Australian Government
Department of Defence
Defence Science and Technology Group

Vibration Testing of Energetics

Lachlan Burgess-Orton

Research Engineer - DSTG

What is Vibration?

(Courtesy of NASA)

What is Vibration?

(Courtesy of NASA)

Vibration in Transportation Context

Palletized

- Vibration from aircraft and engines during flight transmits into palletized EO stored onboard.
- Vibration generated from unevenness of ground during road transportation transmits directly into palletized EO.

Figure 1: Example of palletized EO [1]

Captive Carriage

Unsteady aerodynamic forces acting along entire body of EO exposed to the flow induces vibration.

Figure 2: Captive carriage of numerous EO on an aircraft [2]

Why do we Conduct Vibration Testing of Explosive Ordinance?

To validate estimated safe life of ordinance based on environmental vibration experienced during transportation and captive carriage.

What we don't want!

Figure 3: Truck destroyed during transportation [3]

Figure 4: Aircraft destroyed in flight [4]

Types of Ground Vibration Testing (GVT)

Modal GVT

Goal - Measure natural frequencies of a structure and modal shapes at these frequencies.

Method - Use low force shakers to apply different vibration profiles to excite the structure at different frequencies, measuring the response with accelerometers or a laser vibrometer.

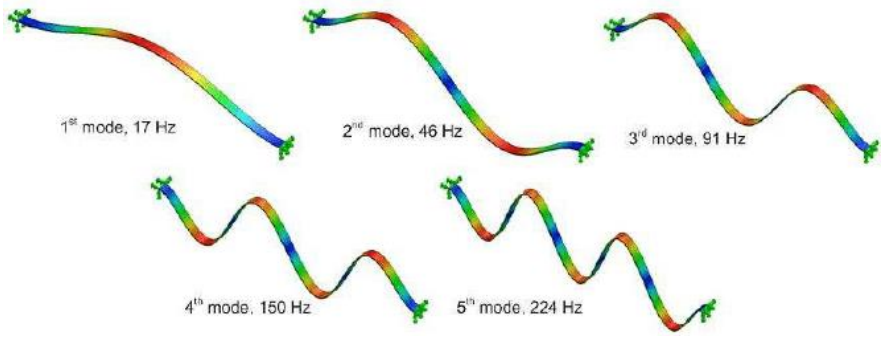

Figure 5: Example of natural frequency values and shapes for a clamped beam [5]

Spectrum GVT

Goal - Apply representative vibration spectrum to structure for a specified period of time to demonstrate safe life limit.

Method - Use high capacity shaker/s to impart representative forces across a frequency band, using accelerometers to keep the structures response within the set profile.

Figure 6: Horizontal single shaker test setup [6]

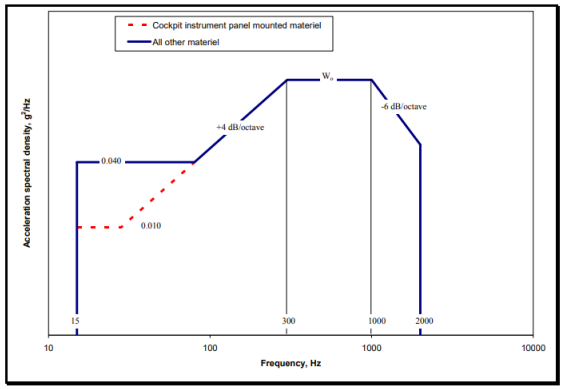

Figure 7: Jet transport aircraft vibration exposure [7]

Explosive Ordinance Testing – What we currently do in Australia

- Large capacity individual shakers testing in single axis at a time.
- Achieve high accuracy of vibration profile at single control point but severe under/over test along rest of structure.

Figure 1: Single shaker single axis test setup [8]

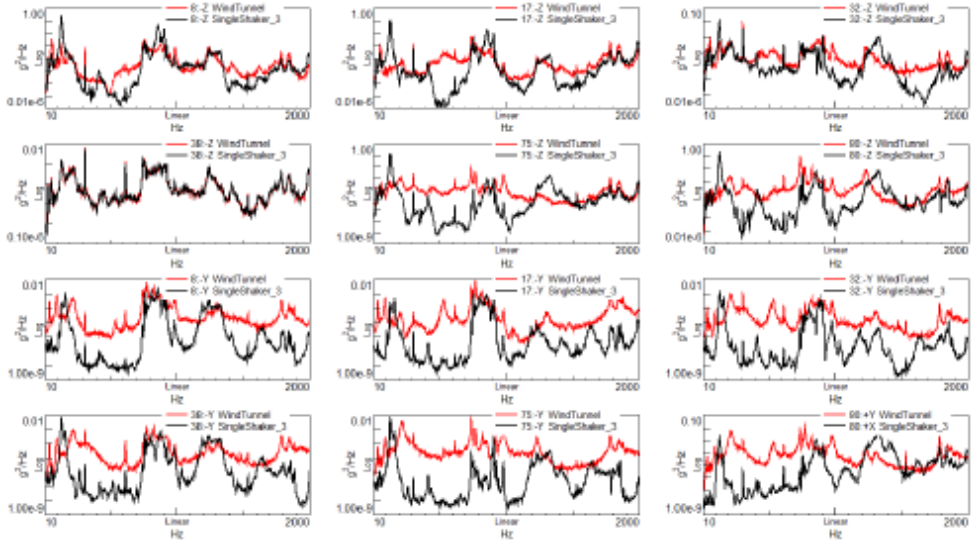

Figure 3: Comparison between wind tunnel data (red) and single shaker single axis test (black) [8]

What is Multi Input Multi Output (MIMO)

- MIMO is the use of two or more excitation sources on a structure with two or more control points used to drive excitation.
- MIMO control research first began in the late 60's [9, 10].
- MIMO controllers/software readily available.
- MIMO testing features in some standards such as MIL Std 810 [7].

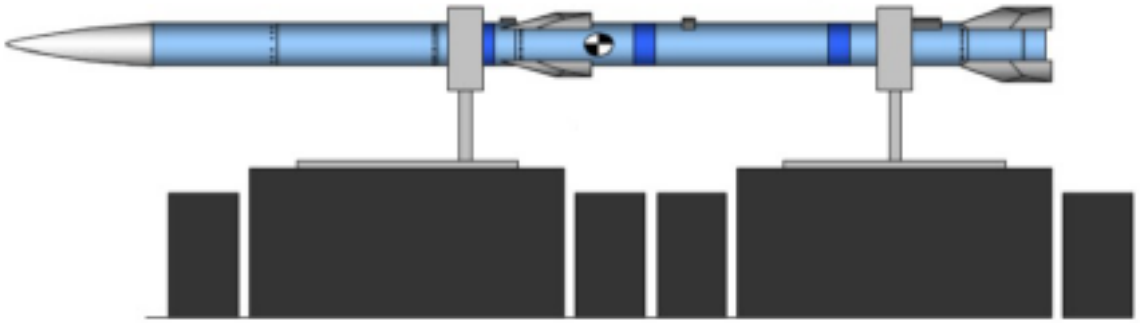

Figure 4: Multi shaker single axis test setup with MIMO control [11]

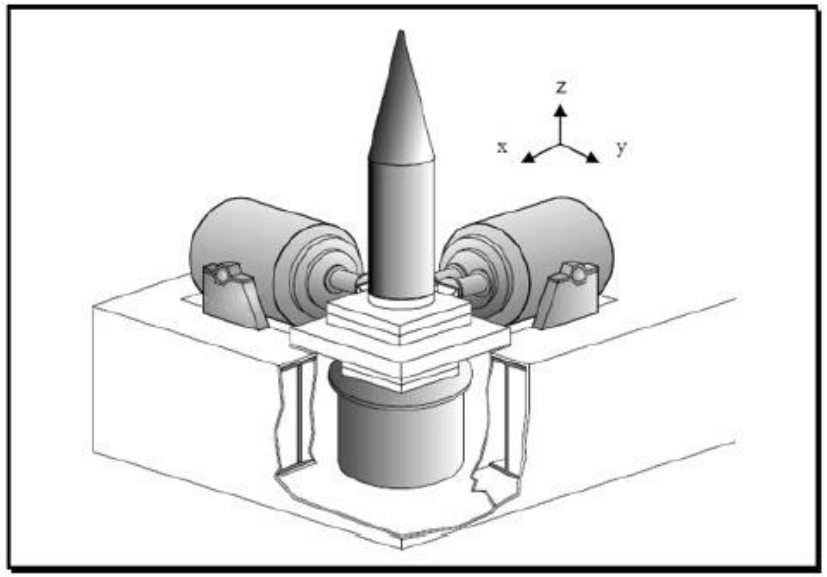

Figure 5: Multi shaker multi axis test setup with MIMO control [7]

Details of Multi Input Multi Output (MIMO) Control [8]

- At beginning of test, low level random spectrum applied to measure response of structure at control points.
- Frequency Response Function (FRF) estimated between input signals and response at control points.
- Using the Spectral Density Matrix (SDM) and FRF, the drive signals are solved for assuming a linear response of the structure and an inverse FFT calculates the time history drive signal.
- Controller applies drive signal and measures input at all control points, updating the SDM live as required.

What does the FRF and SDM look like?

FRF for MIMO Control [8]

- The Frequency Response Function (FRF) is a matrix describing the relationship between the excitation source (F) and output response at a control point (Y).
- Can be square (same number of shakers and control accelerometers) or rectangular (more control accelerometers than shakers).

2 MIMO control methods

- Square → Equation easily solved and perfect theoretical drive signal generated.
- Rectangular → Rectangular matrix inversion must be numerically solved, resulting in a least square error in the drive signal solution.

	F_1	F_2
Y_1	$H_{1,1}$	$H_{1,2}$
Y_2	$H_{2,1}$	$H_{2,2}$

Figure 6: Square FRF matrix [8]

	F_1	F_2	F_3
Y_1	$H_{1,1}$	$H_{1,2}$	$H_{1,3}$
Y_2	$H_{2,1}$	$H_{2,2}$	$H_{2,3}$
Y_3	$H_{3,1}$	$H_{3,2}$	$H_{3,3}$
Y_4	$H_{4,1}$	$H_{4,2}$	$H_{4,3}$
Y_5	$H_{5,1}$	$H_{5,2}$	$H_{5,3}$
Y_6	$H_{6,1}$	$H_{6,2}$	$H_{6,3}$
Y_7	$H_{7,1}$	$H_{7,2}$	$H_{7,3}$
Y_8	$H_{8,1}$	$H_{8,2}$	$H_{8,3}$
Y_9	$H_{9,1}$	$H_{9,2}$	$H_{9,3}$
Y_{10}	$H_{10,1}$	$H_{10,2}$	$H_{10,3}$
Y_{11}	$H_{11,1}$	$H_{11,2}$	$H_{11,3}$
Y_{12}	$H_{12,1}$	$H_{12,2}$	$H_{12,3}$
Y_{13}	$H_{13,1}$	$H_{13,2}$	$H_{13,3}$

Figure 7: Rectangular FRF matrix [8]

SDM for MIMO Control [8]

- Spectral Density Matrix (SDM) is a matrix describing the amplitude of each DOF and relative motion between DOF's.
- Auto spectral Density (ASD) describes the magnitude of response across a frequency band (orange diagonal terms).
- Cross Spectral Density (CSD) possesses magnitude and phase information across a frequency band (green terms).
- SDM is derived from in service environmental test data or based on defined test spectrum.
- Control locations for MIMO testing are determined by accelerometer locations during environmental data collection.

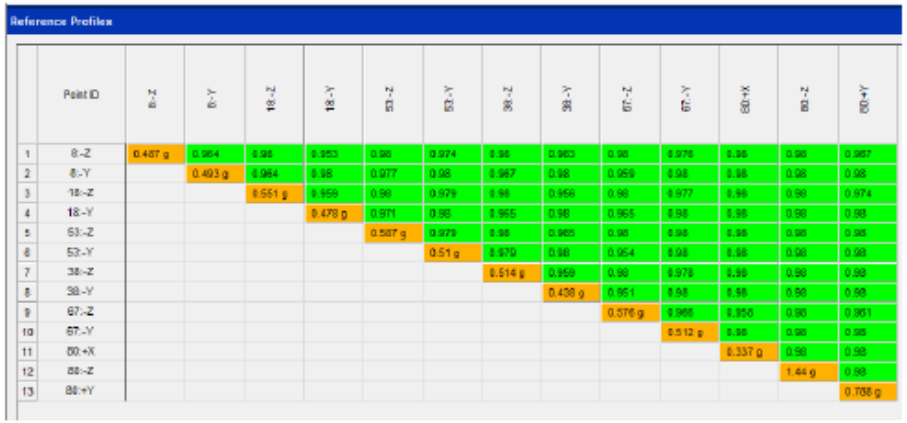

Figure 8: SDM matrix which is symmetrical around the diagonal [8]

What Needs to be Considered for MIMO Testing?

Is the structure's vibration response linear?

- Impacts controller prediction of excitation input.

How many inputs and control points will the test have?

- Number of control points limited by accelerometer locations during environmental data collection.
- Number of inputs limited by shaker infrastructure.

What control strategy will be used?

- Square control → Same number of control points and excitation sources. Perfect environmental loads replicated at control points but poor at other locations.
- Rectangular control → More control points than excitation source. Superior replication of environmental loads along structure but will never be perfect.

How representative are the fixture boundary conditions?

How many axes will be tested in simultaneously?

Benefits of MIMO

- Allows for complex control of vibration response at multiple locations along a structure.
- Enables Operating Deflection Shape (ODS) to be matched to environmental response across entire frequency band (similar concept to modal shapes).

  → Ensures strain fields throughout structure are the same as in service.

  → Accurate replication of elastic strain fatigue or plastic deformation which are primary failure modes.
- Enables multi-axis testing with control over both the input spectrum and structures response to better replicate specific environments and capture any peak responses from summation of forces in two orthogonal axis. This also reduces test time.
- Can be used on palletized or captive carriage configurations.
- More representative testing will reduce the reliance on high safety factors for EO vibration life limits.

Difficulty of Captive Carriage Vibration Testing

- Distributed aerodynamic loads are difficult to replicate in a lab environment.
- Loads applied from all directions, not just single axis.
- Availability of flight test loads data to characterize vibration environment.

Usefulness of MIMO Control for Captive Carriage Problem

- Reduced test time through multi axis testing.
- Use multiple control points and shakers to gain greater accuracy in environmental loads applied.
- More representative time to failure testing can be conducted.

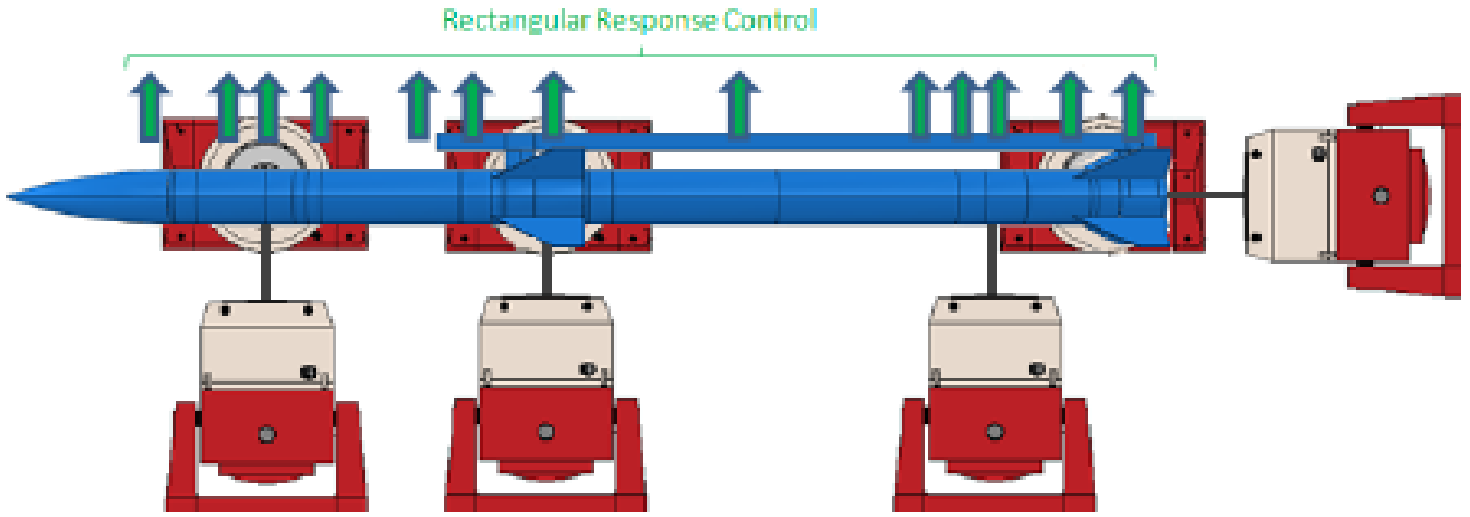

Figure 9: Test setup example for multi axis MIMO control missile test[8]

Recent Research [8]

In 2018 Dr Chris Roberts completed a comparison between three test setups to simulate captive carriage of a 3 kg dummy missile to evaluate pro's and con's.

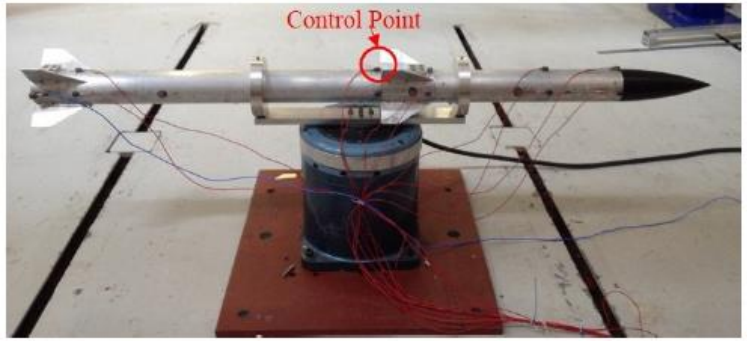

Figure 10: Single axis single shaker with no MIMO control [8]

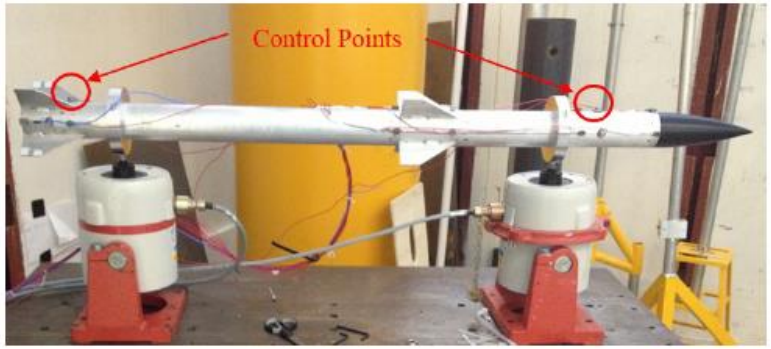

Figure 11: Single axis dual shaker with MIMO control [8]

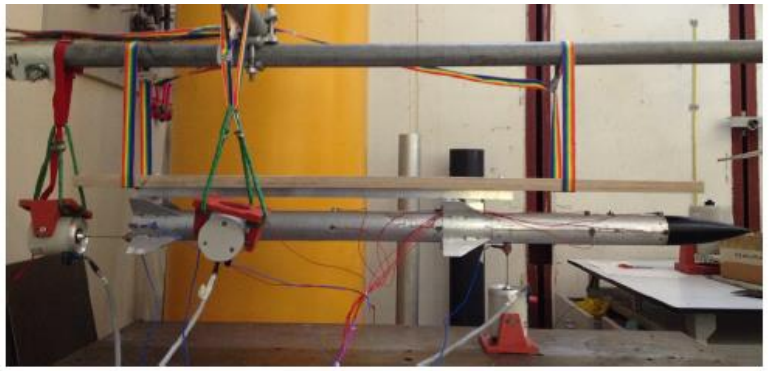

Figure 12: Multi axis multi shaker with MIMO control [8]

Recent Research Cont. [8]

Testing demonstrated an increased number of control points increased how well structures response matched wind tunnel data

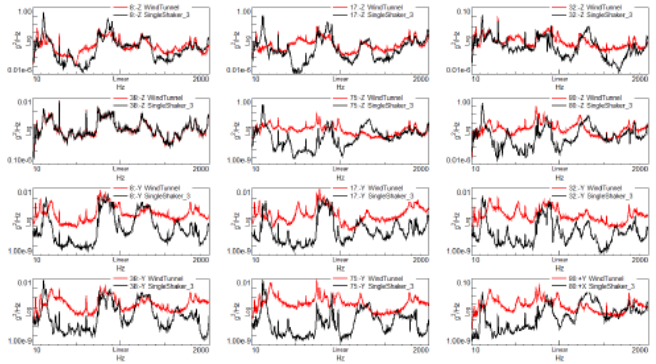

Figure 13: Single axis single shaker with no MIMO control [8]

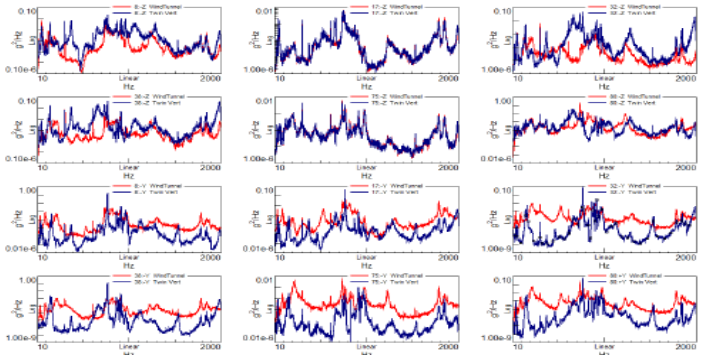

Figure 14: Single axis dual shaker with MIMO control [8]

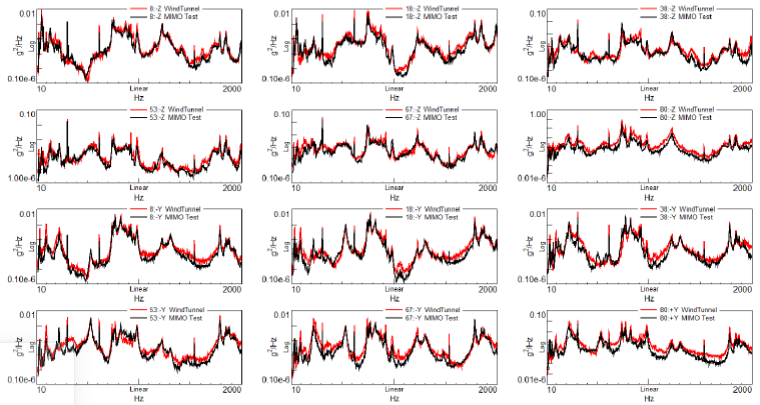

Figure 15: Multi axis multi shaker with MIMO control [8]

Recent Research Cont. [8]

Multi axis MIMO testing with more control points (requiring rectangular control) was superior in matching modal shapes, which will induce more representative strain fields.

→ More representative failure modes when testing for service life.

→ Greater confidence in predicted time until failure results in longer safe life.

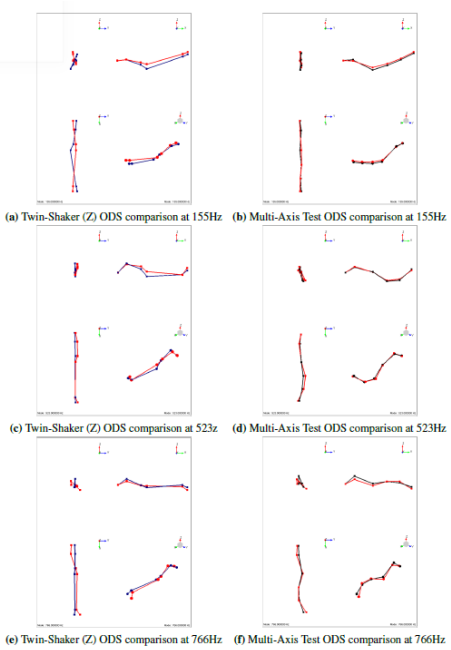

Figure 16: Comparison of single axis dual shaker (left) modal shapes to multi axis multi shaker (right) modal shapes [8]

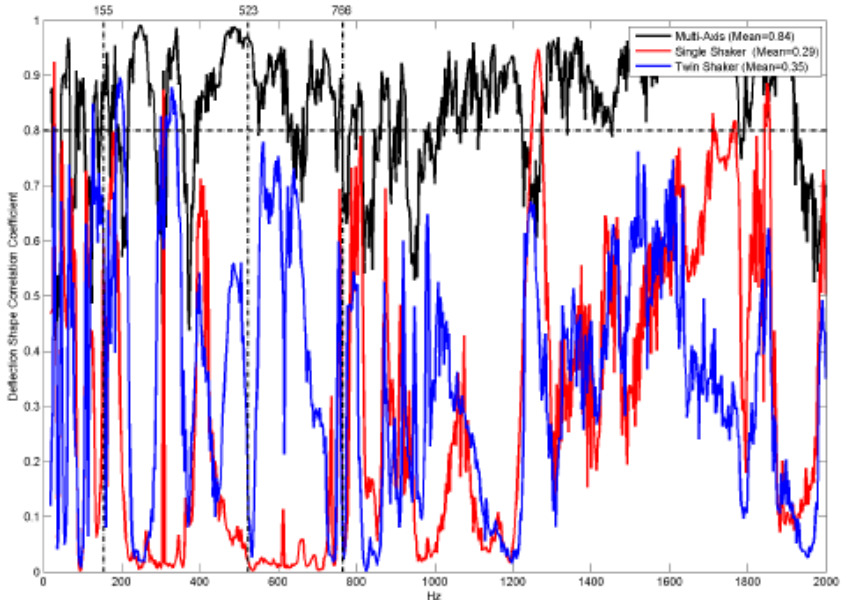

Figure 17: Plot demonstrating how well each test matched the wind tunnel response data of the missile [8]

Other Notable Research

- Daborn demonstrated similar results on 60 kg structure when using 8 shakers and 2 control points [12]. This type of testing has been coined as Impedance-Matched Multi Axis Testing (IMMAT).
- Brown et al. demonstrated an increase time to failure between from single DOF testing to IMMAT testing [13].

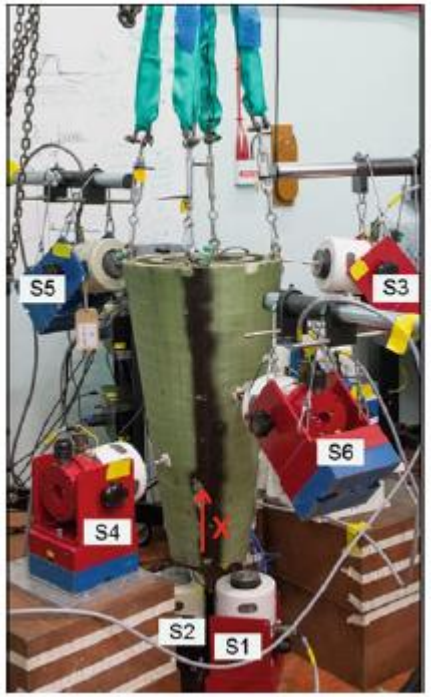

Figure 18: IMMAT testing of 60 kg structure [12]

- Research has also been conducted into optimizing control strategies, force requirements, shaker location placement and control accelerometer placement [8, 14, 15, 16, 17, 18, 19, 20, 21] which can all be leveraged.

Conclusions

- Importance of vibration testing EO has not gone away, but superior technology and methodologies are now available.
- Utilizing MIMO controlled IMMAT testing in multiple axis will increase understanding of EO safe life limits -> allow for relaxation of conservative safety factors and longer service life.
- Shorter test times by testing in 3 axis at once.
- Method can be used for both road transport and captive carriage cases.

Where do the challenges lie?

- Gathering representative vibration input data of the EO in transport environments for impedance matching.

References

- [1] Wikipedia. Rapid Dragon (missile system). (2024) [Accessed 02/10/2024]; Available from: https://en.wikipedia.org/wiki/Rapid_Dragon_%28missile_system%29.
- [2] NARA & DVIDS Public Domain Archive. A close-up view of the bottom of a 33rd Tactical Fighter Wing F-15C Eagle aircraft, showing the two AIM-9 Sidewinder missiles on each wing and four AIM-120 Advanced Medium-Range Air-to-Air Missiles (AMRAAMs) on its fuselage weapons stations. The aircraft is on a flight out of Eglin Air Force Base, Fla. (2024) [Accessed 02/10/2024]; Available from: https://nara.getarchive.net/media/a-close-up-view-of-the-bottom-of-a-33rd-tactical-fighter-wing-f-15c-eagle-aircraft-6dc6e6.
- [3] XAN Logstics. Fire Prevention for Truck Drivers. (2024) [Accessed 02/10/2024]; Available from: https://xansystems.com/fire-prevention-for-truck-drivers/
- [4] Avraham, M. Russian fighter jet shot down by Israeli Air Force fighter jet; Is this in our future?. (2015) [Accessed 02/10/2024]; Available from: https://thecurrantime.com/russian-fighter-jet-shot-down-by-israeli-air-force-fighter-jet-is-this-in-our-future/.
- [5] Zaman, I., et al. (2014) Study of Passive Vibration Absorbers Attached on Beam Structure. Applied Mechanics and Materials **660** 12/01 511-515.
- [6] Selič, V. Structural Testing using Sine Processing. (2020) [Accessed 02/10/2024]; Available from: https://metromatics.com.au/structural-testing-using-sine-processing/.
- [7] Department of Defense. MIL-STD-810 G:Environmental Engineering Considerations and Laboratory Tests. Department of Defense, Aberdeen Proving Ground, Aberdeen, Maryland, 2008.
- [8] Roberts, C. (2018) *Improving Ground Based Test Simulations of Aerodynamically Induced Vibration*, University of Bristol
- [9] Wonham, W. (1967) On pole assignment in multi-input controllable linear systems. *IEEE Transactions on Automatic Control* **12** (6) 660-665
- [10] Dosch, J. J., Leo, D. J. and Inman, D. J. (1992) *[1992] Proceedings of the 31st IEEE Conference on Decision and Control*:16-18 Dec. 1992
- [11] Ministry of Defence. DEF STAN 00-35: Environmental Handbook for Defence Materiel. UK Defence Standardization, Ministry of Defence, Glasgow, 4th edition, Sept 2006.
- [12] Daborn, P. M. (2017) *Shock & Vibration, Aircraft/Aerospace, Energy Harvesting, Acoustics & Optics, Volume 9*, Cham:2017//, Harvie, J. M. and Baqersad, J. (eds.), Springer International Publishing
- [13] Thomas Brown, J. P., Glen Throneberry, Kevin Cross, Washington DeLima, Martin Sanchez, Stephen Aulbach (2022) *Comparative failure analysis of components exposed to multi-axis and single axis vibration testing*.
- [14] Hunter, N. F., Cross, K. R. and Nelson, G. (2019) *Topics in Modal Analysis & Testing, Volume 9*, Cham:2019//, Mains, M. and Dilworth, B. J. (eds.), Springer International Publishing
- [15] D'Elia, G., et al. (2020) Analyses of drives power reduction techniques for multi-axis random vibration control tests. *Mechanical Systems and Signal Processing* **135** 2020/01/01/ 106395
- [16] Maji, A., et al. (2022) Error analyses of a Multi-Input-Multi-Output cantilever beam test. *Journal of Vibration and Control* **28** (21-22) 3426-3437
- [17] Musella, U., et al. (2017) Analyses of Target Definition Processes for MIMO Random Vibration Control Tests. In. 135-148
- [18] Mayes, R., et al. (2020) Optimization of Shaker Locations for Multiple Shaker Environmental Testing. *Experimental Techniques* **44** (3) 2020/06/01 283-297
- [19] Musella, U., et al. (2020) *Special Topics in Structural Dynamics & Experimental Techniques, Volume 5*, Cham:2020//, Dervilis, N. (ed.), Springer International Publishing
- [20] Rohe, D. P., Nelson, G. D. and Schultz, R. A. (2020) *Sensors and Instrumentation, Aircraft/Aerospace, Energy Harvesting & Dynamic Environments Testing, Volume 7*, Cham:2020//, Walber, C., Walter, P. and Seidlitz, S. (eds.), Springer International Publishing
- [21] Moreno, K. J., Sriram Malladi, V. V. N. and Tarazaga, P. A. (2021) *Special Topics in Structural Dynamics & Experimental Techniques, Volume 5*, Cham:2021//, Epp, D. S. (ed.), Springer International Publishing

Questions?