Force Measurement for Wind Tunnel Facilities
Current Practices and Research Investments

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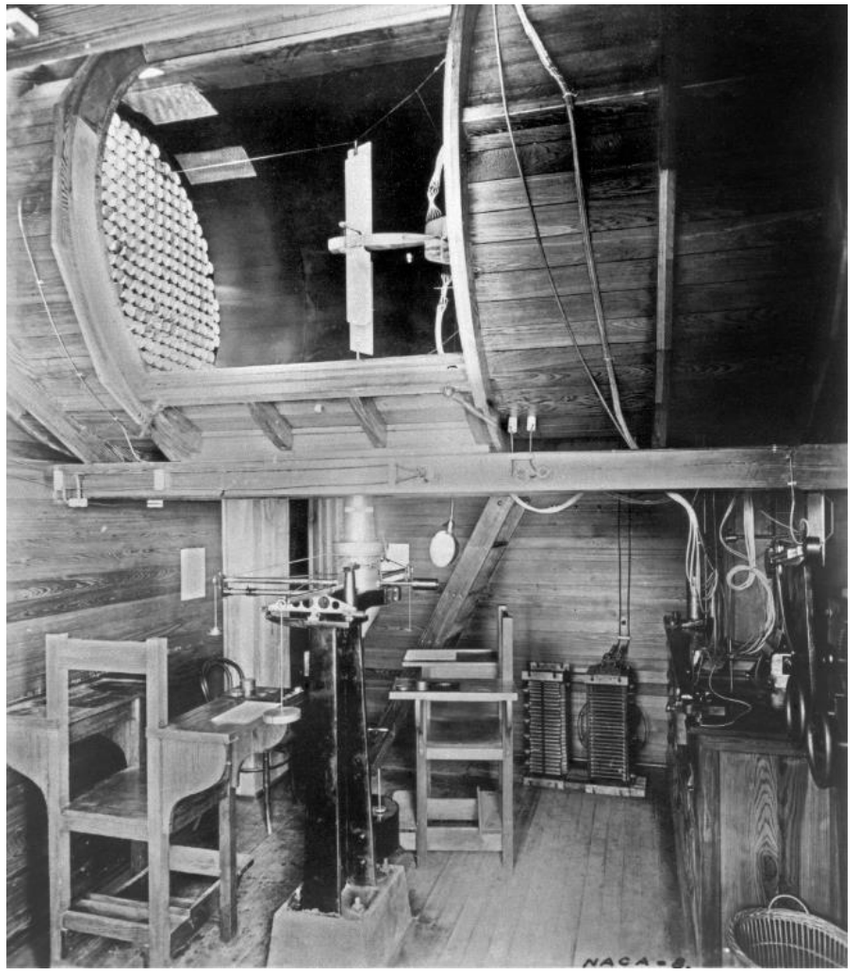
Western Regional Strain Gage Committee Fall Conference
September 30 – October 2, 2024

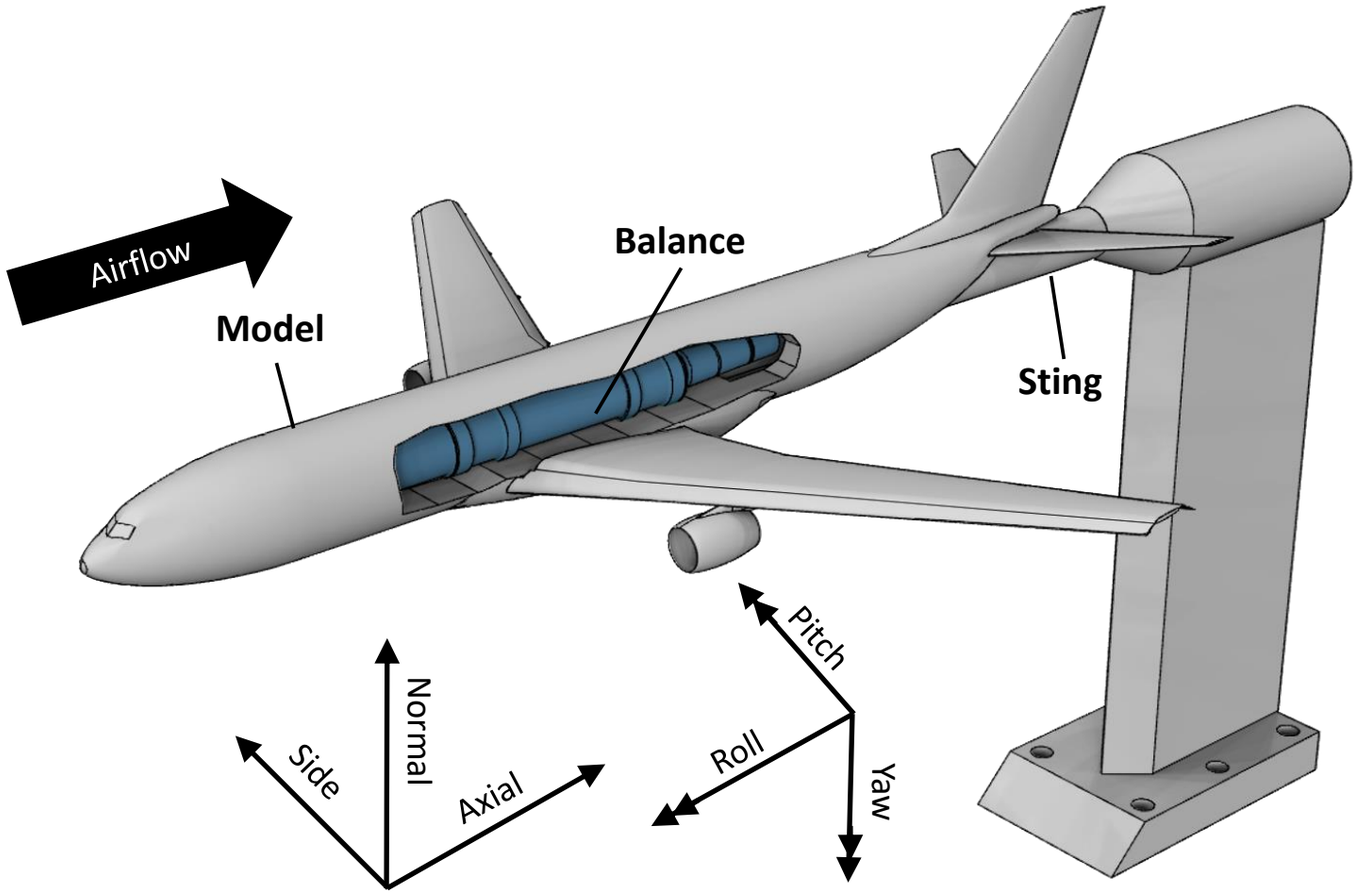
Outline

- **Introduction to strain gage balances used in NASA's wind tunnel facilities.**
- **Research areas:**
  - Additive manufacturing of wind tunnel balances.
  - Topology optimization to produce novel force transducer designs.
  - Dynamic force measurement.

What are Strain-Gage Balances?



Mechanical balance below wind tunnel (NACA 1921).



Depiction of 6-component internal wind tunnel balance

- **Transducers used to measure the aerodynamic loads encountered by a wind-tunnel model during a wind-tunnel test.**
- **Balances commonly measure six-components.**

Typical LaRC Style Balance

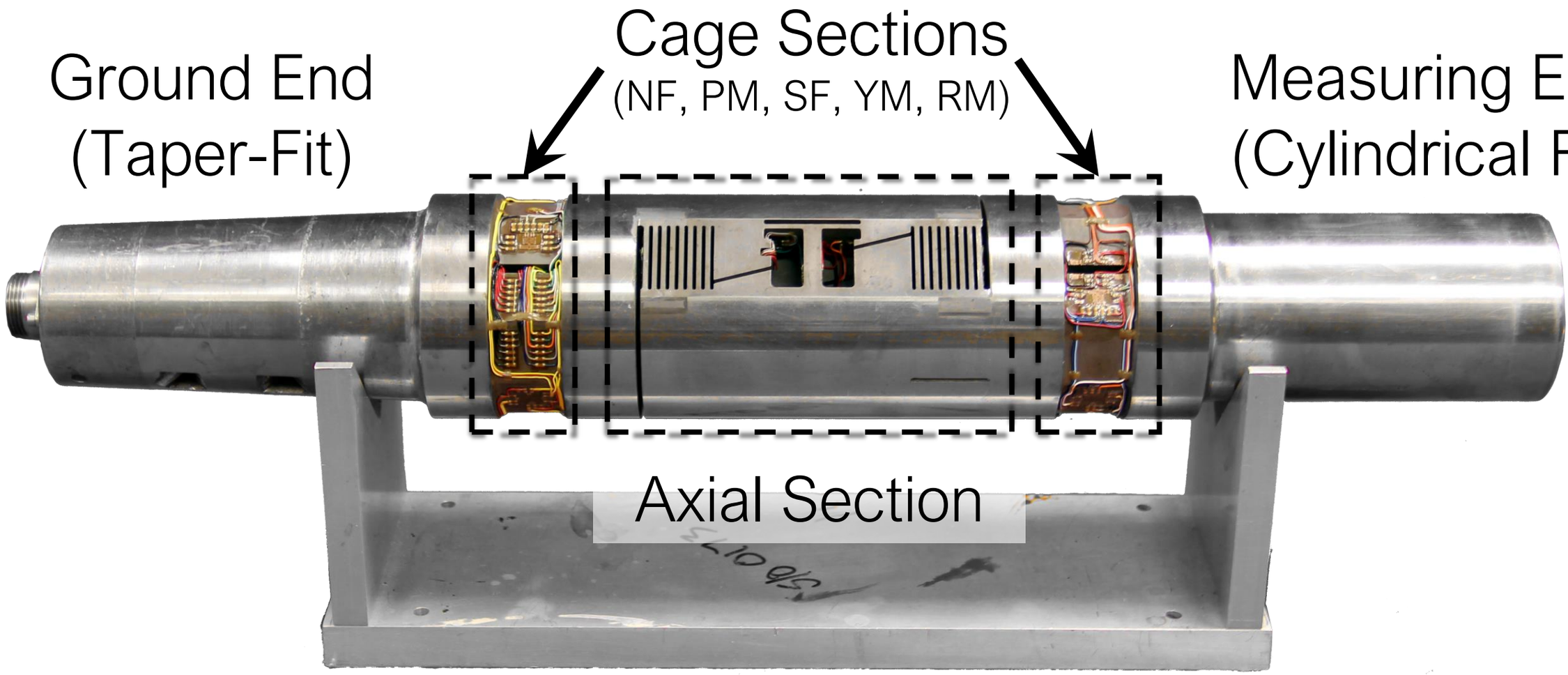
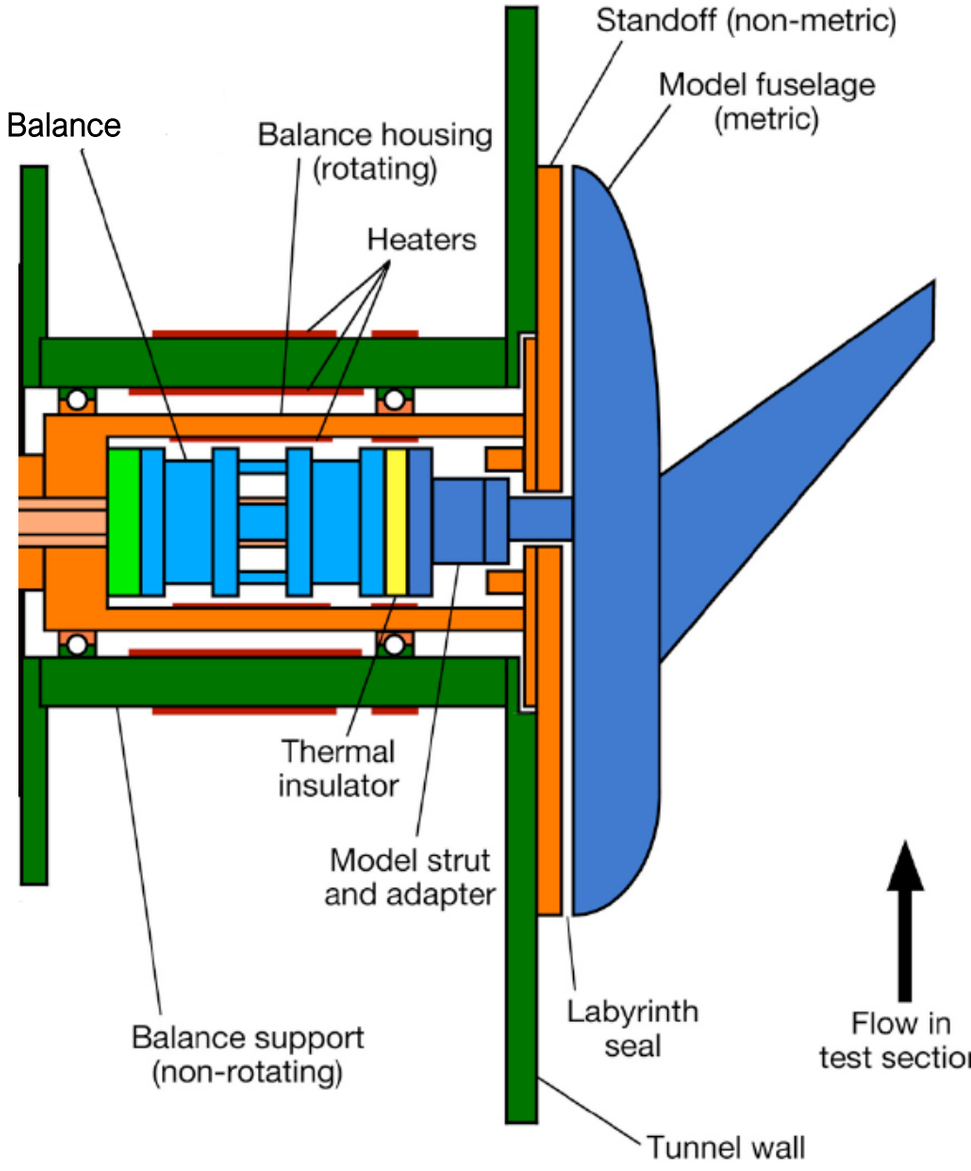


Photo of six-component internal wind tunnel balance.

- **0.5 to 7.0 in. in diameter and 0.5 to 12,000 lbf in capacity.**
- **Monolithic structure with non-line-of-sight features.**
- **Analytical mechanics formulations guide the design of cage and axial sections (documented in NASA TM [1]).**

Semi-span Balance for Half Model Testing



Depiction of semi-span model configuration with balance.

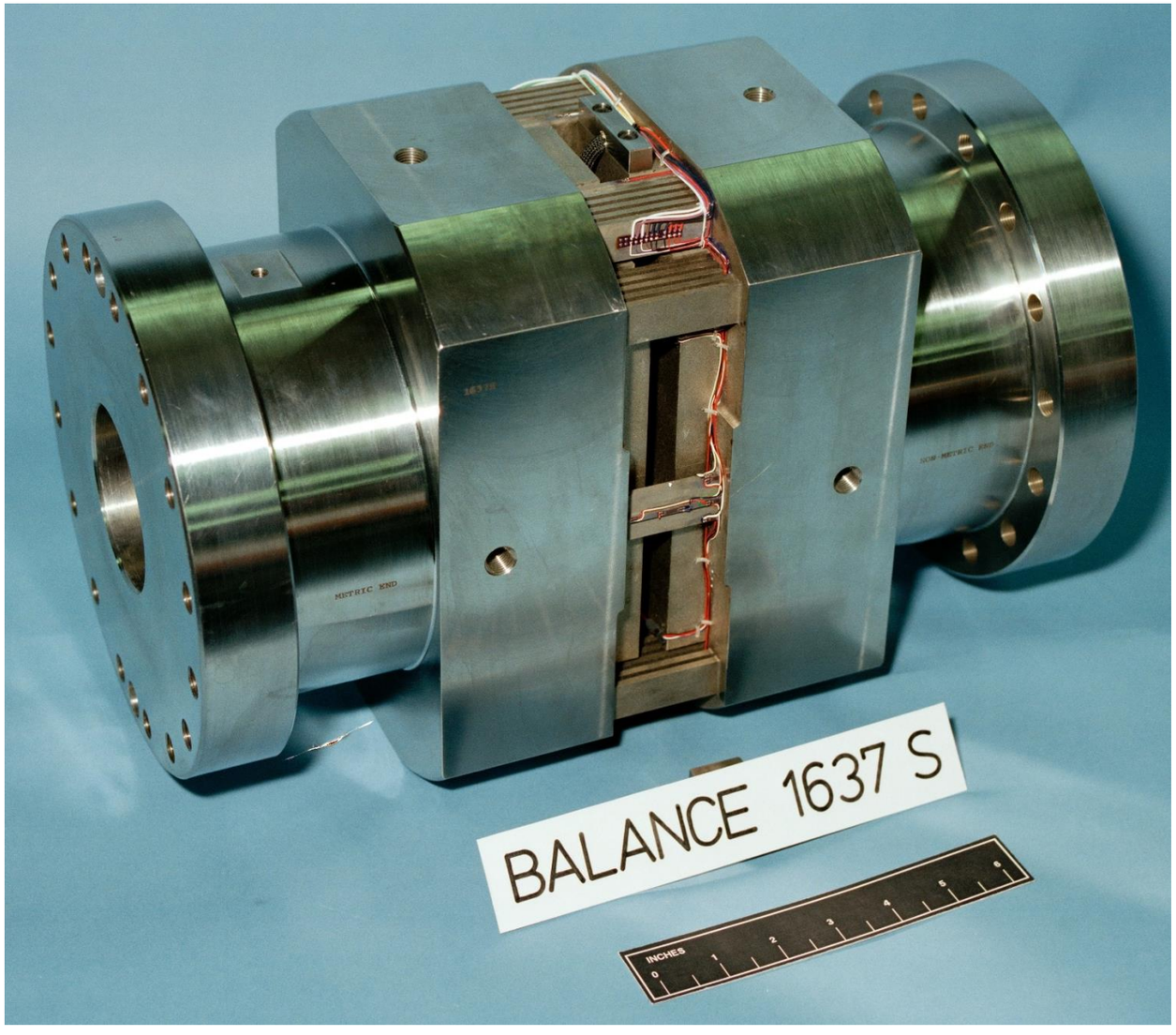
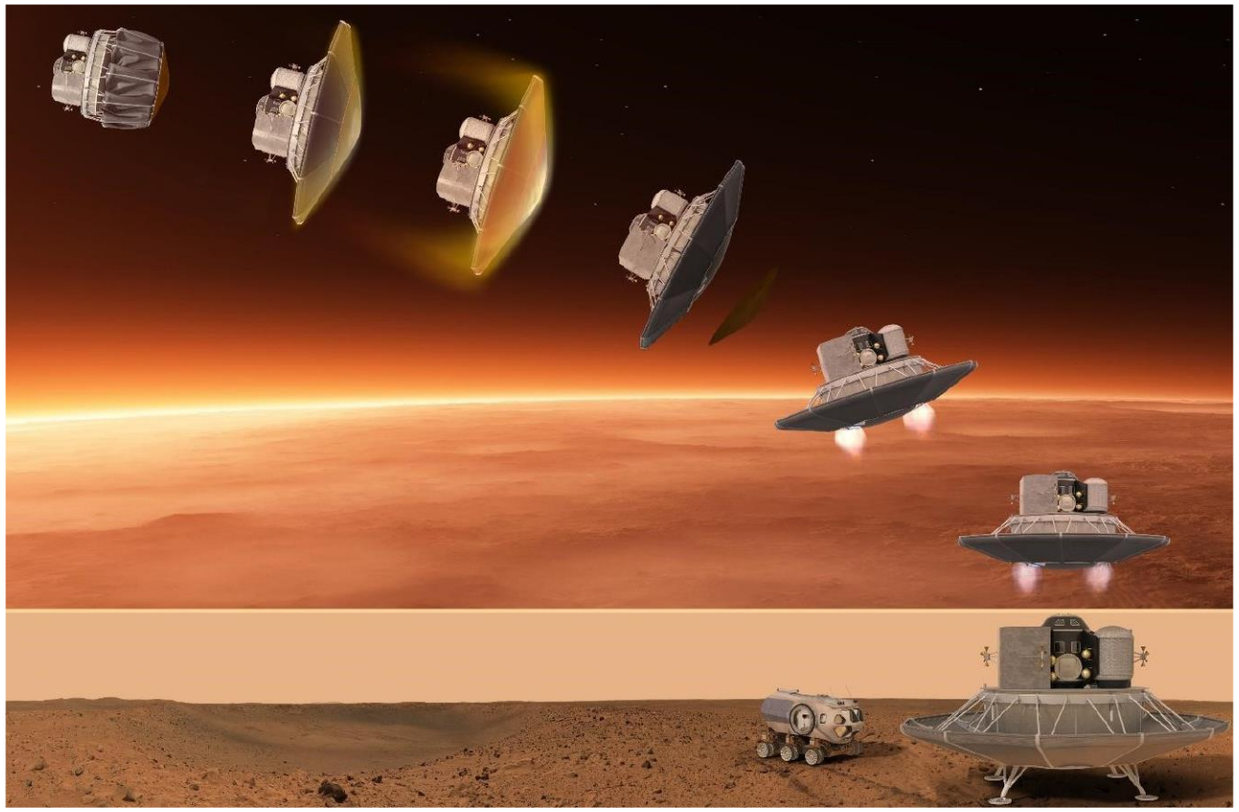


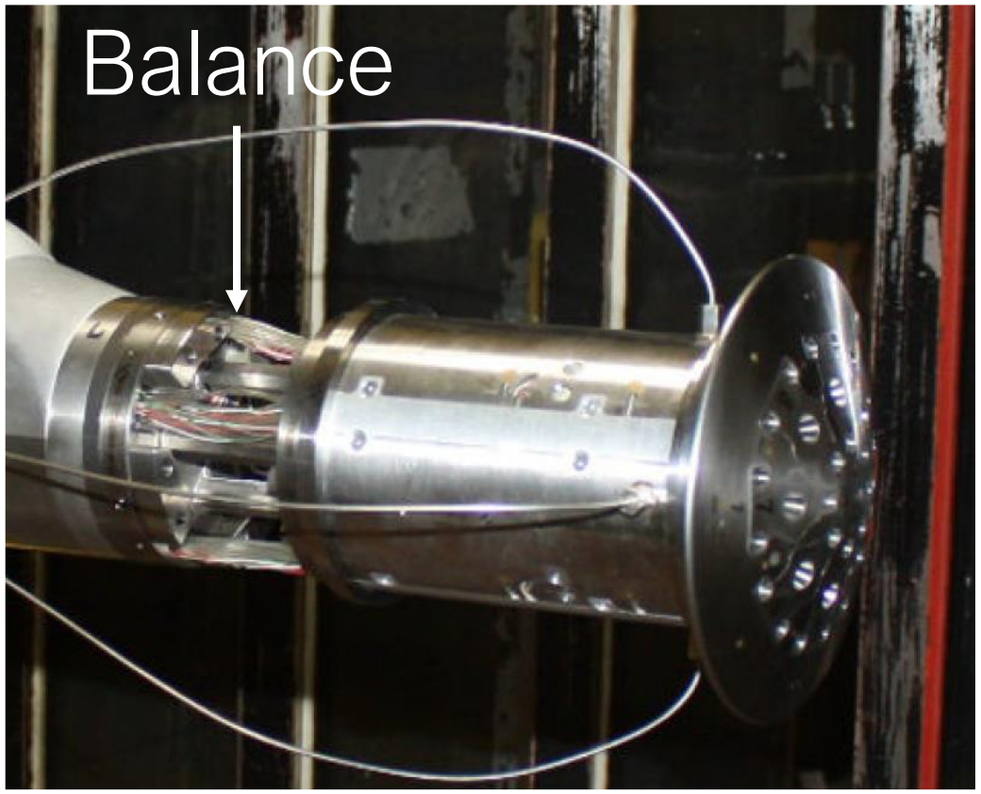
Photo of five-component semi-span balance.

- **Balance (typically 5-component) used to measure loads on a partial span of a wind tunnel model.**

Flow-Through Balances



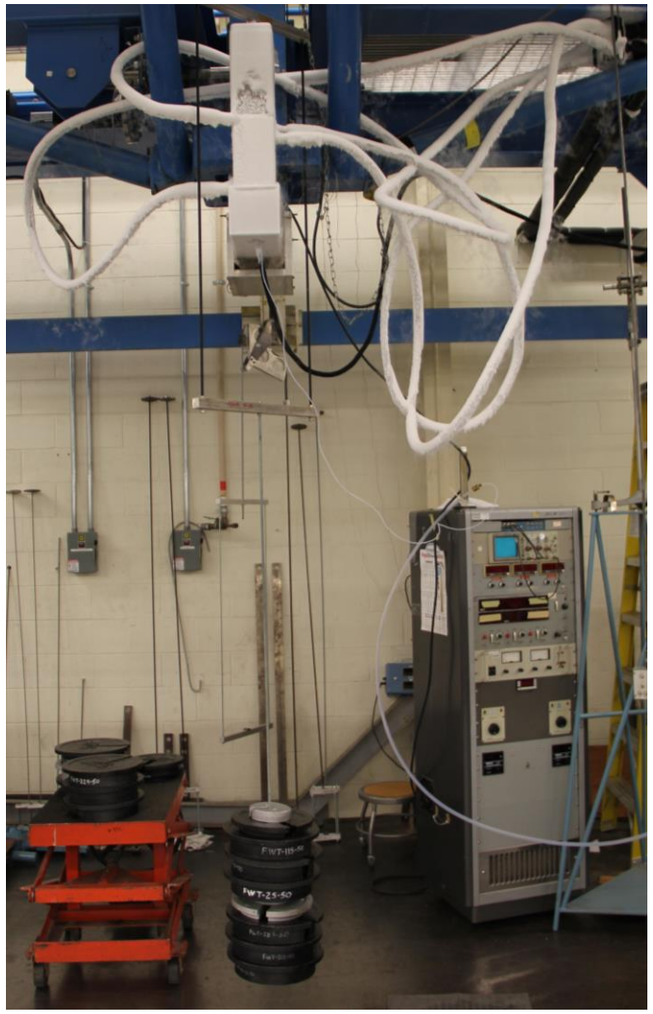
Depiction of entry vehicle using retropropulsion.



Wind tunnel test to characterize retropropulsion forces.

- **Mostly used for entry vehicles.**
- **Requires calibration with applied pressure.**
- **Gas flow effects must be considered.**

Wind Tunnel Thermal Environments



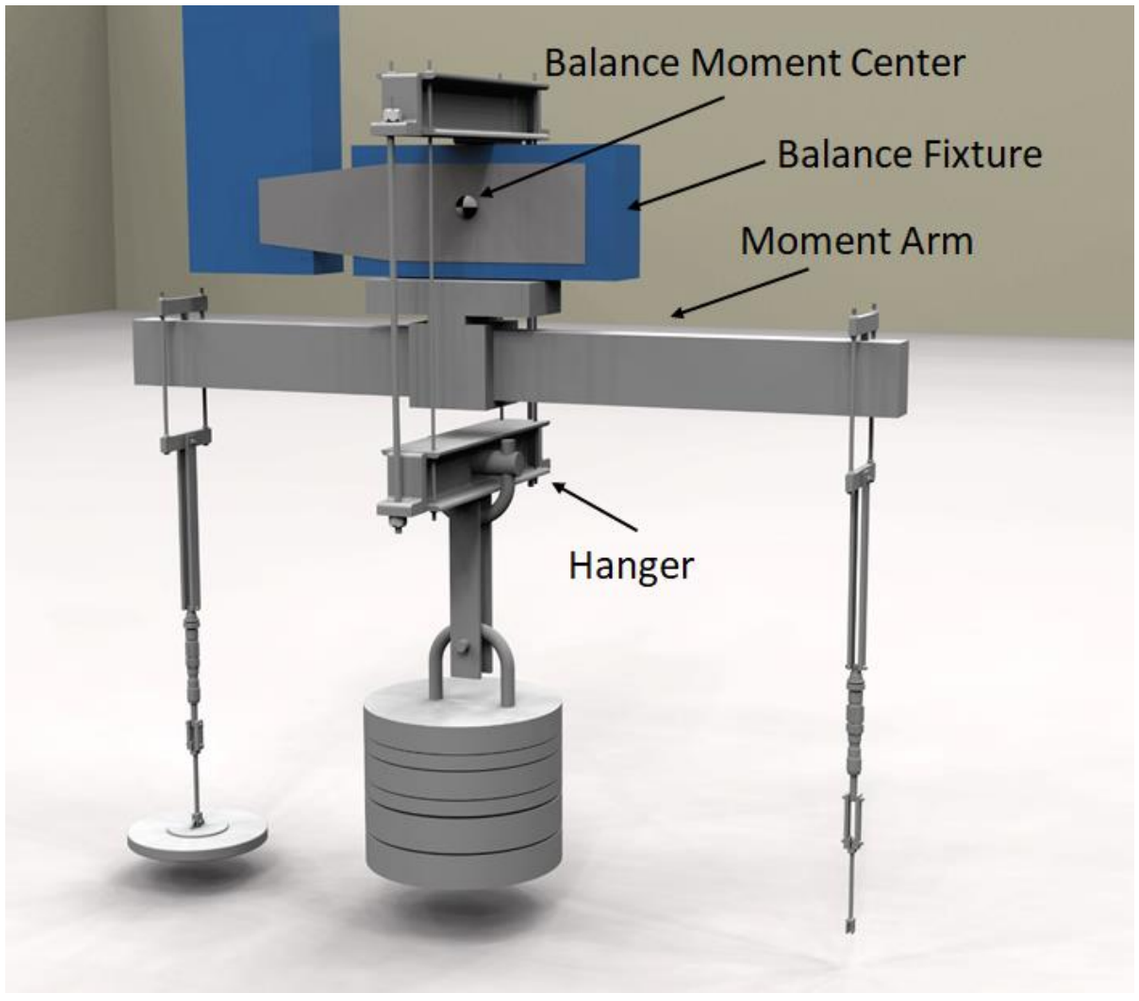
Cryogenic calibration of balance.

Balance with cooling shield installed.

- **Cryogenic and elevated temperature calibration to account for temperature effects.**
- **Balance cooling shields to minimize aero-heating effects.**

Balance Calibration – Long Arm [2] – Multivector

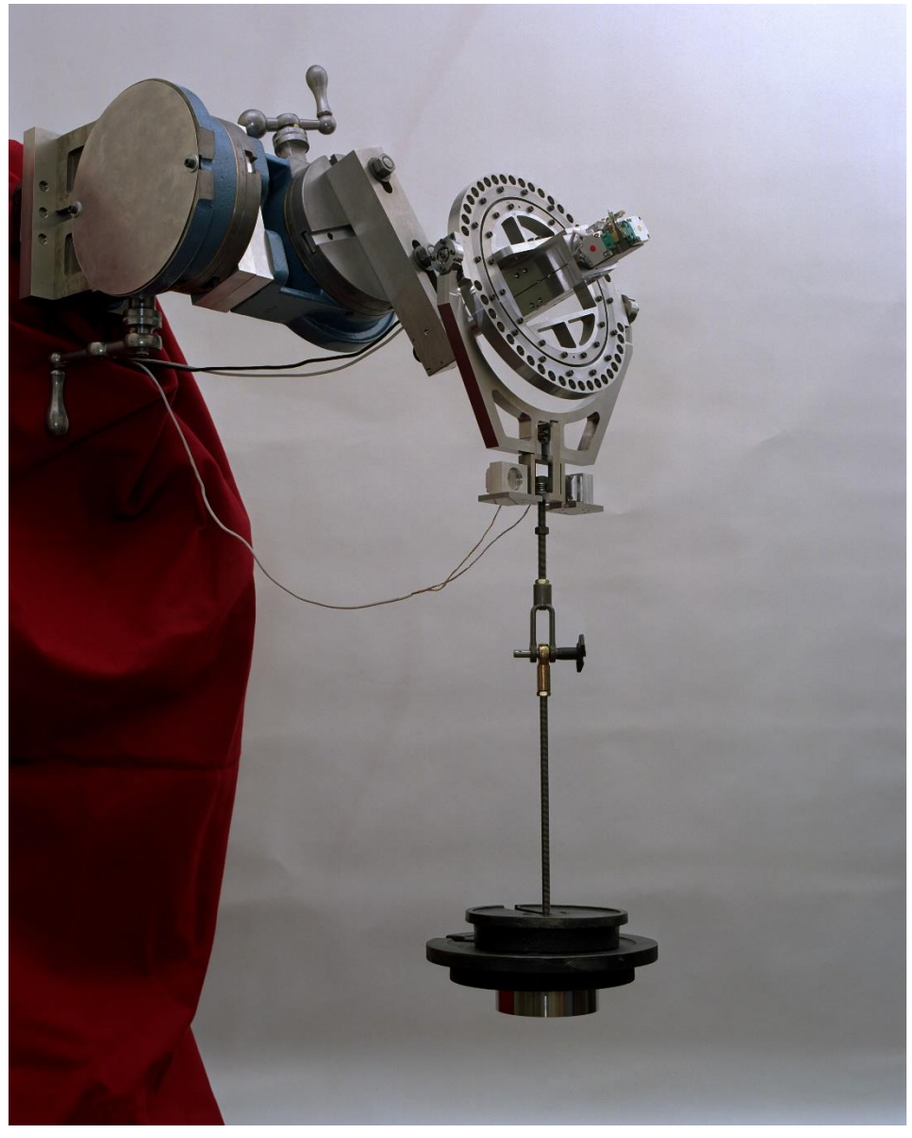
- **Dead weight calibration with releveling for each applied load.**
- **Cable loads achieve vectors perpendicular to gravity.**
- **1 & 2 component loads applied to estimate coefficients of 2nd order model.**
- **3 & 4 component loads used for confirmation points.**



Depiction of long arm calibration.

Balance Calibration – Single Vector [3]

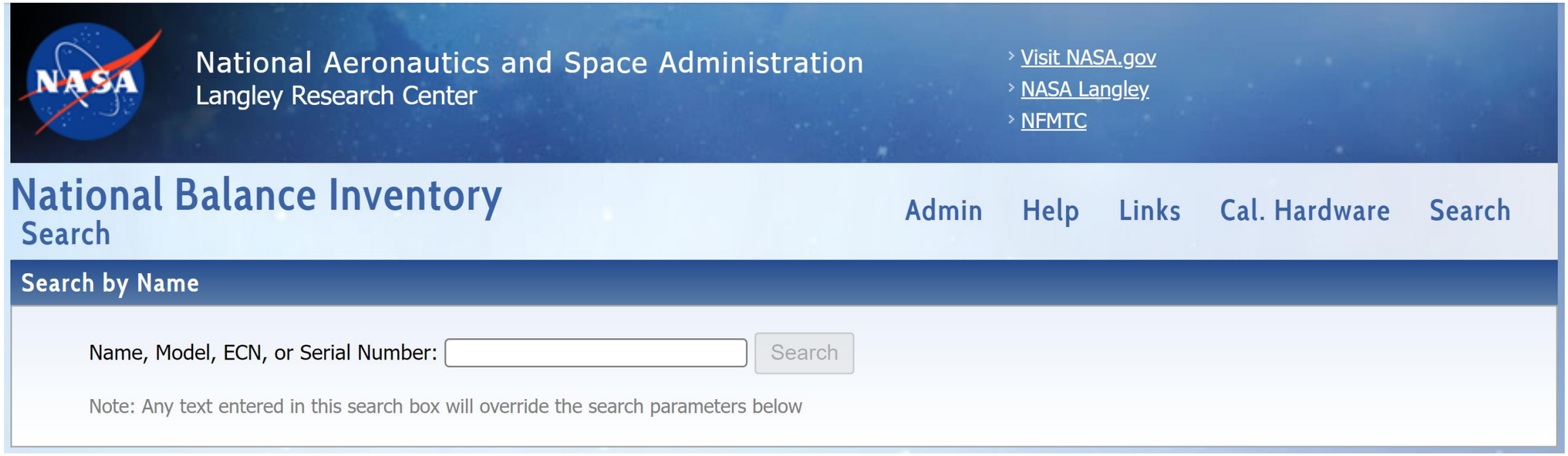
- **More efficient means of calibration leveraging six-component loadings.**
- **Balance is pitch and rolled to angles that are precisely measured.**
- **Dead weight is applied and forces are resolved based on angular position.**



Depiction of single vector calibration.

Balance Inventory and Operational Readiness

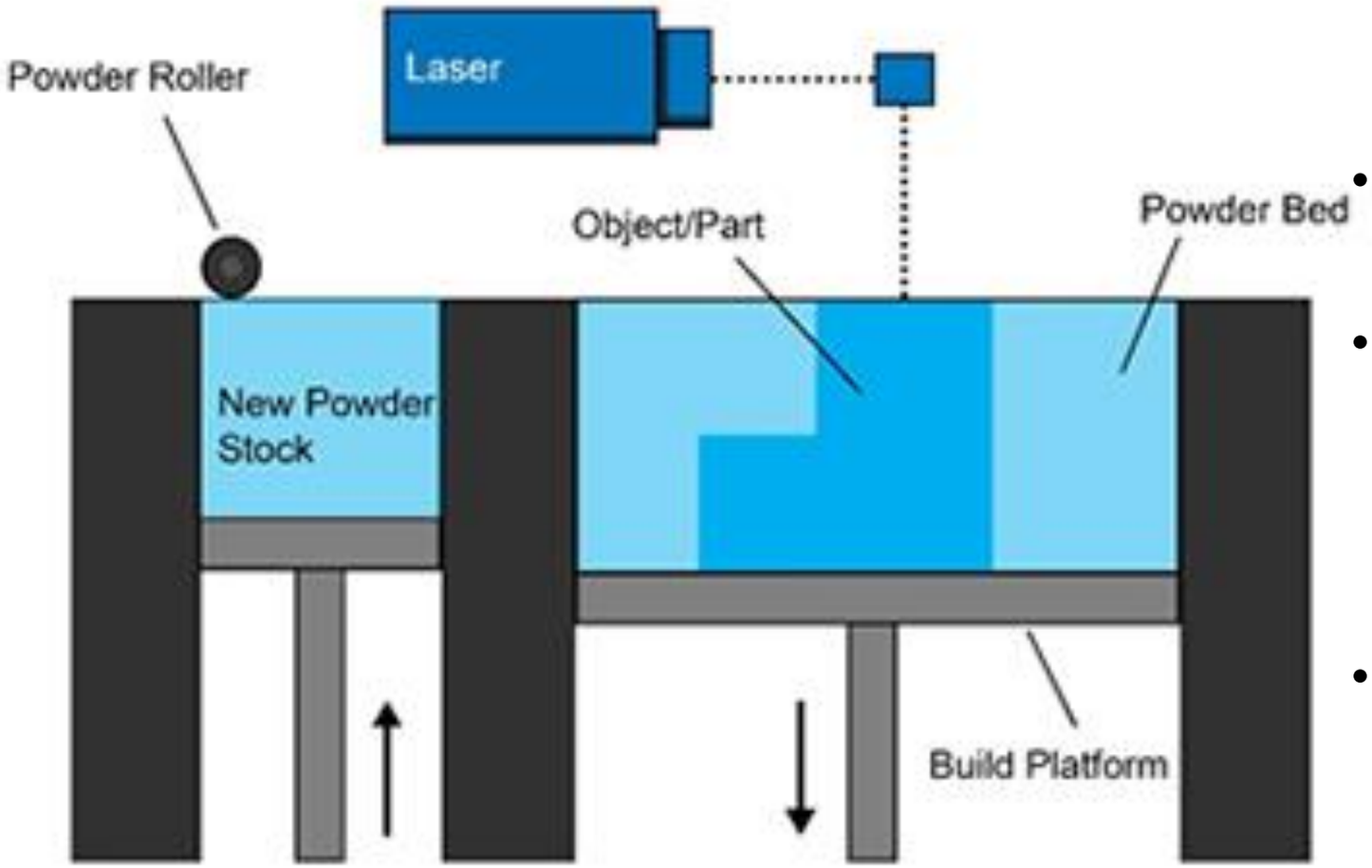
- **National Balance Inventory (NBI)**
  - https://nbi.larc.nasa.gov
  - Database of many balances within the U.S. (not just LaRC balances)
  - Salient characteristics and outline drawings available
- **Balance fabrication, strain gaging, and calibration supported by contract partners (Force Measurement Support Services contract).**



Research Areas

- **Additive manufacturing.**
- **Topology optimization.**
- **Dynamic force measurement.**

Additive Manufacturing – Powder Bed Melting



Depiction of additive laser powder bed melting system .

Source:https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion

- **Buildup of part layer by layer.**
- **Focused on laser powder bed melting because of its relative maturity.**
- **Geometric complexity of balances well suited for AM processes.**

Motivation

- **Faster manufacturing time (balances readied in 3 months additively as opposed to 12 months conventionally).**
- **Some cost reduction – more expected as process matures.**
- **Enabling new designs.**

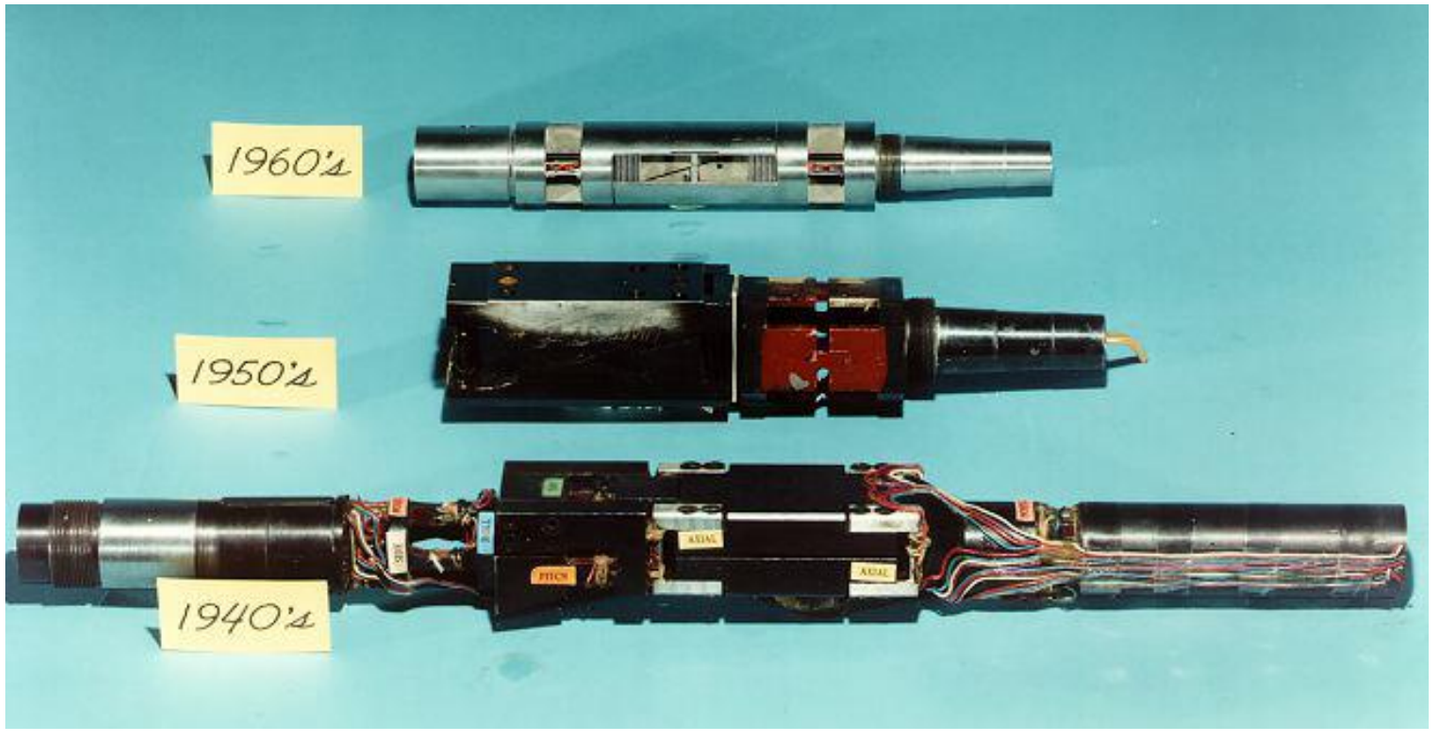
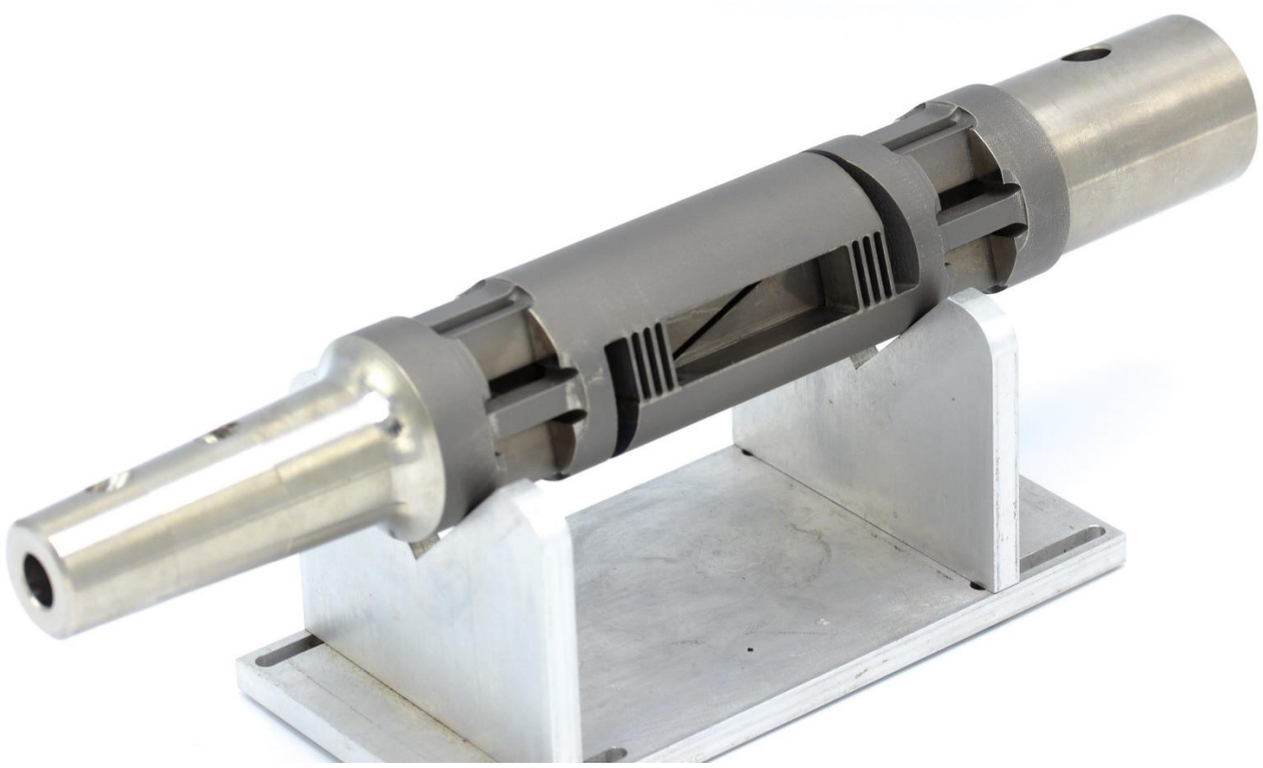


Photo of balance design evolving with manufacturing advances.

AM Balances for Operational Use



Additively manufactured wind tunnel balance.

- **Balances manufactured from both 17-4 and Ti-6Al-4V powders.**
- **In both cases, AM balances perform comparably to conventionally manufactures balances [4,5].**
- **Established qualification framework for structural parts in LaRC's wind tunnel facilities. First AM balance planned for use.**

Topology Optimization (with UMBC)

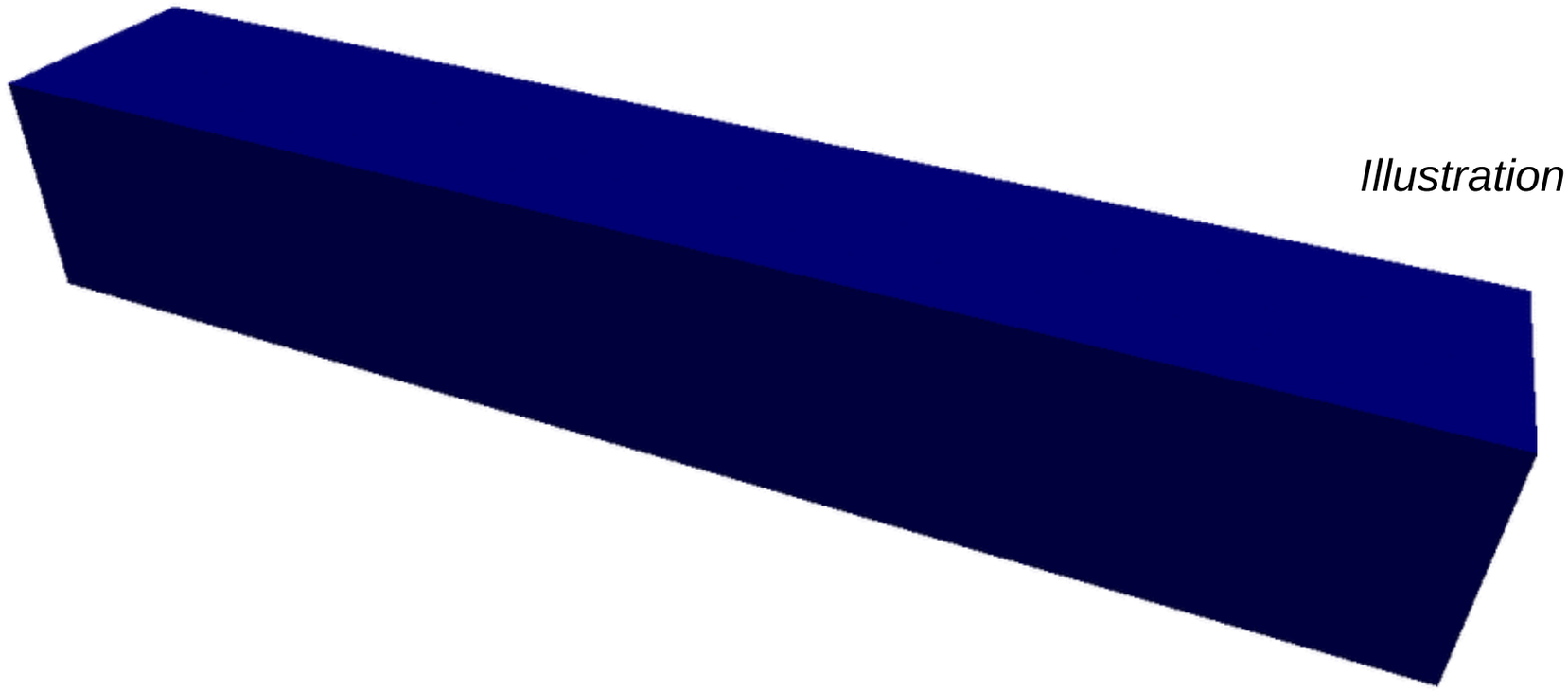
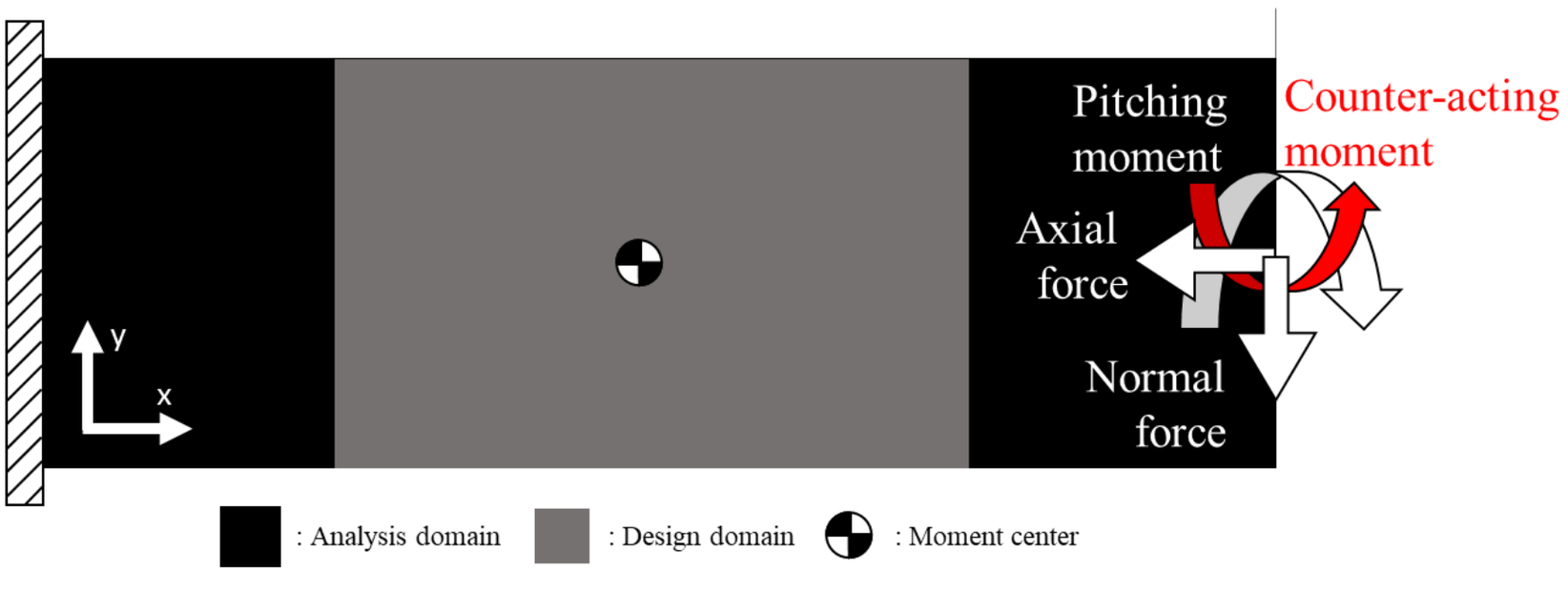


Illustration of a topology optimization solution.

- **Determines optimal material distribution for a given set of boundary conditions, constraints, and optimization criteria.**
- **Finite-element based optimization method.**
- **What's new? Applying it to transducer design.**

Problem Formulation

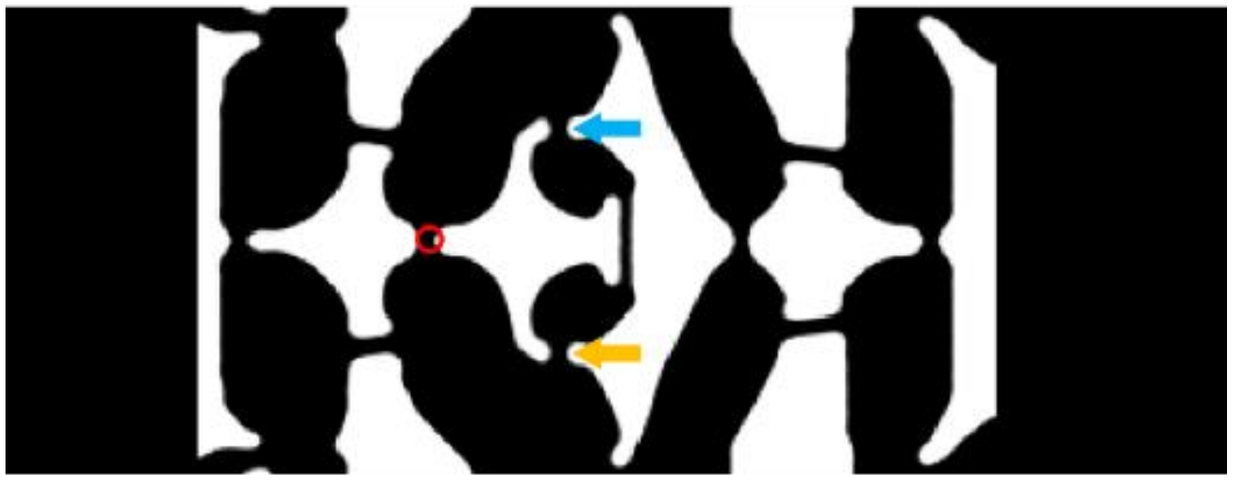


Component	Load
Normal (lb)	1000
Axial (lb)	75
Pitch (in-lb)	2500

Boundary conditions for topology optimization of wind tunnel balance axial section.

- **Chose to optimize a wind tunnel balance axial section subject to in-plane normal and pitch loads (2-D).**
- **Includes targets for AF bridge output with AF, NF, and PM applied and limits on the allowable maximum von Mises stress.**
- **Note that boundary conditions, geometry, material, etc. could all be adjusted to accommodate different problem formulations.**

Optimization Result and Post Processing

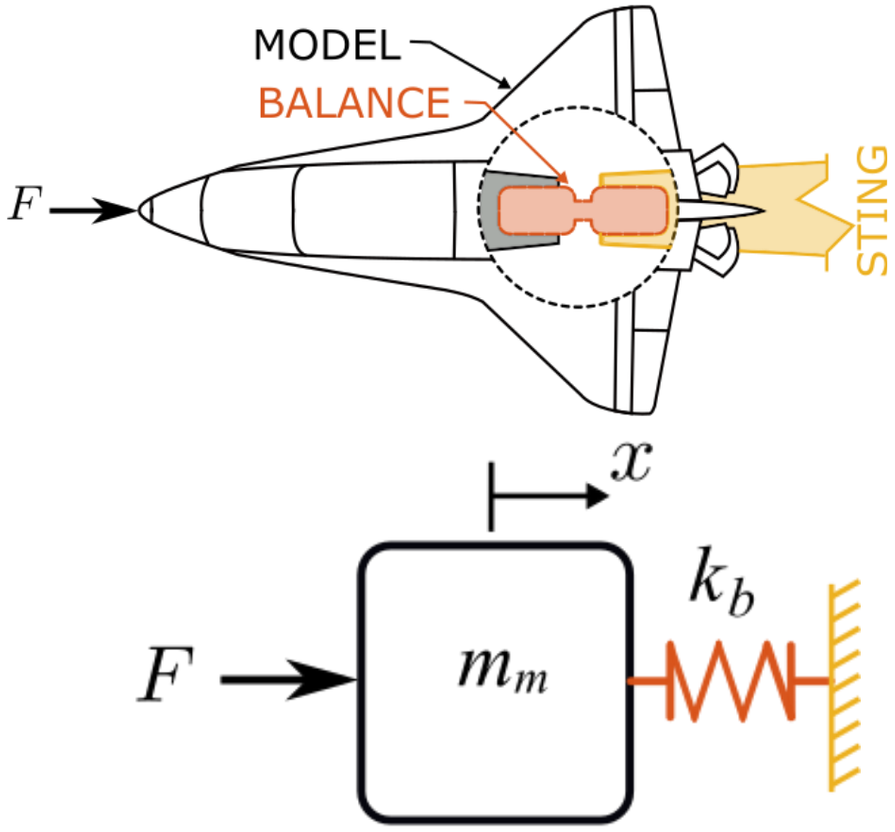


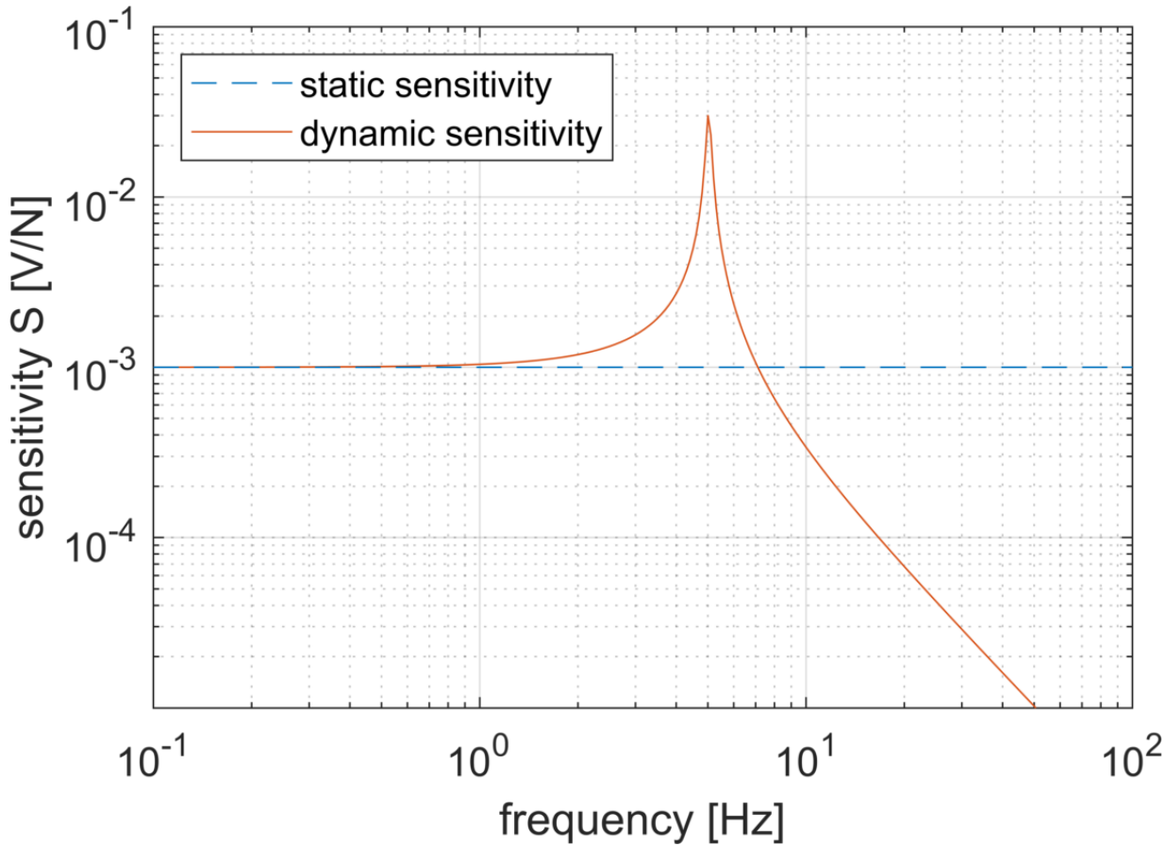
Applied Load	Axial Gage Strain (μm/m)				Axial Bridge Strain (μm/m)
	1	2	3	4	
Axial	399	-369	399	-369	384
Normal	-460	474	459	-474	0
Pitching	-267	278	267	-278	0

(left) Topology optimization solution (right) Axial force gage and bridge outputs for the design.

- **Post-processing (tweaking) of the topology optimization solution is performed in more traditional finite-element packages.**
- **Solutions assume use of a Wheatstone bridge (beams in bending).**
- **Produces novel transducer designs satisfying design constraints [6,7].**

Dynamic Force Measurement (with NIST and PSU)





(left) Reduced order model of a wind tunnel force measurement system with the model and sting represented as rigid masses (right) Representation of measurement system as a 1-DOF spring damper.

- **Force transducers typically calibrated statically but may experience and be expected to measure time varying forces.**
- **At what frequency is the static calibration no longer sufficient from a measurement uncertainty standpoint?**

Dynamic Force Measurement

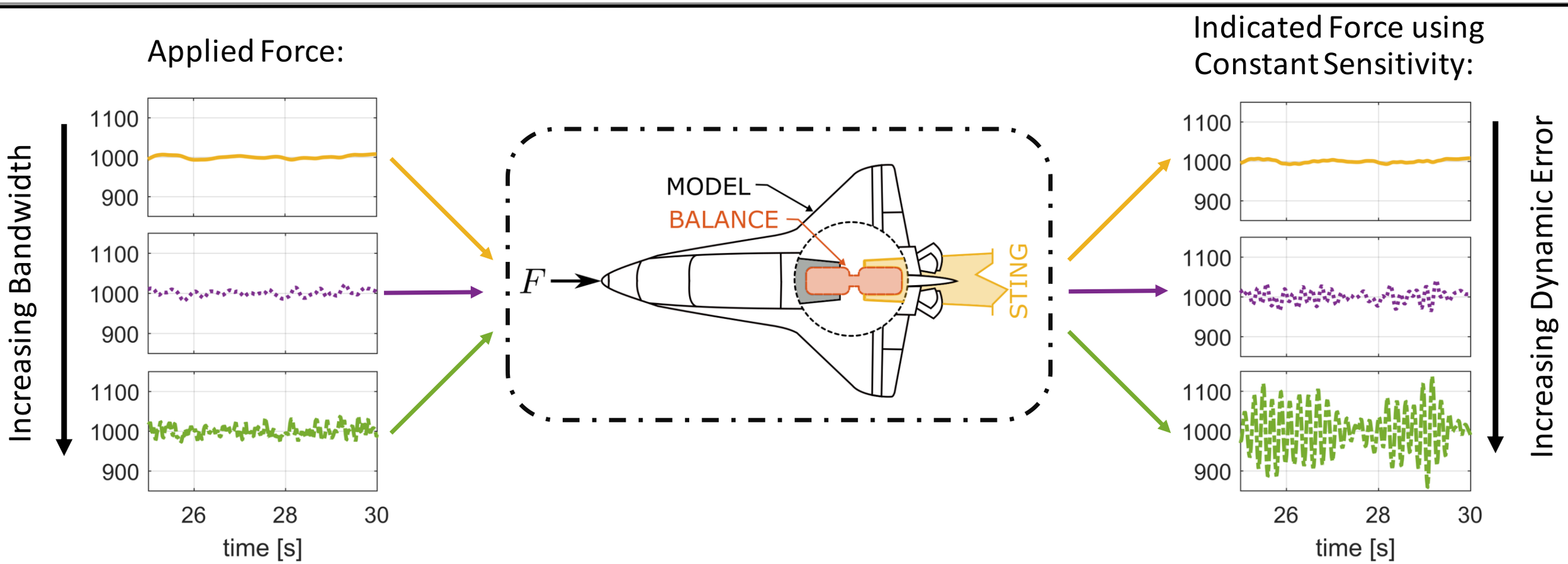


Illustration of how the applied force may differ from the measured force due to system dynamics.

- **Example of effect of applied force bandwidth on dynamic error.**
- **Currently investing in the development of acceleration compensation techniques to expand the measurement bandwidth.**
- **Note that with appropriate averaging static force is unchanged.**

Summary

- **Our group maintains the expertise to design six-component balances and methodologies to calibrate and evaluate them.**
- **Through our contract partners we maintain the capability to manufacture, strain gage, and calibrate six-component balances.**
- **Additive manufacturing of balances is transitioning to an operational capability.**
- **Topology optimization used to produce novel transducer designs.**
- **Dynamic sensitivity ≠ static sensitivity.**
- **Look forward to discussing collaborative opportunities.**

References

1. **DE Burns, PA Parker, BD Phillips, TL Webb, and D Landman (editors). *Wind tunnel balance design: A NASA Langley Perspective.* Technical Report TM-2020-220570, NASA/TM, 2020.**

2. **AJ Ferris. *Strain Gauge Balance Calibration and Data Reduction at NASA Langley Research Center*. First International Symposium on Strain Gauge Balances, NASA / CP-1999-209101 / PT2, 1999, pp. 565–572.**

3. **PA Parker, M Morton, N Draper and W Line. "A single-vector force calibration method featuring the modern design of experiments," AIAA 2001-170. 39th Aerospace Sciences Meeting and Exhibit. January 2001.**

4. **DE Burns and PA Parker. *Additively Manufactured Wind-Tunnel Balance.* Journal of Aircraft 2020 57:5, 958-963.**

5. **DE Burns and PA Parker. *Titanium Wind Tunnel Balance Leveraging Additive Manufacturing*. Journal of Aircraft 2024 61:2, 606-610.**

6. **MK Sung, S Lee, & DE Burns. *Robust topology optimization of a flexural structure considering multi-stress performance for force sensing and structural safety*. Struct Multidisc Optim 65, 6 (2022).**

7. **MK Sung, S Lee, DE Burns, & JT Persia. *Selective Amplification and Suppression of Strain in a Multi-Axis Force Sensor Using Topology Optimization*. Proceedings of the ASME 2023 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. August 20–23, 2023.**