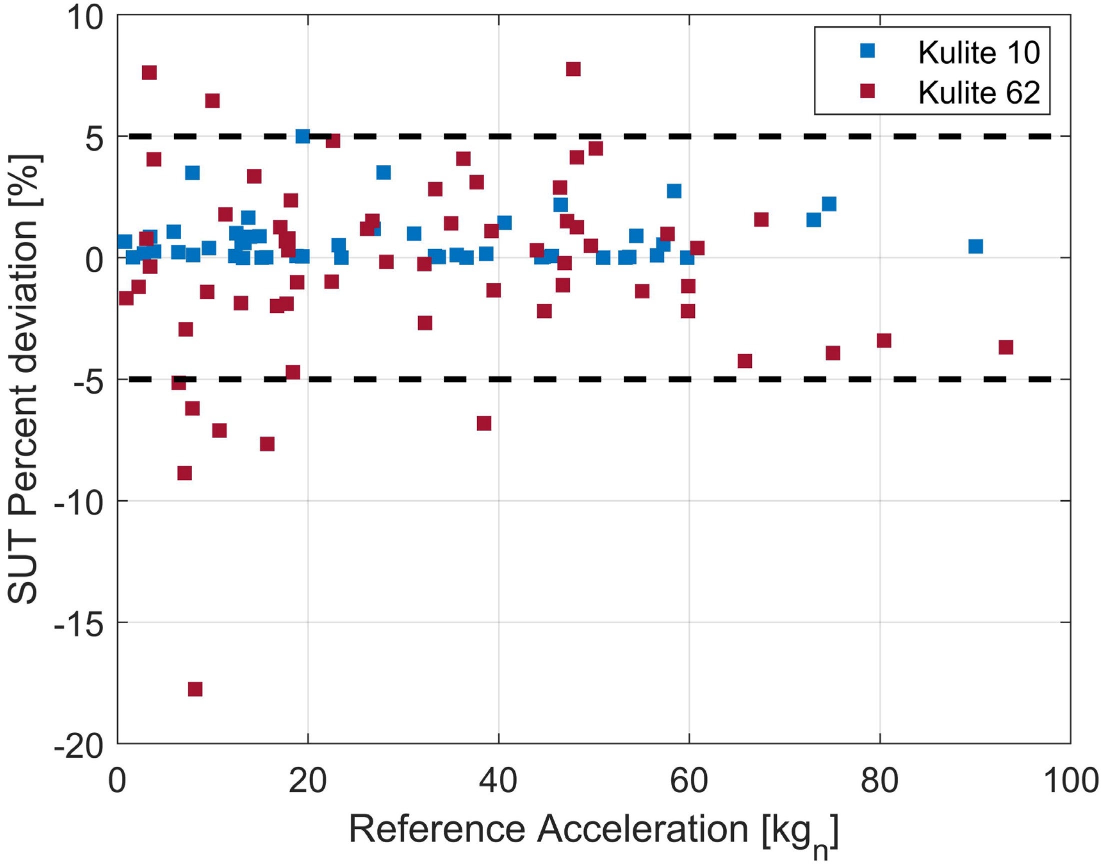
Results – Axial Response Linearity





Kulite sensors demonstrated linearity in forward and reverse configurations over range of use

Results – Axial Response Linearity



Kulite 10 displayed a tighter bound on the linearity response over the range of tested values

Results – Axial Response Linearity

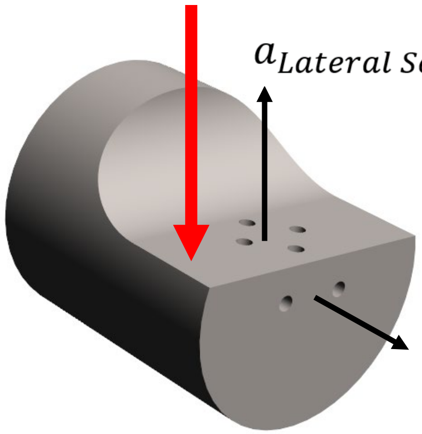
Model	Rated acceleration	Acceleration level for >5% deviation	5% deviation level to rated ratio
Endevco 7280A-20k [1]	20 kg_n	~ 45 kg_n	~ 2.25
Endevco 7280A-60k [1]	60 kg_n	~ 70 kg_n	~ 1.17
Endevco 7270AM4-20k	20kg_n	-	-
Endevco 7270AM4-60k [1]	60 kg_n	> 60 kg_n	> 1
PCB 3991A10-20kg [1]	20 kg_n	~ 35 kg_n	~1.75
PCB 3991A10-60kg [1]	60 kg_n	> 70 kg_n	> 1.17
PCB 3501A12-20kg	20 kg_n	-	-
PCB 3501A12-60kg [1]	60 kg_n	> 65 kg_n	> 1.08
Kulite GMD-280-60KG (10)	60 kg_n	>90 kg_n	> 1.5
Kulite GMD-280-60KG (62)	60 kg_n	>90 kg_n	> 1.5
Analog Devices ADXL 377 – 200g	200 g_n	-	-
TE Connectivity Model 3038 – 6000g	6 kg_n	>8.5 kg_n	>1.4

[1] Beliveau, A., Hong, J., Foley, J., Coker, J., Glikin, N., "COTS Piezoresistive Shock Accelerometers Performance Evaluation," *Proc. SAVIAC 83rd Shock and Vibration Symposium*, New Orleans, LA, November, 2012.

Results – Cross-Axis Sensitivity

$$a_{Laser} = a_{Transverse} + a_{Poisson}$$

$$a_{Lateral\ Sensor} = a_{Transverse} + a_{Poisson} + a_{Cross-axis}$$



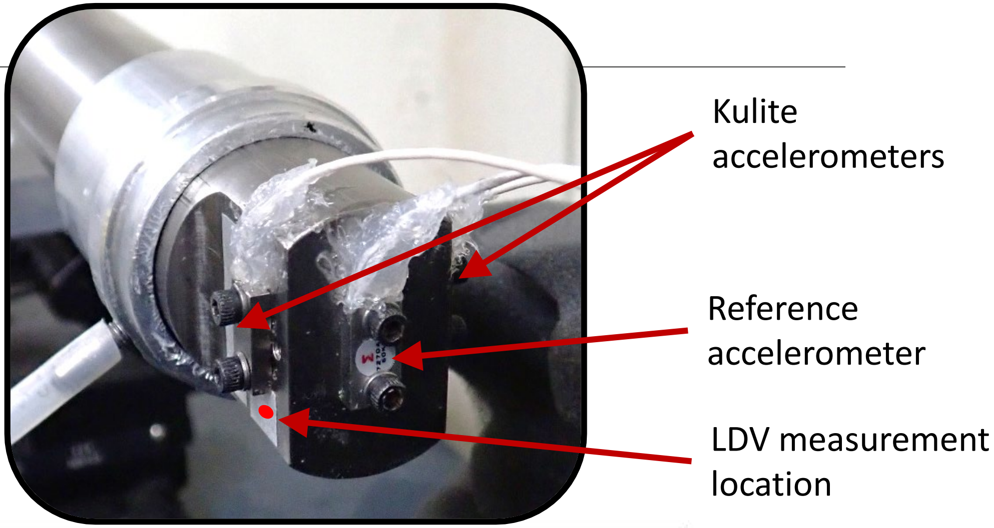
a_{axial}

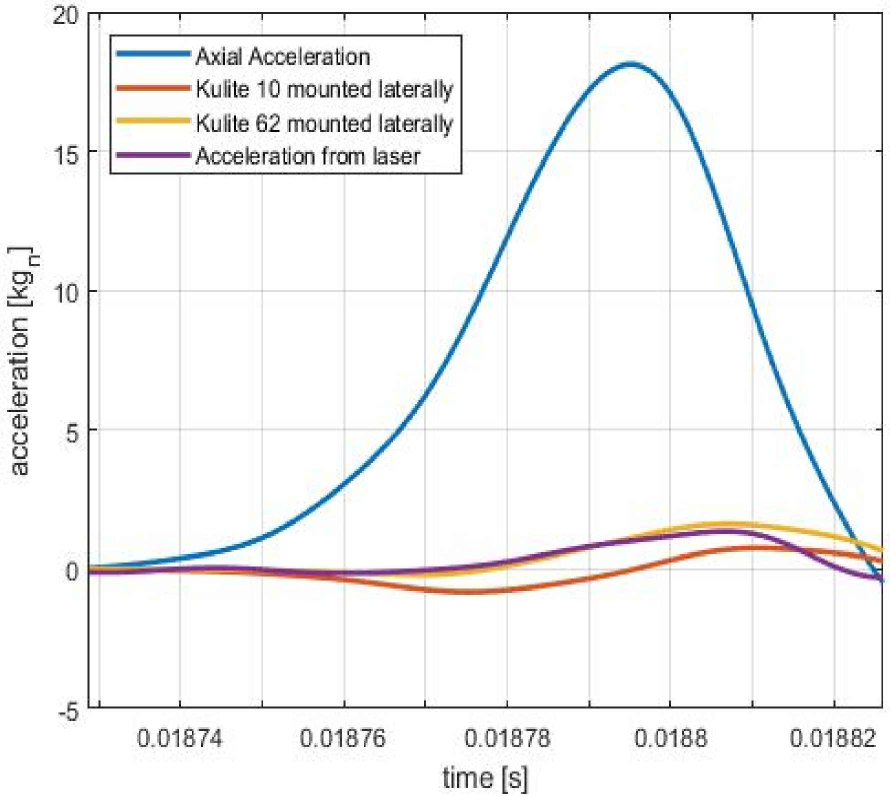
$$a_{Cross-axis} = a_{Lateral\ Sensor} - a_{Laser}$$

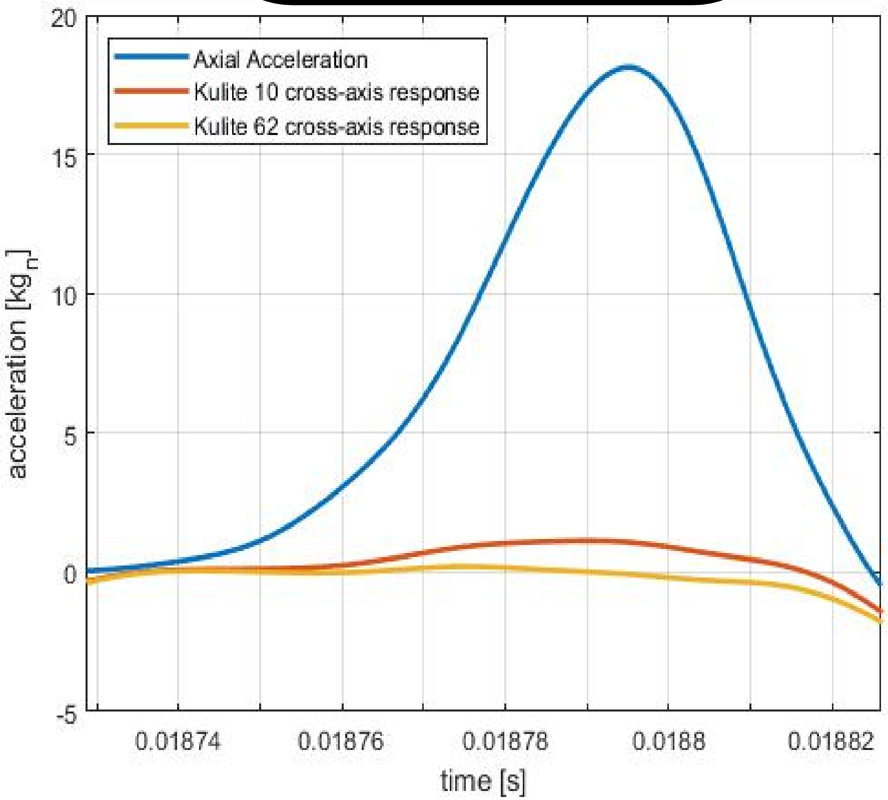
$$Cross\ axis\ Sensitivity = \frac{a_{cross-axis}}{a_{axial}} \times 100$$

Results Cross-axis sensitivity

	Horizontal →	Vertical →
Kulite 8514-9B-62	7.91%	2.65%
Kulite 8514-9B-10	13.67%	6.58%







Results – Cross-Axis Sensitivity

Model	Cross-axis sensitivity (long side)	Cross-axis sensitivity (short side)
Endevco 7280A-20k [1]	3% ± 1%	5% ± 2%
Endevco 7280A-60k [1]	5% ± 1%	5% ± 2%
Endevco 7270AM4-20k	-	-
Endevco 7270AM4-60k [1]	-	-
PCB 3991A10-20kg [1]	4% ± 1%	3% ± 1%
PCB 3991A10-60kg [1]	5% ± .5%	3% ± 2%
PCB 3501A12-20kg	-	-
PCB 3501A12-60kg [1]	-	-
Kulite GMD-280-60KG (10)	13.67%	6.58%
Kulite GMD-280-60KG (62)	7.91%	2.65%
Analog Devices ADXL 377 – 200g	2.2%	-
TE Connectivity Model 3038 – 6000g	-	-

[1] Beliveau, A., Hong, J., Foley, J., Coker, J., Glikin, N., "COTS Piezoresistive Shock Accelerometers Performance Evaluation," *Proc. SAVIAC 83rd Shock and Vibration Symposium*, New Orleans, LA, November, 2012.

Frequency Response

- **Power Spectral Densities**
  - Auto spectral densities

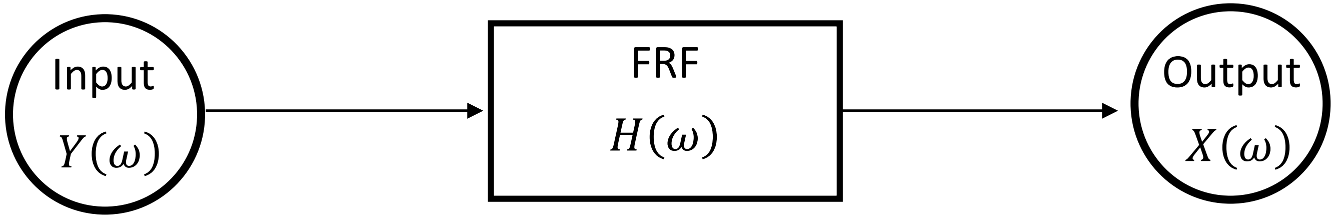
$$G_{XX}(\omega) = \sum_{i=1}^{n} X^i(\omega) X^{i*}(\omega) \qquad G_{YY}(\omega) = \sum_{i=1}^{n} Y^i(\omega) Y^{i*}(\omega)$$

  - Cross spectral densities

$$G_{XY}(\omega) = \sum_{i=1}^{n} X^i(\omega) Y^{i*}(\omega) \qquad G_{YX}(\omega) = \sum_{i=1}^{n} X^{i*}(\omega) Y^i(\omega)$$

Frequency Response

- Frequency Response Function (FRF)



$$H(\omega) = \frac{X(\omega)}{Y(\omega)} \quad \text{or} \quad H(\omega) = \frac{H_1(\omega) + H_2(\omega)}{2}$$

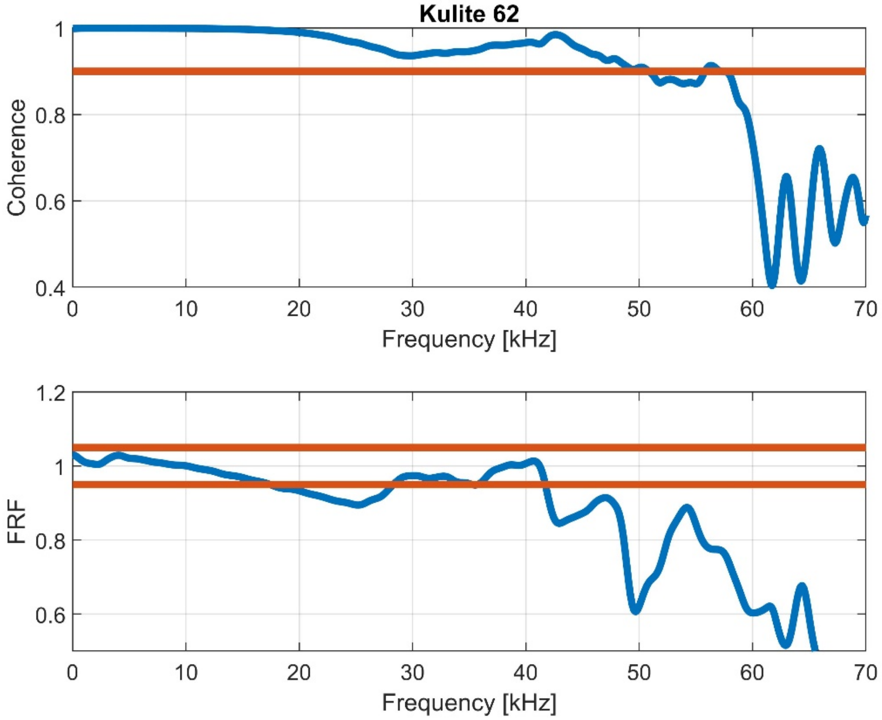
where $$H_1(\omega) = \frac{G_{XY}(\omega)}{G_{YY}(\omega)}$$

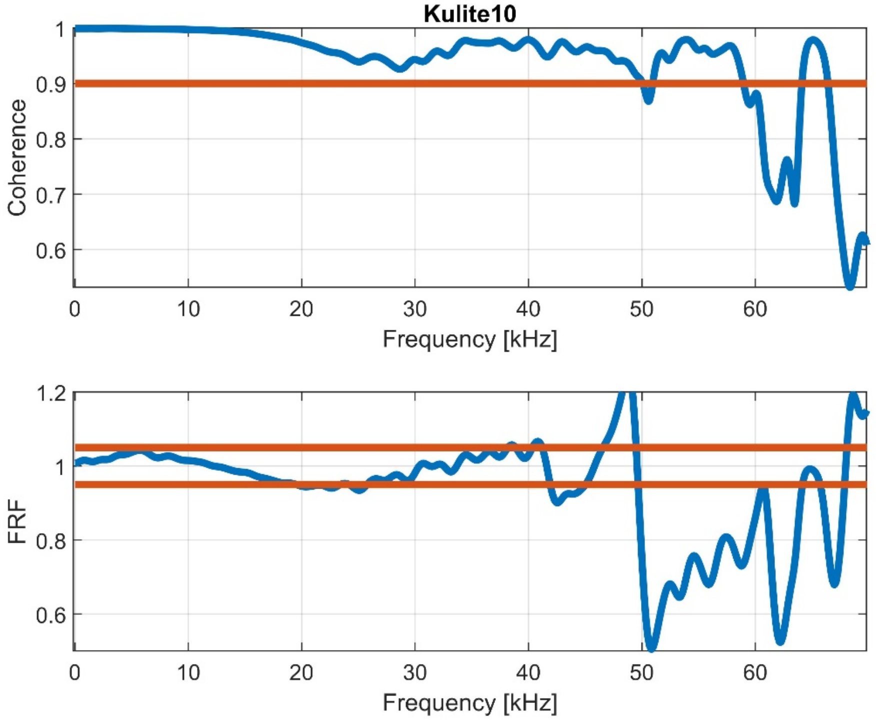
and $$H_2(\omega) = \frac{G_{XX}(\omega)}{G_{YX}(\omega)}$$

- Coherence

$$\gamma_{XY}^2(\omega) = \frac{G_{XY}(\omega)G_{YX}(\omega)}{G_{YY}(\omega)G_{XX}(\omega)}$$

Kulite Frequency Response and Coherence





90% coherence: up to ~51 kHz
FRF Linearity: up to ~17.5kHz

90% coherence: up to ~50 kHz
FRF Linearity: up to ~19.5 kHz

Results – Frequency Response Function

Model	FRF < 1dB
Endevco 7280A-20k [1]	20 kHz
Endevco 7280A-60k [1]	15 kHz
Endevco 7270AM4-20k	-
Endevco 7270AM4-60k [1]	-
PCB 3991A10-20kg [1]	20 kHz
PCB 3991A10-60kg [1]	20 kHz
PCB 3501A12-20kg	-
PCB 3501A12-60kg [1]	-
Kulite GMD-280-60KG (10)	19.5 kHz
Kulite GMD-280-60KG (62)	17.5 kHz
Analog Devices ADXL 377 – 200g	-
TE Connectivity Model 3038 – 6000g	2.5 kHz

[1] Beliveau, A., Hong, J., Foley, J., Coker, J., Glikin, N., "COTS Piezoresistive Shock Accelerometers Performance Evaluation," *Proc. SAVIAC 83rd Shock and Vibration Symposium*, New Orleans, LA, November, 2012.

Conclusions

- All evaluated accelerometers are linear to more than their rated measurement
- The cross-axis sensitivity is <5% for most traditional accelerometers
- Most traditional accelerometers have a bandwidth of ~15kHz while the low cost accelerometer has a bandwidth of ~2.5 kHz

Future work

- Study affects of mounting in surface mount accelerometers
- Cross-axis evaluation of surface mount accelerometers

Acknowledgements and References

Acknowledgments:

Mr. John Scaduto, PI of 19-G-013 Commercial Off the Shelf (COTS) Accelerometer as Impact Switch, for sourcing of low cost accelerometers.

References:

[1] Beliveau, A., Hong, J., Foley, J., Coker, J., Glikin, N., "COTS Piezoresistive Shock Accelerometers Performance Evaluation," *Proc. SAVIAC 83rd Shock and Vibration Symposium*, New Orleans, LA, November, 2012.

Questions?