Practical Considerations of Multicomponent Force Measurements for Space Applications – Part 1

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Agenda

Part 1: Background (today)

- Application Introduction – Multicomponent force Measurement
- Piezoelectric Principles of Operations
- Measuring Chains
- Force Measurement Considerations
- Summary/ Conclusions
- Q&A

Part 2: Applications (October 15th 2020)

- Test Environment Considerations (Noise, Vacuum…)
- Micro-vibration/ Exported Force and Torque (EFT)
- Force Limited Vibration
- Propulsion Testing
- Summary/ Conclusions
- Q&A

Micro-vibration Applications

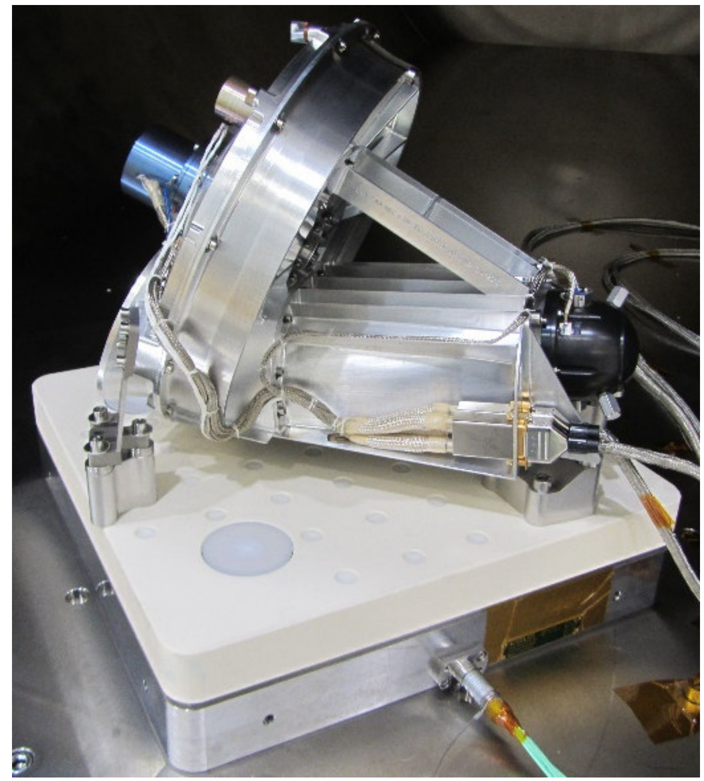
Typical Mechanism Exported Force and Torque Testing

- Vibratory and/or transient events (e.g. Release Mechanisms, Optical Shutters, etc). Goal: characterize exported disturbances

- Mechanism Testing/Exported Force and Torque
  - Cryocooler & EO/IR Imaging
  - Positioners/ Antennas
  - Reaction Wheels/ Attitude Control
  - Control Moment Gyro/Attitude Control
  - Momentum Wheel Systems/Attitude Control
  - Latches/ Clamps/ Reaction force/ moments Docking
  - Actuators/ Motors/ Robotics
  - Booms/ Deployable structures/ Erectable structures
  - Dampers/ Brakes
  - Deployment devices/ Hinges/ Linkages
  - Drives/ Gearing/ Speed Reducers
  - Gimbals/ Pointing/ Servomechanisms

  …and many more

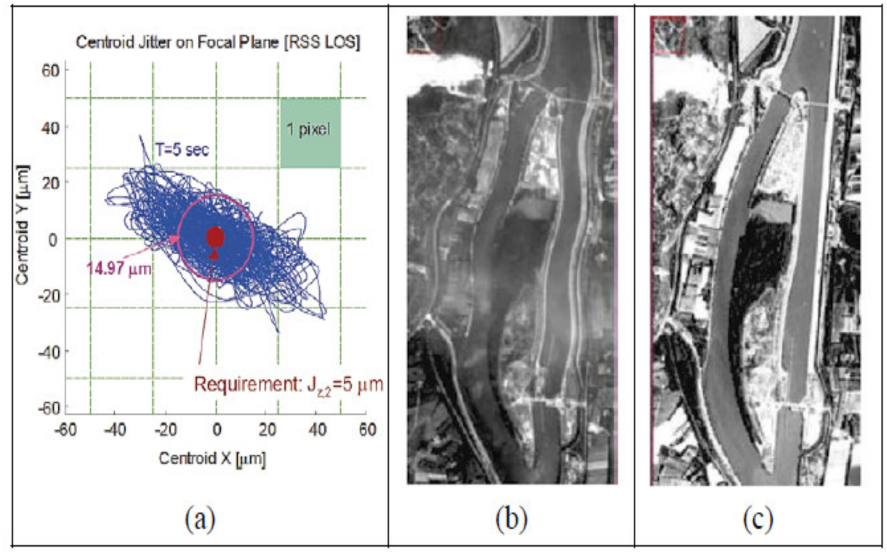
Example: Reaction Wheel
Mounted on Force Dynamometer
Fx,Fy,Fz, Mx,My,Mz



Disturbance Induced by a Reaction Wheel Can affect the Mission

Micro-vibration Disturbances

- Reaction Wheels correct for Attitude position without using Fuel
- Dynamic forces induced by Attitude Determination and Control System (ADCS) generates micro-vibration which affects the satellite pointing.
- Characterization of ADCS and related components is required to manage disturbance sources.
- Micro-vibration usually causes problems for optical imaging systems onboard Earth Observation satellites. The major effect of micro-vibration is the excitation of the support structures for the optical elements during imaging operations **which can result in severe degradation of image quality** by smearing and distortion.



Satellite Pointing (blue line), which is worse than requirement (red dot), resulting in image distortion (b); image without distortion (c)

Exported Force and Torque (EFT) Testing

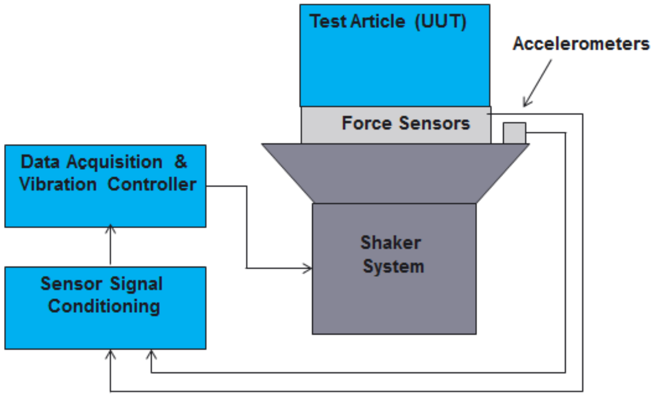
- Mount the Mechanism on Fixture/ Dynamometer.
- Characterizing mechanism disturbances influences the design, compensation, balancing and/or isolation/ damping methods to reduce the effects on the satellite mission.

Force Limited Vibration

Ref: NASA-HDBK-7004C, Force Limited Vibration Testing

- Traditional vibration testing controls the input acceleration to the frequency envelope of the flight data. Limiting the test acceleration responses to those predicted for flight is highly dependent on analysis & usually requires limiting the acceleration responses at many locations - large test items. Could result in over-testing, destruction, overdesign and/or cost/schedule impact if the UUT is broken.

- Alternately, limiting the input force at the fixed base resonances of the UUT is less dependent on analytical models and provides automatic notching w/o over-testing. Force limiting automatically notches the acceleration at a test item's resonances, by measuring and limiting the reaction force between the test item and the shaker table.



- Force Limiting replicates the test article resonant response for the actual flight mounting condition. Flight equipment is typically mounted on a relatively lightweight structure, which has a mechanical impedance comparable to that of the mounted equipment (Shakers have near infinite mechanical Impedance).

- Real time "Extremal Control" - controls UUT vibration based on the maximum of several inputs (e.g. F, A)
  - At frequencies other than the test item resonances, the acceleration test specification usually controls the test level. However, at the test item resonances, the base reaction force increases where the force control specification limits the input force.
  - Force Control Limits – are based on legacy flight data, analysis and added safety margins.

Propulsion Systems – Examples

Space launch propulsion, or in-space propulsion applications

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Designers generally discuss spacecraft performance in amount of change in momentum per unit of propellant consumed also called specific impulse. The higher the specific impulse, the better the efficiency.

- Chemical rockets have a lower specific impulse (~300s) but high thrust.
- Ion propulsion engines have higher specific impulse (~3000s) and low thrust.

Chemical Propulsion: Systems that operate through chemical reactions that heat and expand a propellant (or use a fluid dynamic expansion as in a cold gas) to provide thrust.

- Earth Storable (Hydrazine, Green Propellants, ADN, HAN, …)
- Cryogenic - Liquified Gases at Low Temp (LOX, Methane, Liquid Hydrogen (LH), …)
- Solids (premixed oxidizers and Fuels)
- Hybrids (solid fuels and liquid oxidizer)
- Gels
- Cold Gas (Store inert gases to increase thrust)
- Warm Gas (Heated Gas to create thrust of increase pressure)

Electric Space Propulsion: Converts electric energy to interact with and accelerate a reaction mass to generate thrust.

- Electrostatic – uses electrostatic fields to ionize and accelerate a propellant (e.g. Ion engines, Hall thrusters, Electrospray propulsion)
- Electromagnetic – propulsion which interacts with a reaction mass using electromagnetic fields (e.g. Pulsed inductive thruster, Magnetoplasmadynamic (MPD) thruster, Electrodynamic launch, e.g. double-sided linear induction motor (DSLIM)….)
- Electrothermal – Propulsion heats propellant prior to expansion through a nozzle (e.g. Resistojets, Arcjets….)

Example Dynamometer Based Propulsion Testing

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- Characterization of thrust as a function of propellant mixture, chamber, nozzle
- Ignition needs to be fast as possible to achieve operation without consuming excess fuel. Shut should be quick to burn residual propellants
- During Operation thrust fluctuations could indicate operational issues
- Thrust Misalignment also a consideration in some cases

- Application Considerations
  - Dynamometer Footprint, Dyno Load handling and Frequency Response
  - Multi-component (Fx, Fy, Fz, Mx, My, Mz)
  - Vacuum Operation
  - Noise/ Resolution
  - Rangeability
  - Calibration and Partial Ranges
  - Thermal Isolation

Dynamometer using 4 pcs. Triaxial Load Cell to resolve 6-components Fx, Fy, Fz, Mx, My, Mz

Components of a Measuring Chain

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Measuring Chain

Sensor

- Converting a physical measurand to electrical signal

Cable

- Transmitting the electrical signal from the place of measurement to the place of processing

Signal Conditioning

- Manipulating the analog signal to meet the requirements of the next processing stage

Data Acquisition

- Analog-to-digital conversion
- Storage of the digital signal

Visualization & Analysis

- Displaying the values in different ways for analysis of the measurements

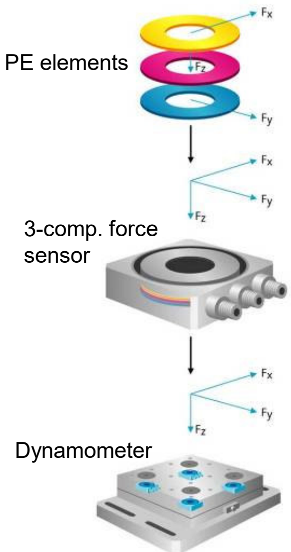
Sensors with integrated Electronics

Integrated Signal Conditioning + Data Acquisition

Piezoelectric Instrumentation

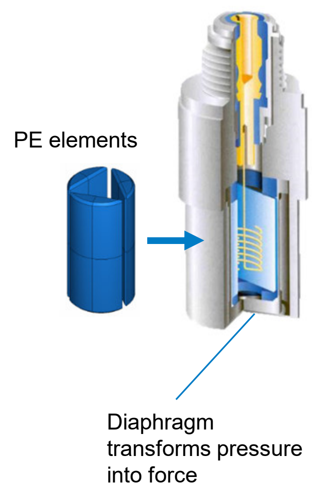
Measurands

Force



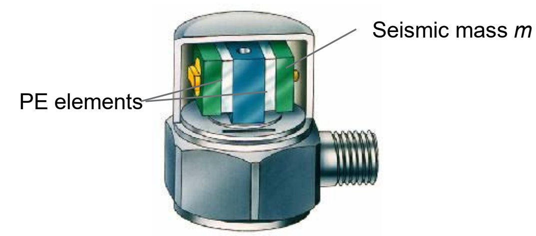
- Force produces a proportional charge

Pressure



- Charge produced by a force is proportional to pressure
- $p = \frac{F}{A}$

Acceleration



- Charge produced by a force is proportional to acceleration
- Newton's 2nd law:

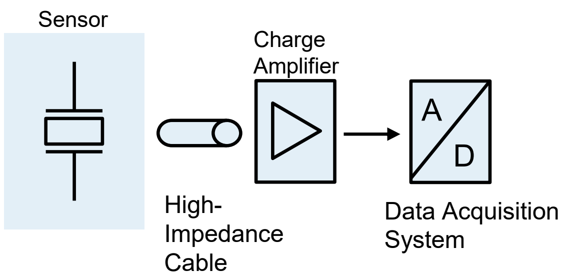
$$F = m \cdot a$$

PE and IEPE Sensor

Piezoelectric Sensor Principles

PE (pC/mu)

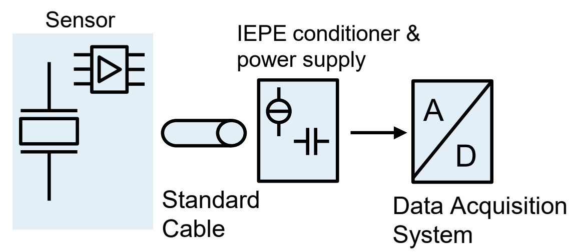
(<u>P</u>iezo<u>E</u>lectric)



- Sensor does not contain electronics
- High impedance cable required
- Very wide temperature range
- Externally rangeable with charge amplifier
- Huge measuring range
- Quasi-static (long TC) as well as highly dynamic measurements possible
- Reset/Measure Tares the measurement to remove static loads from the dynamic range

IEPE (mV/mu)

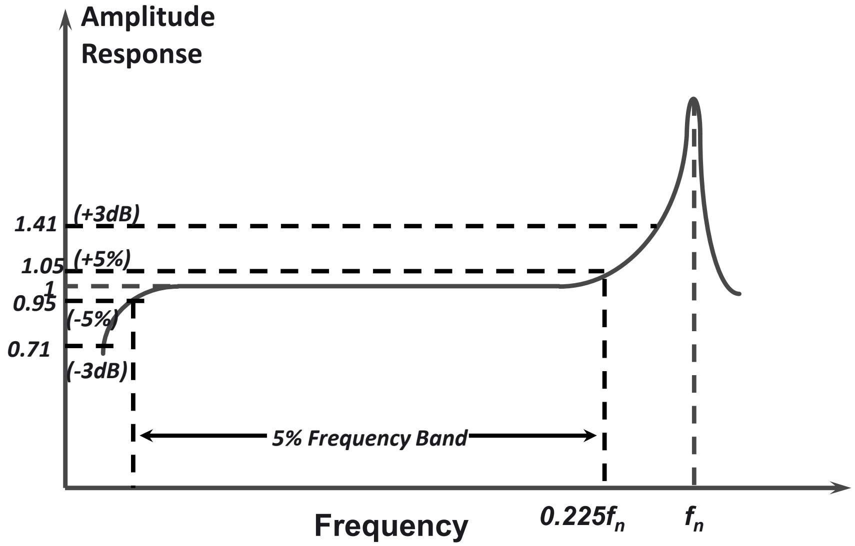
(<u>I</u>ntegrated <u>E</u>lectronics <u>P</u>iezo<u>E</u>lectric)



- Sensor contains internal charge to voltage converter – Powered by IEPE Constant current supply
- Standard cable for sensor connection
- Many DAQ systems offer an integrated IEPE power supply required for operation
- Integrated TEDS inside sensor possible
- Only dynamic measurements possible
- Measuring range is fixed
- Temperature range limited with internal sensor integrated electronics
- Not Resettable

PE and IEPE Sensor

Frequency Response



- Most piezoelectric sensors follow the upper frequency rule
  - $f_{+5\%} = f_n/5$;
  - $f_{+10\%} = f_n/3$;
  - $f_{+3dB} = f_{+41\%} = f_n/2$
- Exciting sensor resonances can occur in measurements – Ranging the measuring chain maintains output in the linear region of operation (No Saturation) and the resonances signals can be filtered

High Frequency Relationship

$$\frac{a_o}{a_b} \cong \frac{1}{\sqrt{\left[1-\left(\frac{f}{f_n}\right)^2\right]^2 + \left(\frac{1}{Q^2}\right)\left(\frac{f}{f_n}\right)^2}}$$

f_n = *undamped natural (resonant) frequency (Hz)*

f = *frequency at any given point of the curve (Hz)*

a_o = *output acceleration*

a_b = *mounting base of reference acceleration* $\left(\frac{f}{fn} = 1\right)$

Q = *factor of amplitude increase at resonance*

Low frequency Relationship

$$\frac{V_o}{V_{in}} = \frac{2\pi f(\tau)}{\sqrt{1+[2\pi f(\tau)]^2}}$$

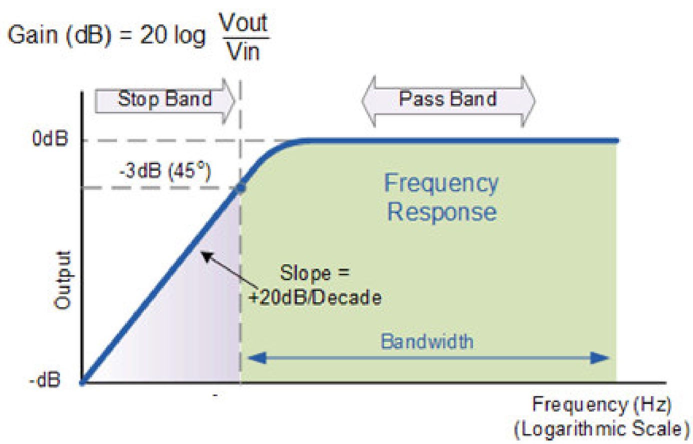
$$\text{phase lead (deg)} = \text{arc tan}\ \frac{1}{2\pi f(\tau)} \cong 80\sqrt{\frac{V_{in}-V_o}{V_{in}}}$$

$$f_{-5\%} = \frac{0.5}{\tau}$$

τ = time Constant (sec)

PE Measuring

Chain Low Frequency: Example



- Single order High Pass Filter. The larger the time constant, τ, the lower the frequency (inversely related). **H(s) = τs/(τs+1)**
  - f(-5%) = 0.5/τ
  - f(-10%) = 0.328/τ
  - f(-3dB) =1/(2$\pi\tau$) = 0.16/τ
  - Long (Quasi-Static), Medium/Short Dynamic

- Lower Measuring Ranges
  - Ex. Micro-vibration and Thruster Test

- Higher Measuring Ranges-
  - Ex. Force Limited Vibration, Propulsion Test

Charge Amplifier Measuring Range	Short TC (sec)	Medium TC (sec)	Long TC (sec)
≥2pC….<217pC	0.033	3	10000
≥217pC…< 4 717pC	0.42	42	100000
≥ 4 717pC….< 102 400pC	10	1000	100000
≥102 400pC….≤ 2 200 000pC	220	22000	100000

Charge Amplifier Measuring Range	Short TC (-5%) Freq (Hz)	Med TC (-5%) Freq (Hz)	Long TC (-5%) Freq (Hz)
≥2pC….<217pC	15.1515	0.1667	~0Hz
≥217pC…< 4 717pC	1.1905	0.0119	~0Hz
≥ 4 717pC….< 102 400pC	0.0500	~0Hz	~0Hz
≥102 400pC….≤ 2 200 000pC	0.0023	~0Hz	~0Hz

Charge Amplifier Measuring Range	Short TC (-10%) Freq (Hz)	Med TC (-10%) Freq (Hz)	Long TC (-10%) Freq (Hz)
≥2pC….<217pC	9.9394	0.1093	~0Hz
≥217pC…< 4 717pC	0.7810	0.0078	~0Hz
≥ 4 717pC….< 102 400pC	0.0328	~0Hz	~0Hz
≥102 400pC….≤ 2 200 000pC	0.0015	~0Hz	~0Hz

Charge Amplifier Measuring Range	Short TC (-3dB) Freq (Hz)	Med TC (-3dB) Freq (Hz)	Long TC (-3dB) Freq (Hz)
≥2pC….<217pC	4.8485	0.0533	~0Hz
≥217pC…< 4 717pC	0.3810	0.0038	~0Hz
≥ 4 717pC….< 102 400pC	0.0160	~0Hz	~0Hz
≥102 400pC….≤ 2 200 000pC	0.0007	~0Hz	~0Hz

PE Measuring chains often permit external adjustment of TC (Long, Medium, Short) to set the low frequency of the measurement chain.

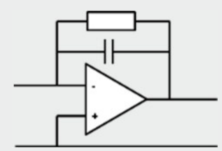
Quasi-Static and Dynamic Measurement

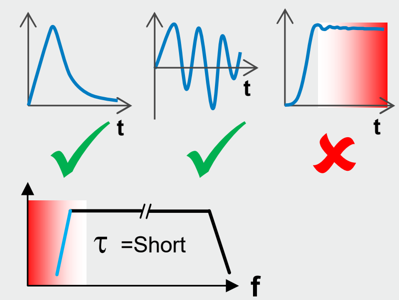
Charge Amplifier

Depending on the signal to be measured, different characteristic are required

- Fast transient (typ. <400ms) or pulsating signals (typ. >0.5Hz)
  → **<u>Dynamic</u>** <u>Charge Amplifier</u> (or measuring mode «short»)

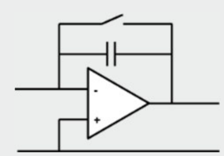
  - Integrated time constant filters DC content
  - No drift due to high-pass characteristic
  - No Reset/Measure required, continuous measurement

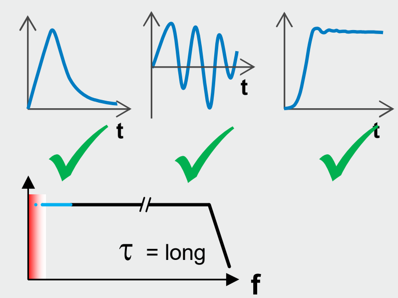




- Slow down to almost static measurements
  → **<u>Quasi-static</u>** <u>Charge Amplifier</u> (measuring mode «long»)

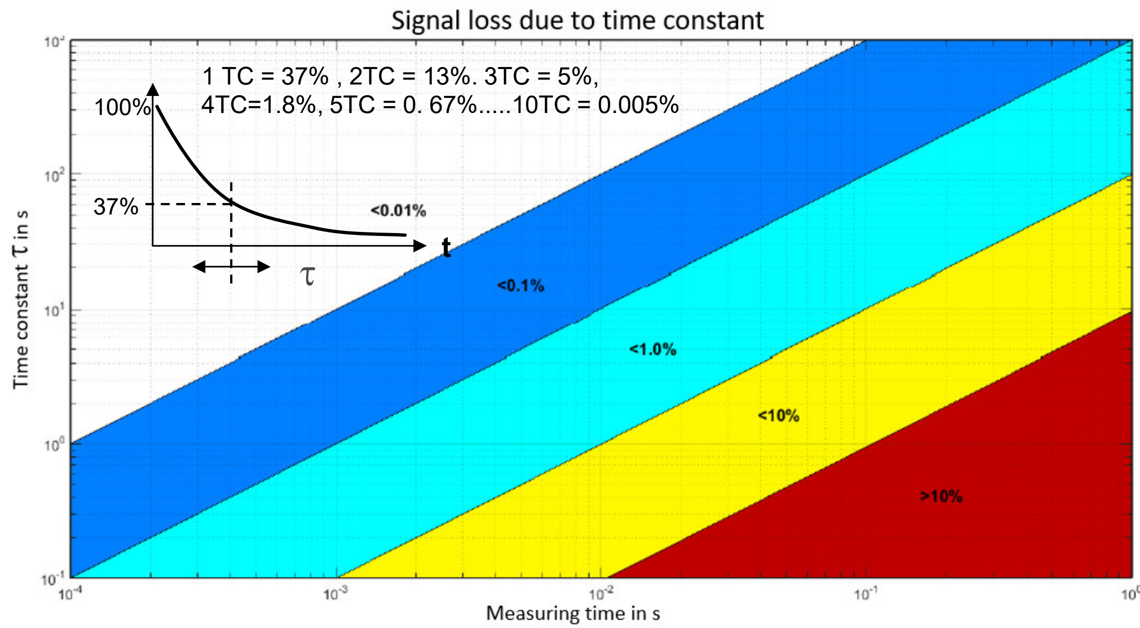
  - For low frequency and dynamic measurements
  - Reset/Measure signal required = «start measurement»
  - Long Time constant supports many signal types
    - Although Drift might become visible after a long time

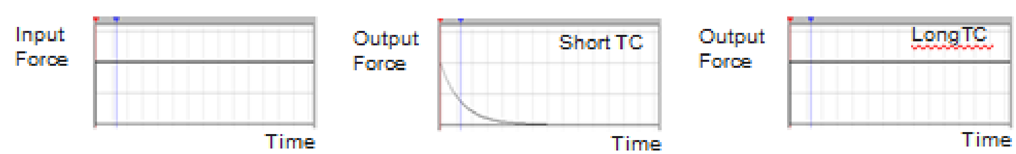




Quasi-Static Measurements

- Quasi-static Measurements are time constant limited or drift limited (0.03pC/sec)
- Transient of Short duration quasi-static events
  - General Rule: TC ≥ 100x duration
- IEPE Measuring chains have a fixed low frequency capability, dependent on the total system time constant . For Example
  - $\tau_{total} = \tau_a \tau_c / (\tau_a + \tau_c)$
  - τ_s = IEPE sensor
  - τ_c = Signal conditioner (ex. Coupler/DAQ)
- Quasi-static events examples of Drift in Quasi-static Measurement – Long Time Constant
  - Sz = 4pC/N = 17.4pC/lb @ 0.03pC/sec,
    - Drift = 0.1lbs/min = 0.5N/min
  - Sx,y = 8pC/N = 35.8pC/lb @ 0.03 pC/sec
    - Drift = 0.05lb/min = 0.25N/min
  - Higher sensitivity sensors such as PiezoStar Reduces drift by factor of 3 compared to quartz.
  - Drift Compensation may be possible
  - Low Quasi-static forces usually not used with Long TC





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Example: Multi-Channel Dual Mode Charge Amplifier

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- Analog amplifier designs typically complement higher precision force measurements such as micro-vibration, force limited vibration etc.
- Available channels: 1…8
- Quasi-static & Dynamic Charge Amplifier
  - PE Amplifier
  - Dual Mode Amplifier (Charge and IEPE)
  - Summing calculator included (Fx, Fy, Fz, Mx, My, Mz)
- Full Scale Measuring Range: 2… 2 200 000pC for ± 10V Output
  - Example 4pC/N, 2pC is 0.5N Full Scale = ±10V
- Remote Control via RS-232C or USB
- AC or DC Powered
- >200kHz Bandwidth - high Frequency of the measuring chain is limited by the Sensor not electronics
- Low Frequency Response is typically Range Dependent based on selection of short, med or long

Example of a PE Measuring Chain Rangeability

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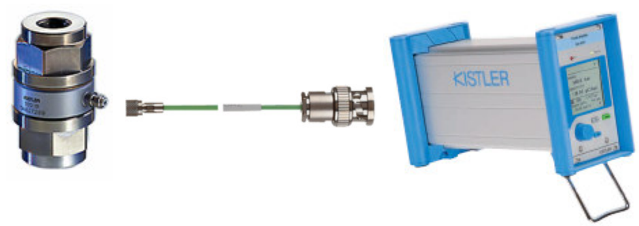
Sensor Sensitivity~4pC/N
Maximum Range~ 10000N



Use one sensor to measure several ranges with Charge Amp

Full Scale Range (FSR = 10V)	Output Scale Factor (N/V)	Broadband Noise rms	Broadband Noise rms
1 N	0.1 N/V	0.0045 Vrms	0.00045 Nrms
25 N	2.5 N/V	0.0012 Vrms	0.003 Nrms
1000 N	100 N/V	0.0006 Vrms	0.06 Nrms
10000 N	1000 N/V	0.0006 Vrms	0.6 Nrms

- Unlike Strain Gauge Measurement Systems, PE measuring chains can be Tared (by reset) --- allocate amplifier dynamic range for the dynamic measurement

Charge amp Noise scales as a function of selected Measuring Range. Once sensor can be externally ranged by Charge Amp for several measuring ranges

For the 1000N case

- If Static Mass = 101.9kg = 999N
- Reset Amplifier – TARES the 101.9Kg mass where the Amplifier output Reads Zero
- Range the amplifier for 1N Full scale for the dynamic signal portion instead results in 0.00045Nrms noise instead of 0.06Nrms noise

DAQ Basics

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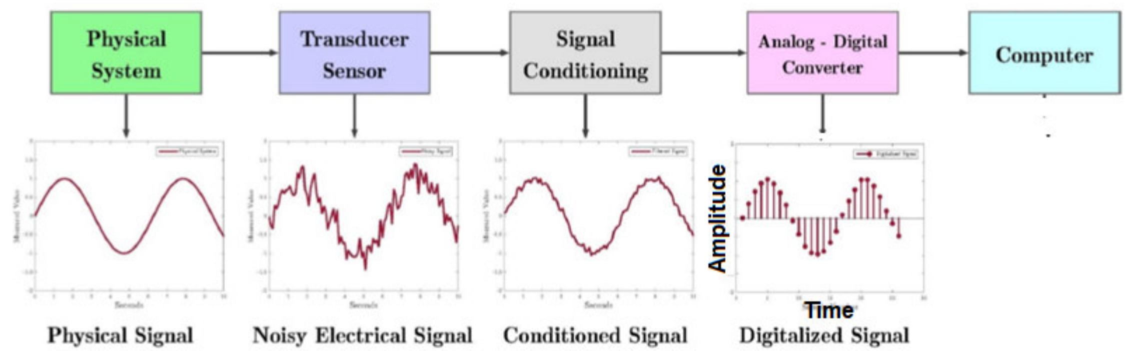
- The sample rate fs and resulting sample interval T=1/fs defines the time ADC resolution
  - Time is divided into fs sample intervals per second, at which a signal value acquired and stored
    - Example
      - fs= 100 samples per second = 100sps;
      - Sample interval = 1/100= 0.01sec

- n = # Bits of the Analog to Digital Converter (ADC)
  - The bit width is the amplitude resolution. The more Bits the better amplitude resolution
  - Signal Amplitude is divided into N possible quantization levels
  - n = # ADC Bits; N = 2^n-1 (signed) # Levels
  - Example:
    - 1N signal has a ±10V Amplitude, then 0.1N/V
    - n = 8 bits, N = 128 levels (signed)
    - Each level 0.078V or 0.0078N Resolution



Force Measurement Bandwidth and Resolution Considerations

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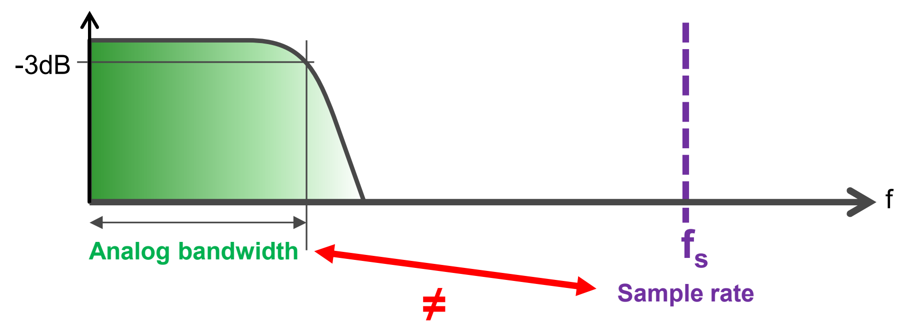
- Signal Conditioning/ Charge Amplifier Analog Bandwidth
  - High upper frequency
  - Low frequency
- Test Article
  - The physical measurement and Test Article determine the desired frequencies of interest and required resolution. For example – Cryo Cooler Harmonics – demand higher frequencies
- Force Sensors + Fixtures
  - Natural Frequency of measurement System needs to satisfy Test Article requirements and could be the limiting factor
  - Lightly Damped second order system
  - Trade off on Amplitude tolerance for wider Bandwidths 5%, 10%, 3dB
- Anti- Aliasing Filters to bandlimit Signals prior to sampling
  - Aliasing happens when sample rate is too low for the analog Bandwidth
  - High Frequencies can appear as low frequencies
  - Get Raw Data record and post process with filtering as needed.

- Analog bandwidth of a system
  → expressed in **Hz**
- Sample rate / sample frequency
  → expressed in **sps** or **s/s** or Hz

≠ Don't confuse them!



- The minimum sample rate is 2*Signal Bandwidth (e.g. Nyquist) to prevent Aliasing
  - Signal Bandwidth = 100Hz → Minimum Sample Rate = 200samples/sec
- Practically it is common to adopt atleast 10 * Signal Bandwidth or Higher relationship between analog bandwidth and sample rate.
  - Signal Bandwidth = 100Hz → For example = 1000samples/sec

LabAmp 5167A & 5165A

Scalable Signal Conditioning, Charge Amps and DAQ Solutions

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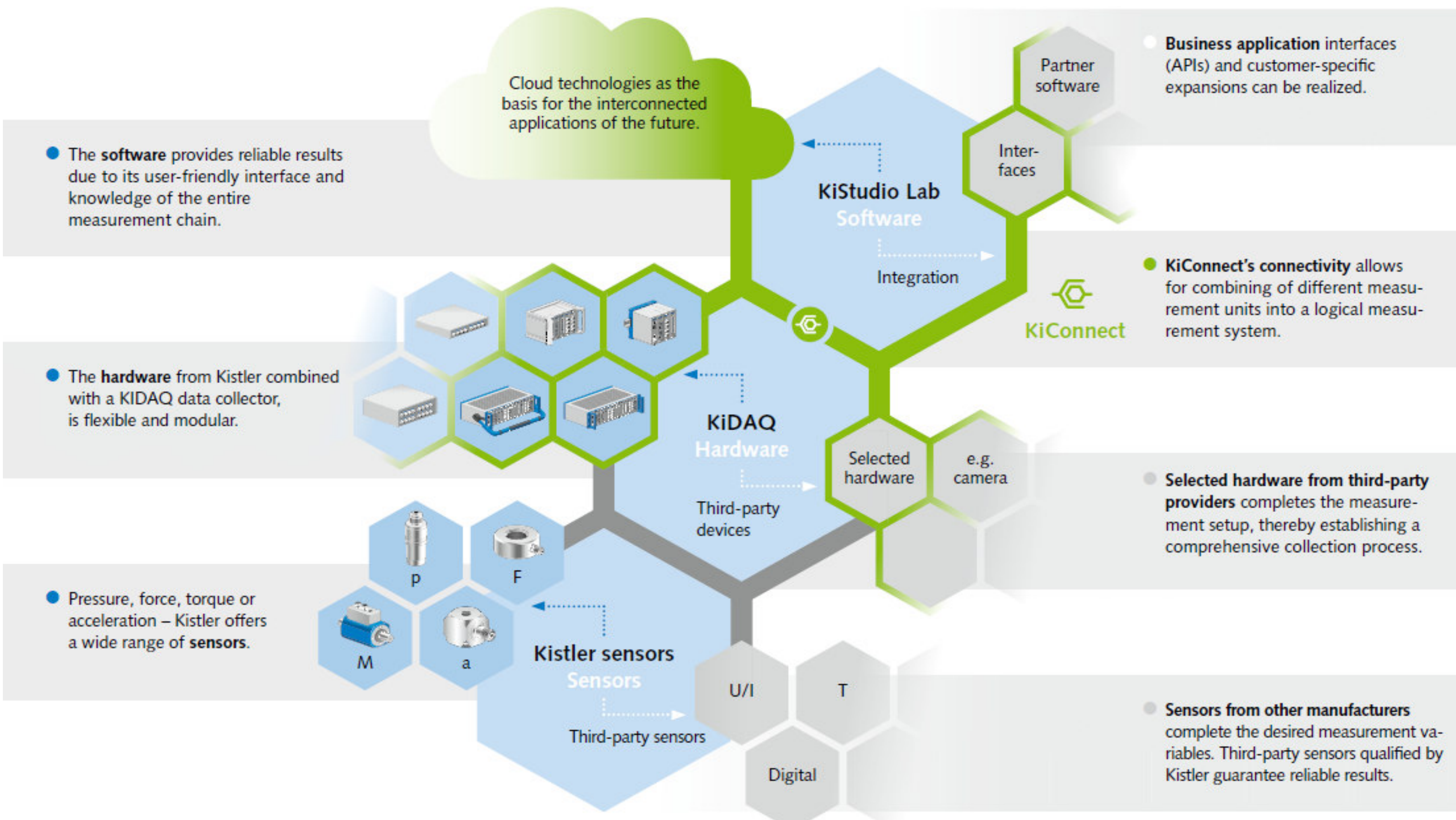
Labamp Type	Features and Benefits
5167A…. 	**Quasi-static and Dynamic Charge Amplifier** • Scalable Solution • 100Mbit Rear Panel Ethernet Interface • 4 or 8 PE Input BNC Connector. Special Version with Fischer Connector for PE Dynamometers • 4 or 8 Analog Output BNC Connectors • 24Bit resolution and Up to 100Ksps per channel • ~0Hz…45KHz Analog Bandwidth • Charge Input Ranges ± 100 pC … ± 1,000,000 pC • Digital inputs or Reset/Measure and Trigger • Low Pass, High Pass and Notch Filters • Long and Short Time Constants • IEEE 1588, PTP Synchronization • Virtual Channels
5165A… 	**Dynamic Dual Mode Charge Amplifier** • Scalable Solution • 100Mbit Rear Panel Ethernet Interface • 1 or 4 Universal Input BNC Connectors • 1 or 4 Analog Output BNC Connectors • 24Bit resolution and Up to 200Ksps per channel • 0*/ 0.1Hz…100KHz Analog Bandwidth • Charge Input Ranges ± 100pC … ± 1,000,000pC • DC Coupled Voltage Input Range: ± 1 V … ± 10 V • Low Pass, High Pass and Notch Filters • TEDS 1451.4 for IEPE Sensors • 4mA/ 10mA IEPE supply to support long cables • Optional IEEE 1588, PTP Synchronization • Optional Virtual Channels

Software Options

- Web Browser-Firmware GUI
- Demo Tool – Labview VI Example
- Multi-Device Client (MDC)
- Dynoware
- Labview Driver/VI
- Application Programming Interface (API)
- jBeam – Analysis, Visualization and Reporting Tool (Type 2897A2)

KiDAQ

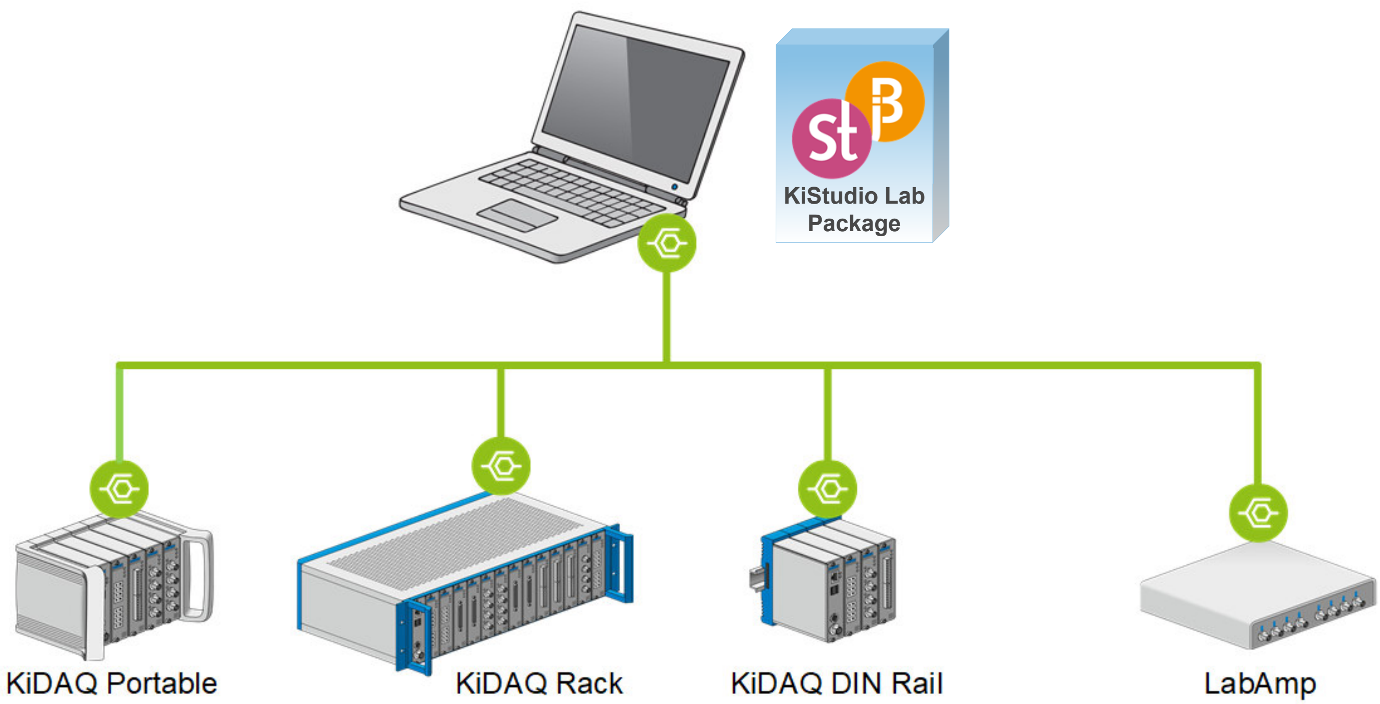
Scalable - Modular DAQ Solutions



KiDAQ

Multi-Purpose, Modular, Scalable DAQ System for over 20 Measurands

- Voltage
- Current
- Resistance
- Potentiometer
- Pt100/Pt1000 (RTD)
- Thermocouple
- Strain gauge
- Inductive bridge
- LVDT
- Piezoelectric (charge)
- IEPE (Piezotron)
- Frequency
- Pulse width
- Counter signal
- Time
- Status



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KiDAQ

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Measurement Modules

	Measurement module type	5501A	5502A	5505A	5506A	5509A	5512A	5514A	5517A	5518A	5521A	5522A	5525A	5526A	5528A	5529A	5531A[1]	5534A	5535A[1]
	Analog input channels	2	4	8	8	4	4	8	8	2	8	4	4	4	4	4	-	-	-
	Digital input channels	2	-	2	2	-	-	-	-	4	-	-	-	-	-	-	4	8	6
	Sampling rate per channel (S/s)	100 k	20 k	20 k	20 k	100 k	100 k	20 k	20 k	20 k	100	10	20 k	100 k	100 k	100 k			
Analog signals	Voltage	■	■	■ < 10 V	■ < 60 V		■	■			■ < 80 mV								
	Voltage (isolated 1.2 kV)													■	■	■			
	Voltage (range up to 1.2 kV)														■	■			
	Current	■	■	■										■	■				
	Resistance	■	■									■							
	Potentiometer	■	■																
	Pt100, Pt1000 (RTD)	■	■									■							
	Thermocouples	■	■								■								
	Thermocouples (isolated 1.2 kV)												■						
	Strain gauges	■	■						■	■									
	Inductive full and half bridges									■									
	LVDT (Displacement)									■									
	Piezoelectric sensors					■													
	IEPE sensors (Piezotron)	■					■												
	MEMS capacitive sensors (K-Beam)							■											
Digital signals	Frequency																■	■	■
	Pulse width																■	■	■
	Counter signal																■	■	■
	Time																■	■	■
	Status	■		■	■					■							■	■	■
	TEDS	■					■												

KiStudio Lab Software Package

Editions «Starter» and «Professional»

*Easy to use measurement software **KiStudio Lab** and powerful tool for analysis (post processing) **jBEAM***

Standard feature set for **simple measurements and analysis**

Features for **advanced measurements and analysis**

Additional license for **advanced analysis** (post-processing)

KiStudio Lab and jBEAM benefits

- **KiStudio Lab** provides a platform to get quick results and displays the whole measurement chain and provides quick navigation to set-up and acquire Data
  - Freely definable live graphs in the dashboard for easy analysis during measurement.
  - The integrated project management helps to manage all measurement data – also from previous recordings and projects.

- **jBEAM** - Quick and easy data export for analysis
  - Fast and interactive analysis of your data using the extensive visualization tools in jBEAM
  - Flexibility to Create Reports

- KiStudio Starter Package controls one Chassis and includes jBeam Basic
- KiStudio Professional package controls up to 4 Chassis concurrently and includes jBeam Professional

KiStudio Lab Package Editions

Feature Overview

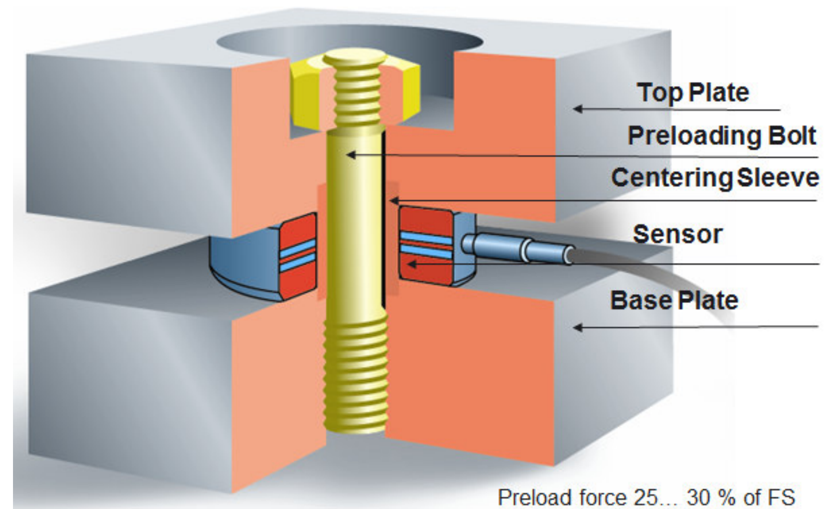
Data acquisition with KiStudio Lab	Starter Package	Professional Package
KiDAQ configuration	✓	✓
LabAmp devices in one setup	**4 (64*)**	**4 (64*)**
KiDAQ devices in one setup	**1**	**4**
Configuration of selected 3rd party		✓*
KiXact		✓*
Live graphs	✓	✓
Triggers	Basic	Advanced*
Online calculation (virtual channels)		✓
Live FFT	Basic	Advanced*

Data analysis with jBEAM	Starter Package	Professional Package
Arithmetics and statistics	Basic	Advanced
Filters		✓
2D axis charts	✓	✓
3D axis charts		✓
FFT	✓	✓
Report generator	✓	✓
Custom formulas		✓
Curve calculations & analysis		✓
File import from 3rd parties		✓
Package features		
Languages EN, DE, ZH	✓	✓
Maintenance and support included	**1 year**	**1 year**
maintenance and support prolongation	**optional**	**optional**

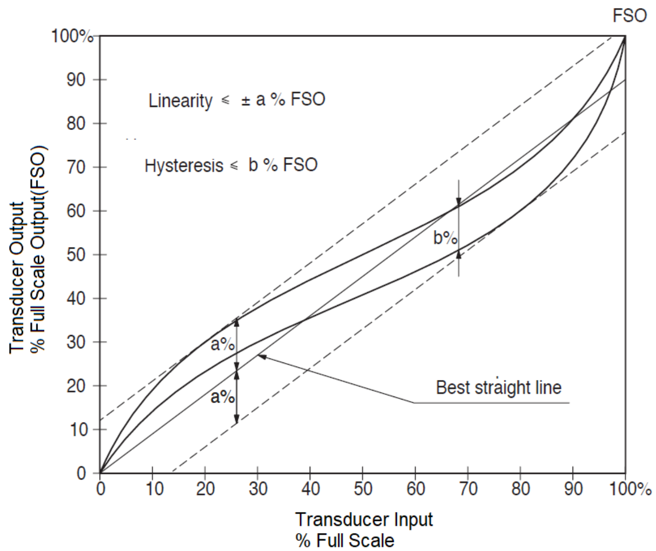
**planned for future releases*

1-Component Force Load Washers and Preloading

Max force vs. size: Low Range 1650 lbs (7.4kN) High Range: 70 tons (623kN)
Sensitivity vs. size: Low Range -17.7 pC/lb (4pC/N) High Range: -17.7 pC/lb (4pC/N)



Preload
Amplitude Linearity



Results of Measurement

Calibrated Range kN	Sensitivity pC / N	Lin incl. Hyst ≤ ± %FSO
0 ... 450	-3,843	0,47
0 ... 405	-3,835	0,44
0 ... 360	-3,826	0,40
0 ... 315	-3,817	0,37
0 ... 270	-3,808	0,34
0 ... 225	-3,799	0,32
0 ... 180	-3,788	0,30
0 ... 135	-3,776	0,26
0 ... 90	-3,762	0,22
0 ... 45	-3,748	0,13

- Amplitude Linearity
- Maintain constant frequency with amplitude variation
- A measure of the closeness of a calibration curve to a straight line through zero
- The slope of the best fit straight line through zero is the sensitivity
- The linearity is half the interval between the two parallels expressed as % of full-scale output (FSO)
- May include Hysteresis also expressed as % of FSO
- Quartz has negligible hysteresis lying well below the stated value. If large Hysteresis appears the force sensor is not mounted properly
- Partial Range Calibrations
- Linearity is an error source
- Sensitivity is based on a smaller operational range and improved linearity over that range compared to the maximum level of sensor

Effect of the Preload Bolt on Sensitivity

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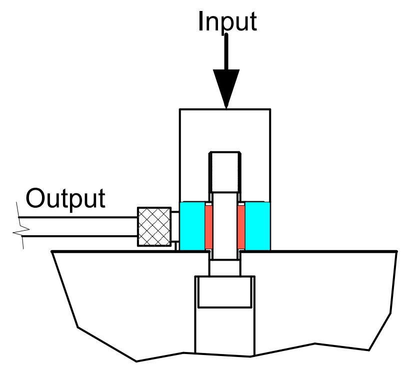
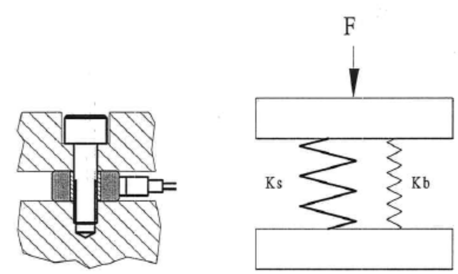
- The preload bolt/ screw is structurally in parallel with the load washer and thus acts as a “force shunt” by carrying a fraction of subsequently applied force past the load washer.
- The force-shunt action reduces load washer sensitivity by 6% to 9%. Calibration certificates supplied with sensors list both un-preloaded and preloaded sensitivities (e.g. 4.05 pC/N vs. 3.71 pC/N)
- User’s who wish to use a different bolt may need to conduct an in-situ calibration.



Force Shunting



$F = K_s \Delta x + K_b \Delta x$

$F_s = Ks \Delta x$

$F_s = Ks/(Ks + Kb) \times F$

If $K_s = 45$ and $K_b = 5$, then

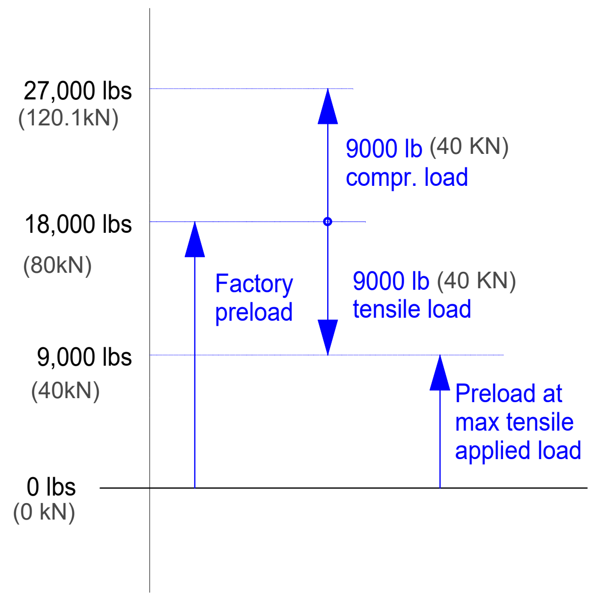
$F_s = 45/50 \times F$, or

$F_s = 90\%$ of F

Preloading

For Tension – Compression Force Measuring Capability

- Force link at right is perfect example
- Factory preloaded to 2/3 of the compression range of the basic load washer
- Stated measuring range is ± 1/3 of basic load washer compression range



3-Component Force Sensor

Parameter Examples

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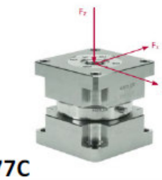
Kistler 3-Component Force Sensor -- Metric	 **9017C..**	 **9027C...**	 **9047C**	 **9067C**	 **9077C**
Standard Preload	9.5 kN	20 kN	70 kN	140 kN	350 kN
Min Plate Thickness	10 mm	15 mm	25 mm	30 mm	50 mm
Sensor OD	19 mm	28 mm	45 mm	65 mm	105 mm
Sensor ID	6.5 mm	8.1 mm	14.1 mm	26.5 mm	40.5 mm
Sensor Height	10 mm	12 mm	14 mm	21 mm	26 mm
Ground Isolated	>10^8 Ω	>10^8 Ω	>10^8 Ω	>10^8 Ω	>10^8 Ω
Fx, Fy Range	±1.5 kN	±4 kN	±15 kN	±30 kN	±75 kN
Fz Range	±3 kN	±8 kN	±30 kN	±60 kN	±150 kN
Fx, Fy Overload	±1.8 kN	±5 kN	±18 kN	±35 kN	±90 kN
Fz Overload	±3.6 kN	±10 kN	±35 kN	±70 kN	±180 kN
Sensitivity Fx, Fy	-25 pC/N	-7.8 pC/N	-8.1 pC/N	-8.1 pC/N	-4.2 pC/N
Sensitivity Fz	-11 pC/N	-3.8 pC/N	-3.7 pC/N	-3.9 pC/N	-2.0 pC/N
Linearity, Hysteresis each	≤±0.5%	≤±0.25%	≤±0.25%	≤±0.25%	≤±0.25%
Crosstalk Fz → Fx, Fy	≤± 1%	≤± 0.5%	≤± 0.5%	≤± 0.5%	≤± 0.5%
Crosstalk Fx ↔ Fy	≤± 2.5%	≤± 2%	≤± 2%	≤± 2%	≤± 1.5%
Crosstalk Fx, Fy → Fz	≤± 2.5%	≤± 3%	≤± 3%	≤± 3%	≤± 1.5%
Axial stiffness	1,471 N/µm	2,220 N/µm	6,207 N/µm	8,308 N/µm	26,605 N/µm
Lateral stiffness	219 N/µm	414 N/µm	1,489 N/µm	1,933 N/µm	6,385 N/µm
Shear stiffness	308 N/µm	606 N/µm	1,938 N/µm	2,446 N/µm	8,039 N/µm
Rotational stiffness	317 Nm/°	907 Nm/°	8,348 Nm/°	26,860 Nm/°	226,730 Nm/°
Bending stiffness	352 Nm/°	933 Nm/°	7,739 Nm/°	29,189 Nm/°	295,800 Nm/°

3-Component Force Link

Parameter Examples

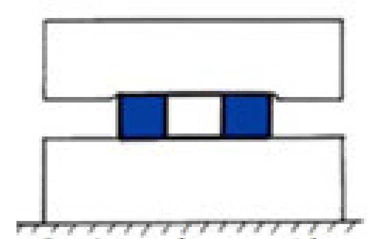
Kistler 3-Component Force Link Metric	 **9317C…**	 **9327C**	 **9347C**	 **9367C**	 **9377C**
Sensor Width, Length	25 mm	42 mm	55 mm	80 mm	125 mm
Sensor Height	30 mm	42 mm	60 mm	90 mm	120 mm
Ground Isolated	>10^8 Ω	>10^8 Ω	>10^8 Ω	>10^8 Ω	>10^8 Ω
Fx, Fy Range	±1.5 kN	±4 kN	±15 kN	±30 kN	±75 kN
Fz Range	±3 kN	±8 kN	±30 kN	±60 kN	±150 kN
Fx, Fy Overload	±1.8 kN	±5 kN	±18 kN	±35 kN	±90 kN
Fz Overload	±3.6 kN	±10 kN	±35 kN	±70 kN	±180 kN
Sensitivity Fx, Fy	-25 pC/N	-7.8 pC/N	-8.1 pC/N	-8.1 pC/N	-4.2 pC/N
Sensitivity Fz	-11 pC/N	-3.8 pC/N	-3.7 pC/N	-3.9 pC/N	-2.0 pC/N
Linearity, Hysteresis each	≤±0.5%	≤±0.5%	≤±0.5%	≤±0.5%	≤±0.5%
Crosstalk Fz → Fx, Fy	≤± 1%	≤± 1%	≤± 1%	≤± 1%	≤± 1%
Crosstalk Fx ↔ Fy	≤± 3%	≤± 3%	≤± 2%	≤± 2%	≤± 2%
Crosstalk Fx, Fy → Fz	≤± 3%	≤± 3%	≤± 3%	≤± 3%	≤± 3%
Natural Frequency (z)	20 KHz	12 KHz	10 KHz	6 KHz	6 KHz
Natural Frequency (x,y)	5.6 KHz	3.2 KHz	3.6 KHz	2.4 KHz	2 KHz
Axial stiffness	877 N/µm	1379 N/µm	2749 N/µm	3,880 N/µm	8,465 N/µm
Lateral stiffness	45 N/µm	73 N/µm	205 N/µm	312 N/µm	1,011 N/µm
Shear stiffness	194 N/µm	391 N/µm	890 N/µm	1,167 N/µm	2,795 N/µm
Rotational stiffness	227 Nm/°	682 Nm/°	4,834 Nm/°	16,093 Nm/°	110,630 Nm/°
Bending stiffness	222 Nm/°	625 Nm/°	4,572 Nm/°	14,778 Nm/°	106,540 Nm/°

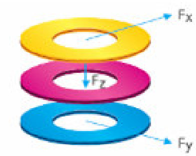
Considerations for Force Dynamometers

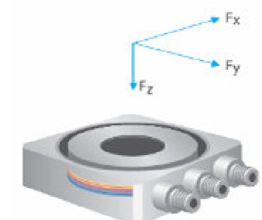
“Make your own” Dynamometer Fixtures or Use off the Shelf/ Custom Dynamometers

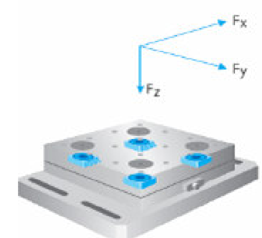
- A Force Dynamometer is comprised of an array of Force sensors between thick metal plates.
  - Sensors are matched for height and sensitivity.
- A dyno can also provide 6 DOF (force and moment) measurements.
- Off-center forces applied to a single load washer because moment loads that, at best, degrade accuracy and, at worst, can break the sensor (cracked quartz).
  - Dyno’s absorb moment loads by differential force reactions within the sensor array
- Force Dynamometers can be of various shapes and sizes square, triangular, rectangular, circular…
  - Moment can be a direct measurement or calculated from a specific geometry

- Installation and Mounting
- Size, Materials/ Tolerances
- Load Bearing Surfaces
- Linearity
- Sensor selection & preloading
- Ground Isolation/Noise
- Sensor Alignment /Cross Talk
- Calibration/ Checkout after Installation
- Force and Moment Equations
- Frequency Response FEA/ Stiffness



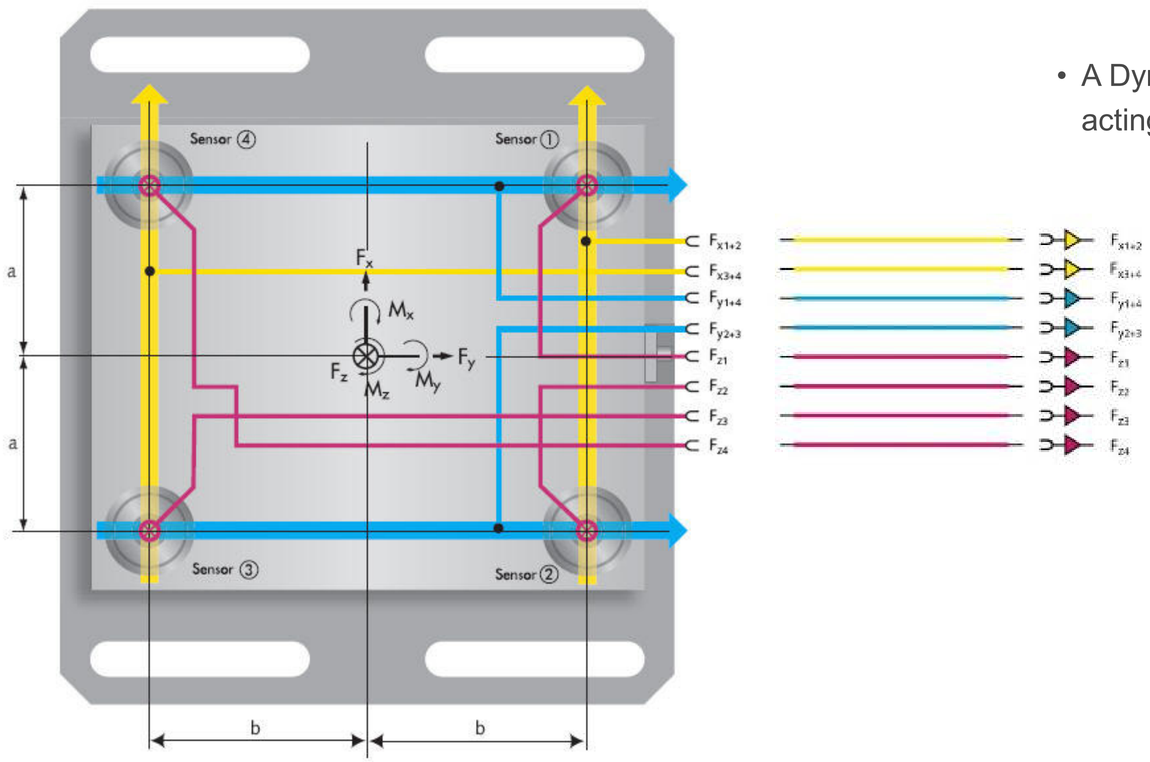






6-Component Measurement

Fx, Fy, Fz, Mx, My, Mz



- A Dynamometer measures the magnitude and direction of Fx, Fy, Fz acting on the dynamometer – but not their spatial location

Charge Amplifier with 8 Channels

Type 5080

Calculation of the three forces F_x, F_y, F_z and the three moments M_x, M_y, M_z

$$F_x = F_{x1+2} + F_{x3+4}$$

$$F_y = F_{y1+4} + F_{y2+3}$$

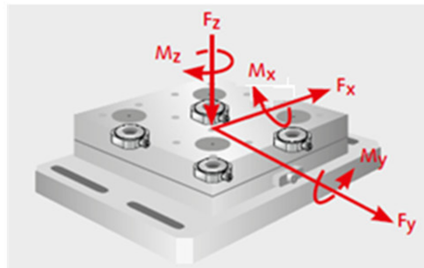
$$F_z = F_{z1} + F_{z2} + F_{z3} + F_{z4}$$

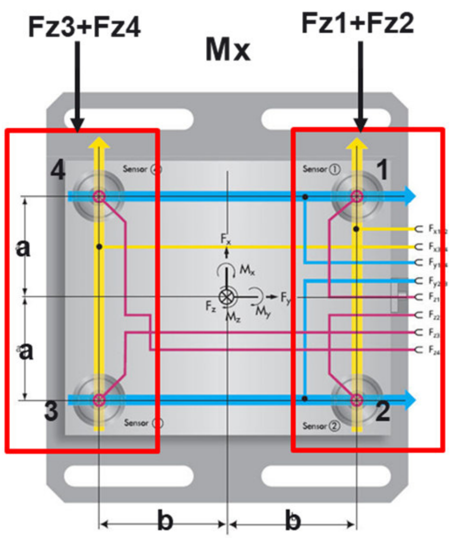
$$M_x = b\,(F_{z1} + F_{z2} - F_{z3} - F_{z4})$$

$$M_y = a\,(-F_{z1} + F_{z2} + F_{z3} - F_{z4})$$

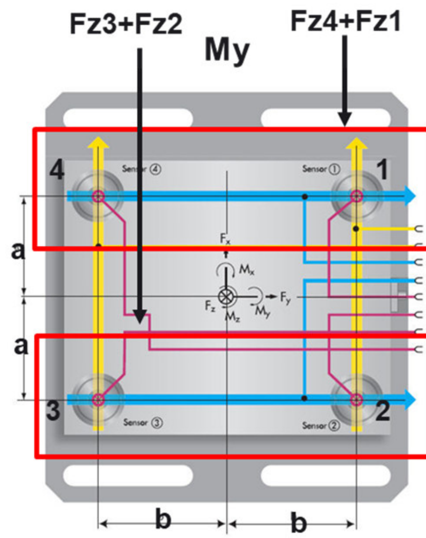
$$M_z = b\,(-F_{x1+2} + F_{x3+4}) + a\,(F_{y1+4} - F_{y2+3})$$

Moment Calculation

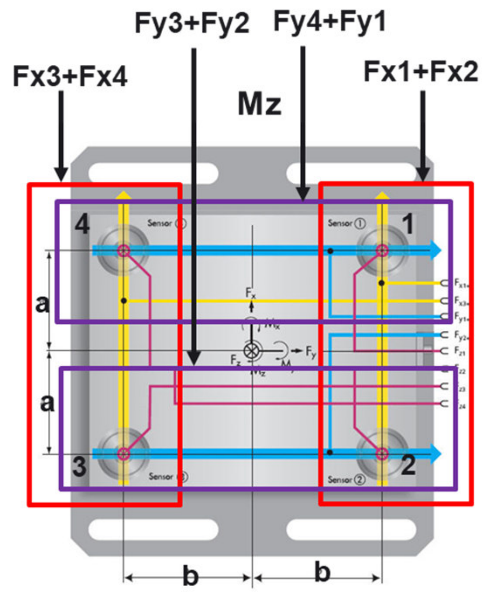




$$M_x = b\,[(F_{z1}+F_{z2}) - (F_{z3}+F_{z4})] = b\,[F_{z1} + F_{z2} - F_{z3} - F_{z4}]$$



$$M_y = a\,[(F_{z2}+F_{z3}) - (F_{z4}+F_{z1})] = a\,[-F_{z1} + F_{z2} + F_{z3} - F_{z4}]$$

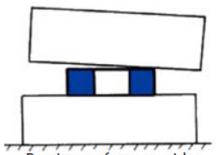


$$M_z = b\,[(F_{x3}+F_{x4}) - (F_{x1}+F_{x2})] + a[(F_{y4}+F_{y1}) - (F_{y2}+F_{y3})] = b\,[F_{x3} + F_{x4} - F_{x1} - F_{x2}] + a\,[F_{y1} + F_{y4} - F_{y2} - F_{y3}]$$

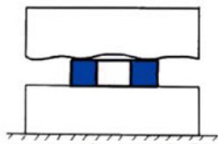
Load Bearing Surfaces

Challenges of Force Measurement: Unlike pressure sensors or accelerometers, most force sensors have top & bottom physical interfaces. This leads to preload, flatness, and parallelism requirements imposed on the force sensor end-user.

Parallelism : 0.0004in (0.01mm)



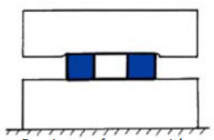
Bearing surfaces must be parallel



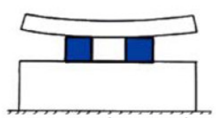
Bearing surfaces must be flat

Flatness: 0.0004 in (0.01 mm) Surface Roughness Ra 63µinch (Rt8.0); 1.6 µm (N7), ground surfaces if possible.

Strength : 22.7Ksi (150 N/mm^2)



Bearing surfaces must be sufficiently strong



Bearing surfaces must be flexurally stiff

Top/bottom Plate Stiffness :

Standard	Stainless Steel	Tempered Steel
DIN	27CrNi17	Ck15
Werkstoff Nr.	1.4057	1.1191
AFNOR	Z15CN16.02	XC42H1;XC45
B.S.	431 S29	080 H46
JIS	SUS 431	S45C
AISI/SAE	431	1045

Typical Stainless Steel Materials for Top and Bottom Plates

- Check Manufacturers data for requirements Mounting Surfaces, Base and Cover Plate Bores
- Standard Preload bolts use ARMCO 17-4 PH (similar to DIN 1.4542) high-strength steel, hardness HRC 46 …48.
- A certain minimum tensile strength is necessary for the top and bottom plate to be able to withstand the large forces of the preloading bolt.
- Dynamometer Rule of thumb~ top and bottom plate minimum thickness ~15% of largest dimension of force plate. Thickness and mass acting on the sensors influence stiffness and frequency response.

Example of Crosstalk: 3 Component

- Cross Talk is the amount of error caused by a measurement on one axis of a sensor as related to another axis
- Manufacturers Specify a maximum Limit on the Data Sheet – where the Calibration certificate provides and actual value

Crosstalk	$F_z \rightarrow F_x, F_y$	%	≤±0,5
	$F_x \leftrightarrow F_y$	%	≤±1
	$F_x, F_y \rightarrow F_z$	%	≤±3

Results of Measurement

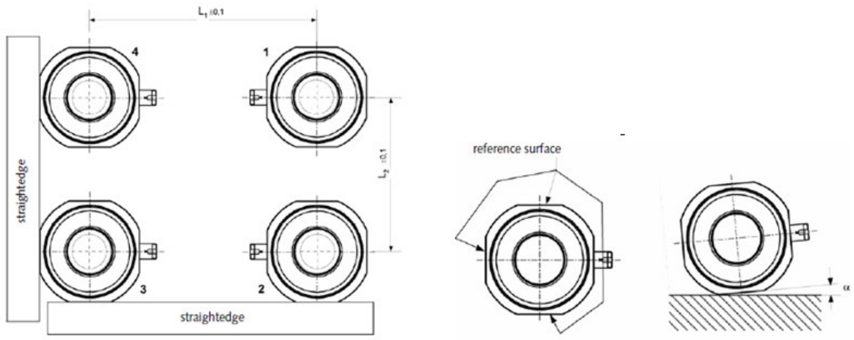
Calibrated Range kN		Sensitivity pC / N	Linearity ≤ ± %FSO	Cross talk %		%	
Fx	0 ... 75	-4,208	0,08	Fx → Fy	0,2	Fx → Fz	-0,2
Fy	0 ... 75	-4,210	0,09	Fy → Fx	-0,6	Fy → Fz	0,3
Fz	0 ... 150	-2,005	0,12	Fz → Fx	0,0	Fz → Fy	0,0
Fz *	0 ... 500	-2,112	0,68				

* without preload

3-Component Force Sensors Alignment

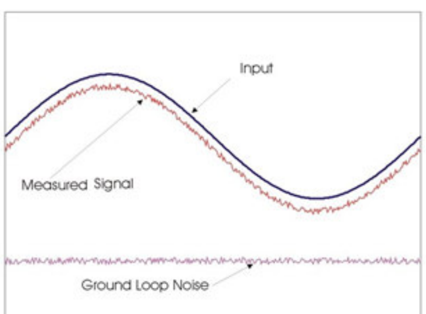
Cross Talk, Height, Ground Isolation

- Sensor “flats” used to align the sensor, and hence the coordinate system.
- An alignment error of α = 1 ° corresponds to an Fx ↔ Fy crosstalk of approximately 2 %.

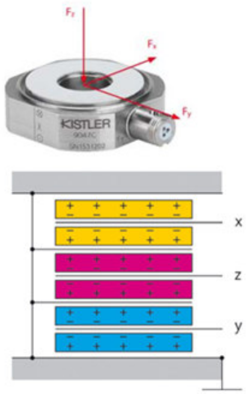


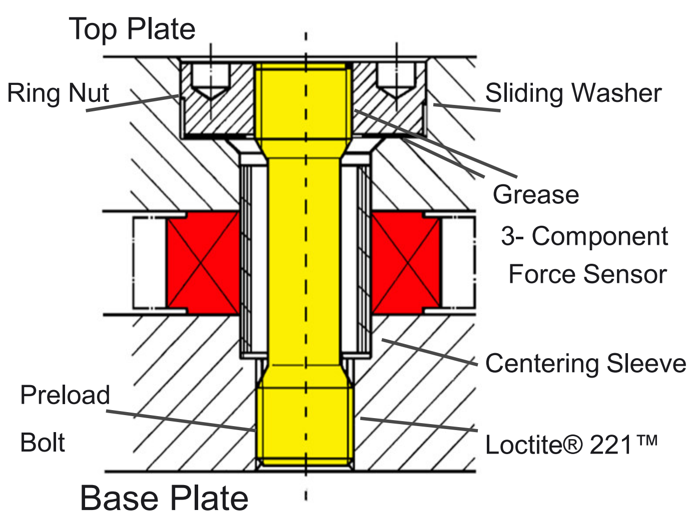
- Large sets of sensors can be ground to a common height to support Dyno applications.
- Ground Isolation – use one common grounding point to eliminate ground loops and related noise

Ceramic Plates



3-Component Force Sensor: Preload



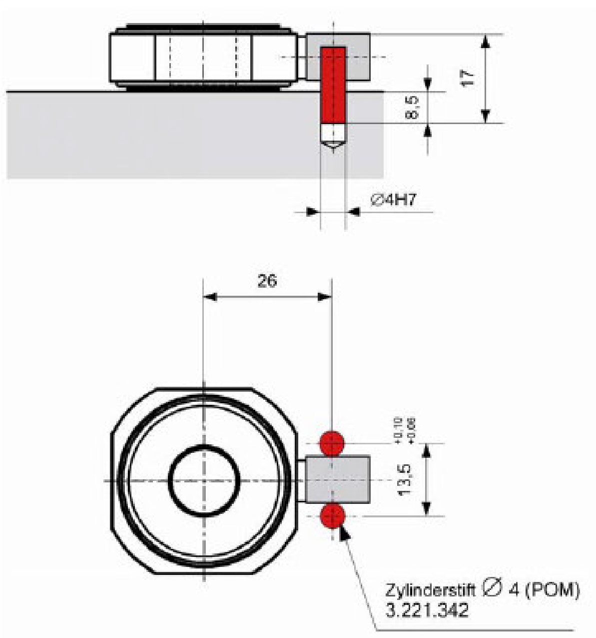


- Accuracy is exploited thru proper mechanical mounting.
- Standard Preload ~70% FS
- Z-axis preload provides static frictional force to enable transmitting X and Y shear loads
- Tensile and Compressive Measurement: Fx, Fy, Fz
- Optimize linearity/stiffness ~ closure of micro-gaps
- Utilizes much of the compressive measuring range
- Not recommended to use less than half recommended preload (reduces the shear forces in half)
- Fx, Fy Shear measuring range as a function of Fz Preload
- Higher internal sensor frictional coefficients provide higher ratio of Fx, Fy Range to Fz Preload (ex. 0.2)
- Measuring Range : Fz is typically 2x Fx, Fy
- Sensitivity X, Y is typically 2x Z (Shear vs. Compressive)
- Preload bolt is structurally in parallel with the load washer and made of tool steel for low force shunt.(6% to 9%.)
- Force Links are factory preloaded

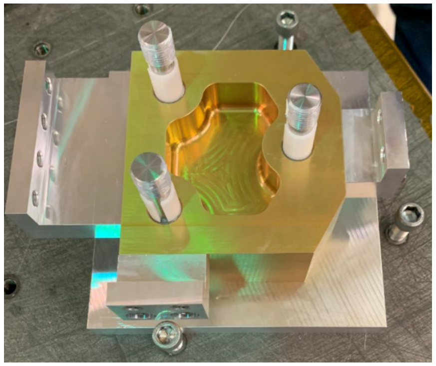
Alignment Methodology Examples

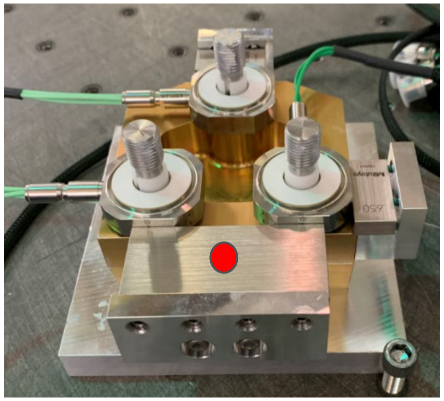
Cylindrical Pins

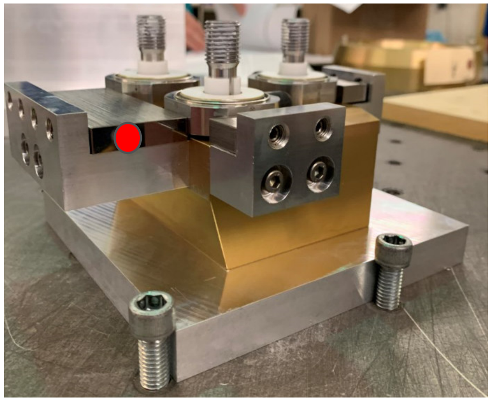
The 3-component force sensor is positioned by two cylindrical pins on both sides of the connector.



Fixture Plates







Preload Example: 4 Sensor Dynamometer

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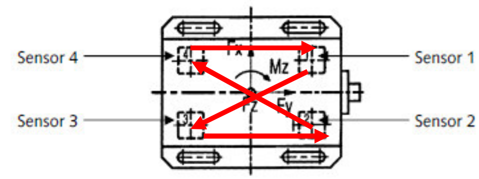
- Connect Z-Axis of Each Sensor to high impedance cable and combine signals using 4:1 Charge Summer into one Quasi-static Charge Amp
- Use unpreloaded Sensitivity for Charge Amp.
- Set Range of Charge Amp at a minimum of 4x standard preload level for one sensor
- Drift 0.03pC/sec, with Typical Sensitivity of 3.8pC/N results in 0.5N/min Drift – over 30 minutes 15N drift which is negligible compared to preload
- Preload bolt has fine thread pitch to ensure self locking of the preloaded sensor. No further precautions need to be taken.



Step	Sensor No.	Total Preload Force kN
1	1	17,5
2	3	35
3	2	52,5
4	4	70
5	1	87,5
6	3	105
7	2	122,5
8	4	140
9	1	157,5
10	3	175
11	2	192,5
12	4	210
13	1	227,5
14	3	245
15	2	262,5
16	4	280

- Preloading carried out in 4-stages Cross-wise in 25% increments

Dynamic Description Model of a Dynamometer

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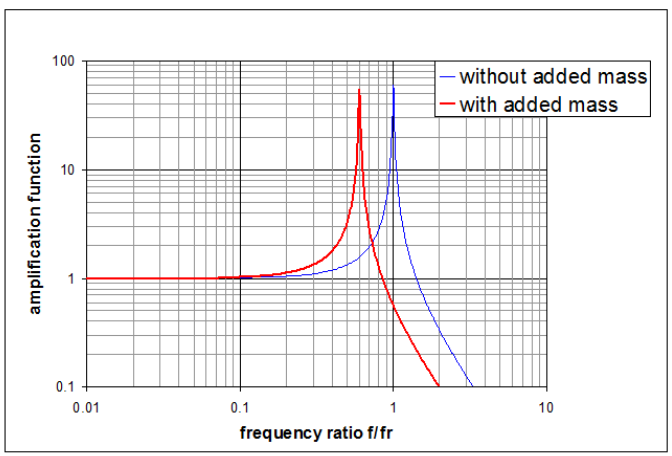
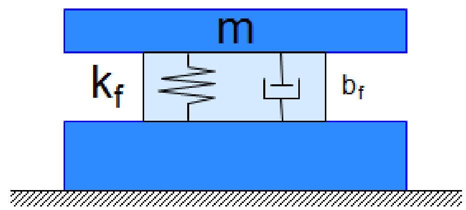
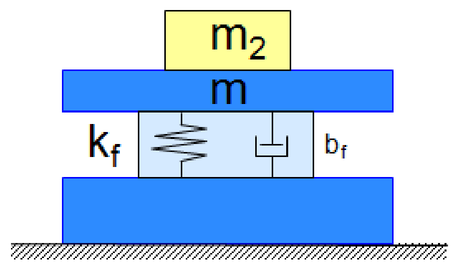
- A dynamometer can be represented as a simple spring mass model consisting of
  - Base plate
  - Oscillating top plate with mass m
  - Spring with stiffness kf
  - Damper with damping coefficient bf
- Piezoelectric sensors and dynamometers usually have a very low damping 0 < D < 0.01





$$f_r = \frac{1}{2\pi}\cdot\sqrt{\frac{k_f}{m}}$$

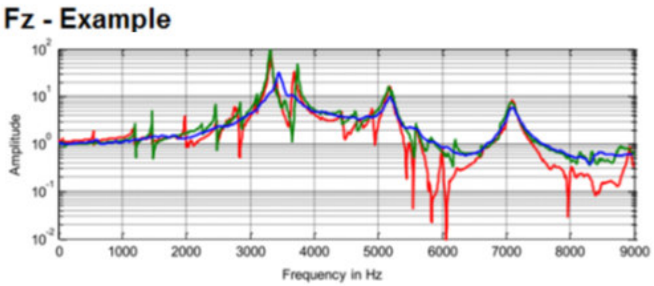


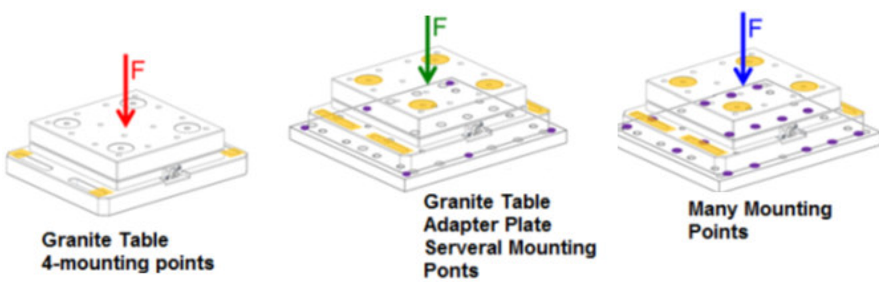
$$f_{r,red} = \frac{1}{2\pi}\cdot\sqrt{\frac{k_f}{m+m_2}}$$

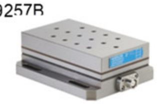
m	mass of top plate
m_2	added mass
k_f	stiffness of spring
f_r	resonance frequency
$f_{r,\,red}$	reduced resonance frequency

Importance of Mounting

- Mounting of dynamometer on flat surface
- The more connections between dynamometer and rigid mounting surface the better

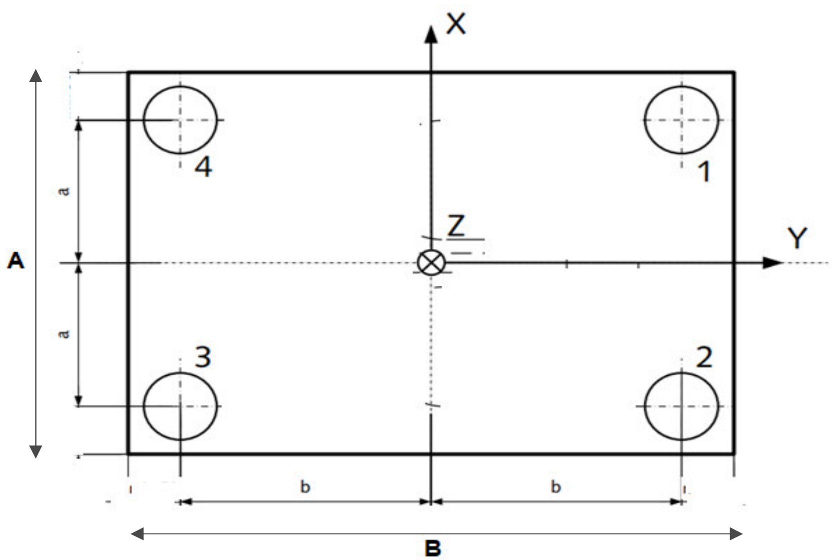




Dynamometer	Plate Size-Metric	Natural Frequency	Measuring Range Metric
9119AA1 	39mm x 80mm (Titanium)	Fx= 6.0KHz, Fy= 6.4KHz, Fz= 6.3KHz.	Fx:±4KN Fy:±4KN; Fz:±4KN Mx:±125N-m My:±125N-m Mz:±250N-m
9119AA2 	107mm x 80mm (Steel)	Fx= 4.3KHz, Fy= 4.5KHz, Fz= 4.4KHz.	Fx:±4KN Fy:±4KN; Fz:±4KN Mx:±150N-m My:±150N-m Mz:±300N-m
9129AA 	90mm x 105mm (Steel)	Fx= 3.5KHz, Fy= 4.5KHz, Fz= 3.5KHz.	Fx:±10KN Fy:±10KN Fz:±10KN Mx:±500N-m My:±500N-m Mz:±500N-m
9139AA 	140mm x 190 mm (Steel)	Fx= 2.9KHz, Fy= 2.9KHz, Fz= 3.0KHz.	Fx:±30KN Fy:±30KN Fz:±30KN Mx:±3000N-m ; My:±3000N-m Mz:±3000N-m
9255C 	260mm x 260mm (Steel)	Fx= 2.2KHz, Fy= 2.2KHz, Fz= 3.3KHz.	Fx:±30kN Fy:±30kN Fz:-10…60KN
9257B 	100mm x 170mm (Steel)	Fx= 3.5KHz, Fy= 3.5KHz, Fz= 3.5KHz.	Fx:±5kN Fy:±5kN Fz:±5kN
9253B11/B12 	600mm x 400mm (Aluminum)	Fx= 800Hz, Fy= 750Hz, Fz= 850Hz.	Fx:±10KN Fy:±10KN Fz: -10KN...20KN
9253B21/B22 	600mm x 400mm (Steel)	Fx= 580Hz, Fy= 550Hz, Fz= 720Hz.	Fx:±15KN Fy:±15KN Fz: -15KN...30KN

General Dynamometer/ Vibration Fixture Relationships

Make your Own or Off the Shelf/ Custom Dynamometer



- Weight of top plate :
  - Steel L x W x H x 7.8 x 10–6 kg/mm3
  - Aluminum L x W x H x 2.8 x 10–6 kg/mm3
  - Ceramic: L x W x H x 3.9 x 10–6 kg/mm3
- Youngs Modulus (Modulus of Elasticity)
  - Steel: 200GPa
  - Aluminum: 70GPa
  - Ceramic: 370GPa

- Top Plate Thickness Typically ~15% of the Maximum dyno Length
  - a ~30% A
  - b ~30% B
- Steel ~3 x Stiffer than Aluminum
- Ceramic
  - ~1.85 x Stiffer Steel
  - ~5.3 x Stiffer than Aluminum
- Aluminum~36% lighter than Steel
- Ceramic~50% lighter than Steel

- Increasing fn
  - Materials selection
  - Higher Stiffness Sensors (ex. High Capacity)
  - Additional sensors (Equivalent Stiffness adds as they are mechanically in parallel)
- FEA used to validate the Dyno design satisfies the measurement requirements

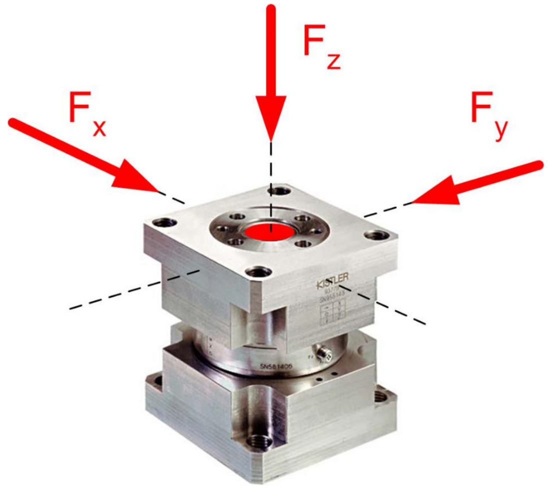
FEA Analysis of Large Dynamometers

Type	Top Plate [mm]
9236A1	260x260x38
9236A2	400x400x38
9236A-EL	400x600x45

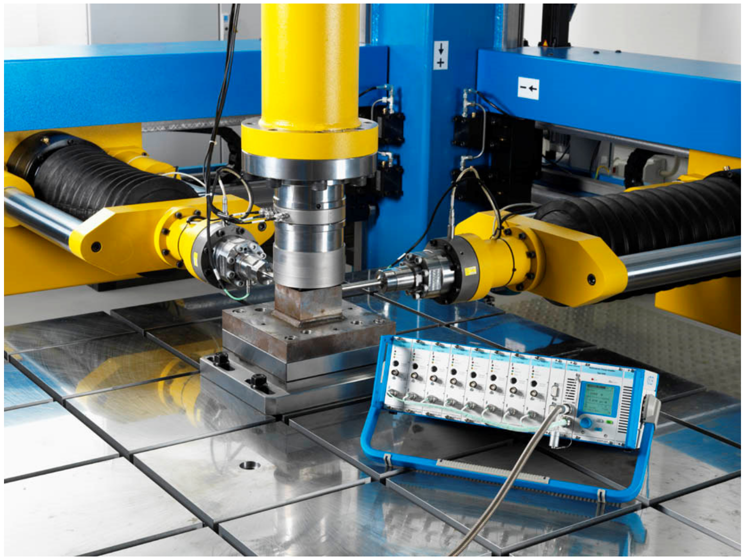
Most piezoelectric sensors follow the upper frequency

- $f_{+5\%} = f_n/5$;
- $f_{+10\%} = f_n/3$;
- $f_{+3dB} = f_{+41\%} = f_n/2$

3-Component High Force Calibration Rig



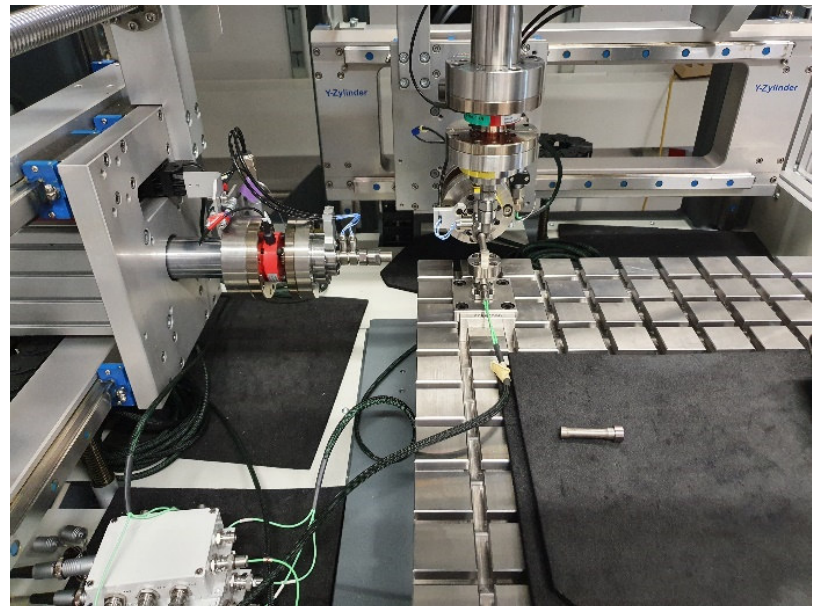
- Determination of sensitivity, linearity and hysteresis per each load direction
- Analysis of cross-talk behavior and cross-talk coefficients
- 100% FSO and Partial Range Calibration



- Manual and fully automatic operation
- Electric Actuators with Strain Gage Force sensor as reference for Control and PE Force reference sensors for calibration
- Calibration of small large UUT up to 2.0m x 2.0m x 0.9m (6.56ft x 6.56ft x 2.95ft)
- Vertical loads up to 500kN (112,000 lbf); Horizontal loads up to 100kN (22,500lbf) and as low as 100N (22.5lbf)
- Torque Calibration determined by moment arm

Micro-Force Press for low Force Calibration

- Electric Actuators with Strain Gage Force sensor as reference for Control and PE Force reference sensors for calibration
- 1N minimum Force, 900N Maximum Force
- Torque Calibration determined by moment arm
- 500mm x 500mm Plate for Large UUT Testing
- Capable to perform 6-component calibration on Dynamometer Force plates as well as Multicomponent force sensors/ force links



Dynamometer Calibration Example

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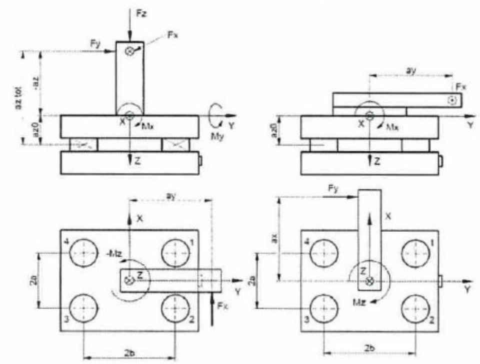
Results of Measurement

Calibrated Range N		Sensitivity pC / N	Linearity[1] ±%FSO
Fx	0 ... 100	-7,796	0,11
Fy	0 ... 100	-7,800	0,07
Fz	0 ... 100	-3,787	0,09

Calibrated Range N·m		adjustment coeff. N·m / N·m	Linearity[1] ±%FSO
Mx	0 ... 19,5	1,008	0,08
My	0 ... -19,5	1,015	0,05
Mz[3]	0 ... 19,5	1,031	0,09

Type Kistler 9236A2

Serial No. 5702362



Crosstalk

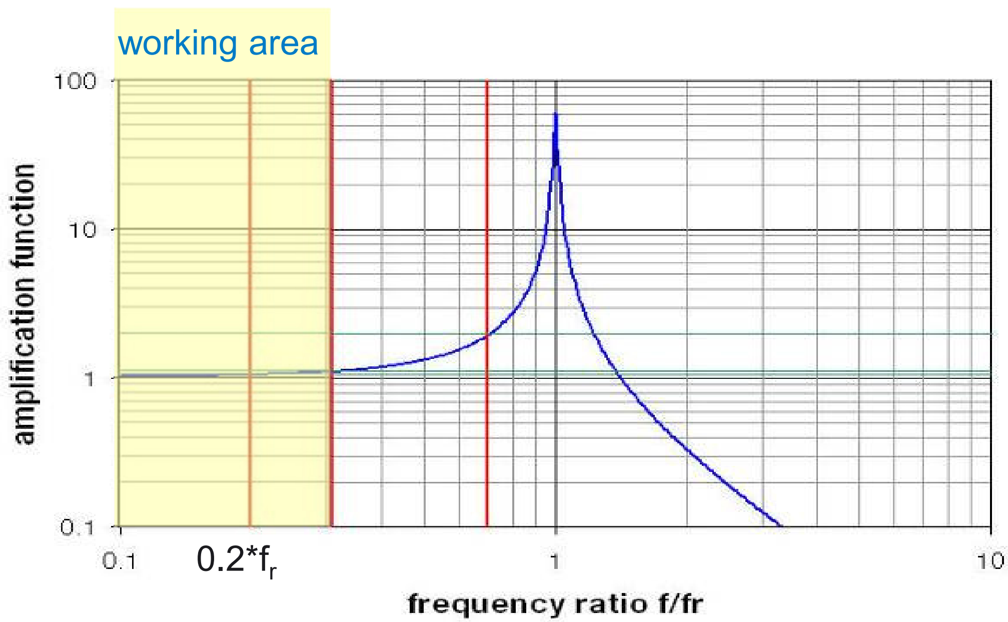
Calibrated Range N		→Fx %	→Fy %	→Fz %	→Mx mN·m/N	→My mN·m/N	→Mz mN·m/N
Fx	0 ... 100		0,0	-0,3	-0,608		-0,190
Fy	0 ... 100	0,7		-0,7		-0,575	0,537
Fz	0 ... 100	-0,1	0,2		4,826	4,042	-0,076

Calibrated Range N·m		→Fx N/N·m	→Fy N/N·m	→Fz N/N·m	→Mx %	→My %	→Mz %
Mx	0 ... 19,5	0,04		-0,04		-0,3	0,3
My	0 ... -19,5		0,00	0,02	0,3		0,1
Mz	0 ... 19,5	0,03	-0,01	-0,02	0,4	0,2	

In-Situ Calibration and Checkout

Low level sweep according NASA-HDBK-7004C

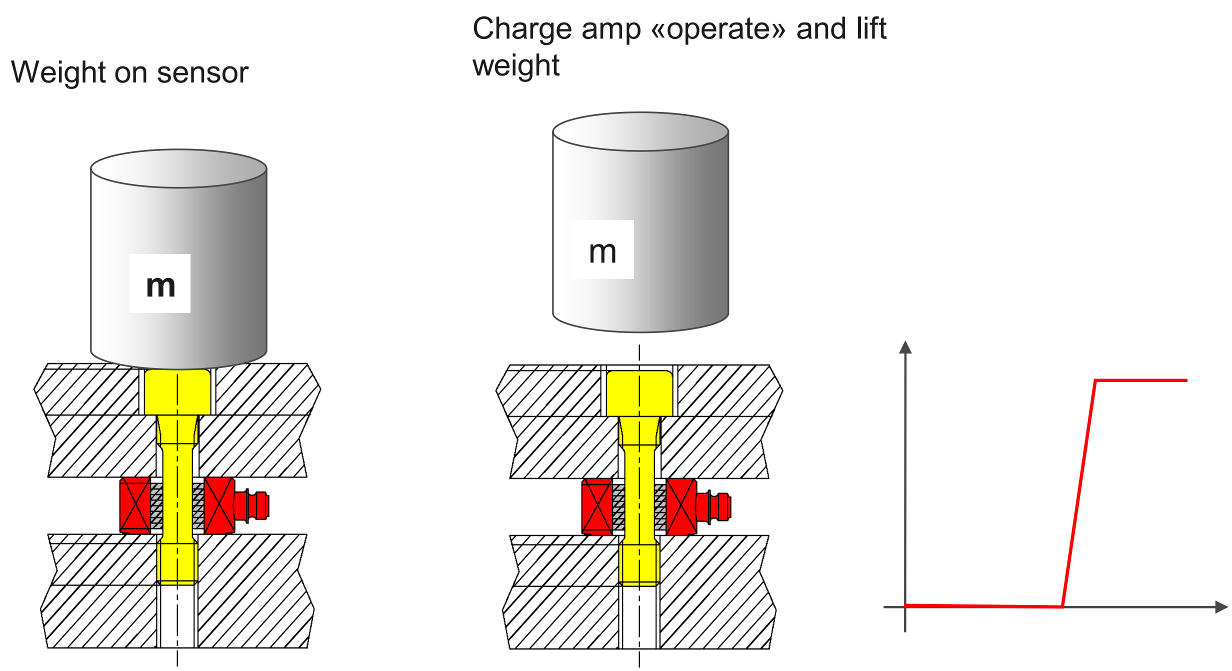
- Calibration can be done with a low level sine sweep sufficiently below the first resonance as a simple way for a calibration.
- Also recommended as a functional test to check if everything is working with mass simulator.
- The low-frequency (below first resonance of the test item) of the apparent mass is compared with the known total mass of the test item.
  - The relevant apparent mass is the ratio of total force to the input acceleration in the shaker direction. (M=F/A)



In-Situ Calibration and Checkout

Static calibration according NASA-HDBK-7004C

- Calibration can also be done with known weights
- Reset charge amplifier, place weight on force sensor set up, switch to operate and lift weight carefully
- The load step can be used to calibrate force sensors. Difficult with large loads, as weights become very heavy and difficult to handle.



Micro-Vibration Ceramic Dynamometer

Measure Forces and Calculate Moments

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- Ceramic (Al_2O_3) Top Plates for larger Dynamometers Force sensors to get 40% higher fn compared to steel.

- Ceramics vs. Stainless Steel
  - Lower Specific Gravity
  - Higher Modulus of elasticity
  - Low Tensile Strength – Acceptable as forces and loads are low in micro-vibration

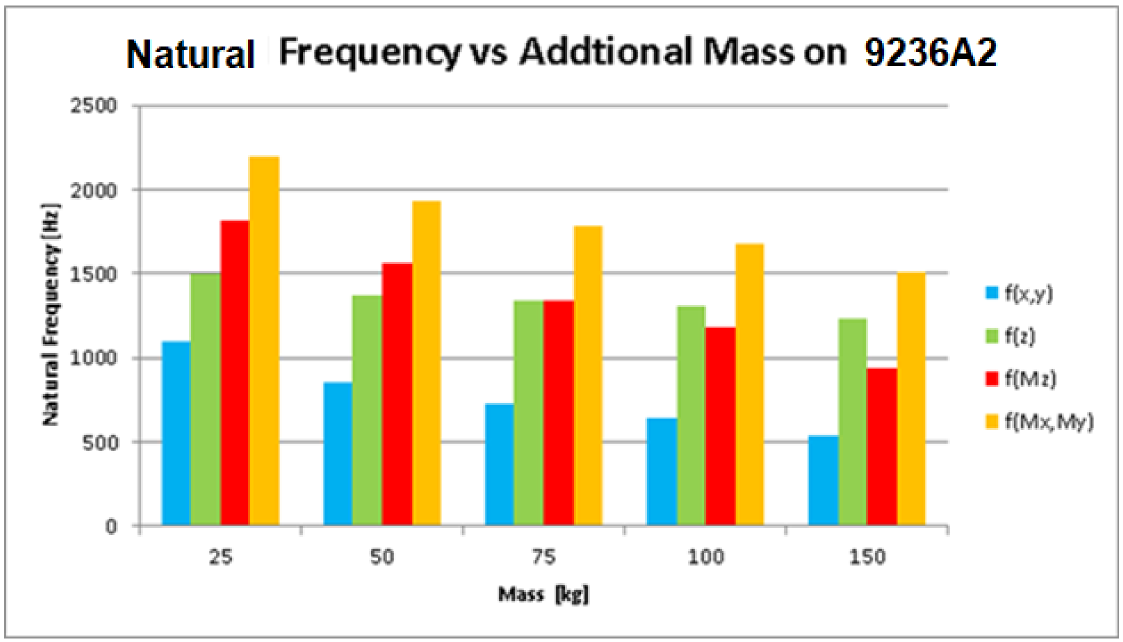
- 9236A2: 6-Comp Dynamometer 15.8” x 15.8” x 3.7”   (400mm x 400mm x 95mm)
  - Fx, Fy, Fz Range : ±113lbf (±500N)
  - Mx, My, Mz Range: ±14.5 ft-lb
  - High Fn: Fnx, y ~1,900 Hz, Fnz ~2,500 Hz
  - Fn with 25lb mass
    - Fnx,y ~1,600 Hz, Fnz ~2,000 Hz

- 9236A1: 6-Comp Dynamometer 10.2” x 10.2” x 3.7”   (260mm x 260mm x 95mm)
  - Fx, Fy, Fz Range : ±113lbf(±500N)
  - Mx, My, Mz Range: ±14.5 ft-lb (± 19.5N-m)
  - High Fn: Fnx, y ~3.500 Hz, Fnz 4,000 Hz
  - Fn with 25lb mass
    - Fnx,y ~2,100 Hz, Fnz ~3,200 Hz

			9236A1	9236A2
Noise RMS (1 Hz ... 10 kHz)[1]	F_x, F_y	N	$\approx 0{,}7 * 10^{-3}$	$\approx 0{,}7 * 10^{-3}$
Broadband	F_z	N	$\approx 1{,}5 * 10^{-3}$	$\approx 1{,}5 * 10^{-3}$
	M_x, M_y, M_z	N·m	$\approx 4{,}0 * 10^{-4}$	$\approx 4{,}0 * 10^{-4}$

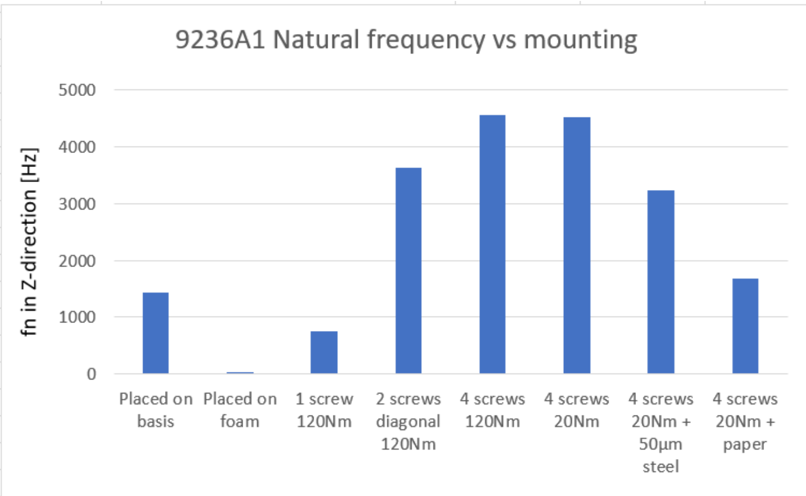
FEM Estimates of Natural Frequencies with Added Mass to 9236A2

- 150Kg static mass is possible for a ceramic Top plate dynamometer but the test article needs to be carefully placed on the dyno top plate and should not be dropped onto the dyno – this is best practice no matter what mass is being used.
- Potential use is for Full Cubesat Test including attitude control/reaction wheel phasing evaluation
- Most piezoelectric sensors follow the upper frequency rule
  - $f_{+5\%} = f_n/5$;
  - $f_{+10\%} = f_n/3$;
  - $f_{+3dB} = f_{+41\%} = f_n/2$



Example: FRF Measurement and Mounting

Mounting Results of 9236A1 showing Natural Frequency in Z using FRF Tap Test



1	Placed on metal base
1a	Placed on foam
3	Mounted with 1 screw (120Nm)
4	Mounted with 2 screws diagonal (120Nm)
5	Mounted with 4 screws (120Nm)
6	Mounted with 4 screws (20Nm)
7	Mounted with 4 screws (20Nm),50µm steel strip beneath one edge
8	Mounted with 4 screws (20Nm),paper beneath one edge

- Ideal mounting configuration is screwed with four screws on the basis (measurement 5)
- Effect of mounting torque is small (almost no difference between 120Nm and 20Nm torque for mounting screws)
- Less Fasteners and Surface flatness can degrade frequency response
- All other configurations are not recommended

Agenda

Part 1: Background (today)

- Application Introduction – Multicomponent force Measurement
- Piezoelectric Principles of Operations
- Measuring Chains
- Force Measurement Considerations
- Summary/ Conclusions
- Q&A

Part 2: Applications (October 15th 2020)

- Test Environment Considerations (Noise, Vacuum…)
- Micro-vibration/ Exported Force and Torque (EFT)
- Force Limited Vibration
- Propulsion Testing
- Summary/ Conclusions
- Q&A

Space Webinar: Practical Considerations of Multicomponent Force Measurement for Space Applications: PART 2

Bill Zwolinski, 15 October 2020

Agenda

Part 1: Background (24 September 2020) See Link Below for recording of event

https://www.youtube.com/watch?v=MNPmvrnqxBg&feature=youtu.be

- Application Introduction – Multicomponent force Measurement
- Piezoelectric Principles of Operations
- Measuring Chains
- Force Measurement Considerations
- Summary/Conclusions
- Q&A

To allow for enough time to cover the content
The Live Webinar will have a Part 1 and Part 2 as shown below

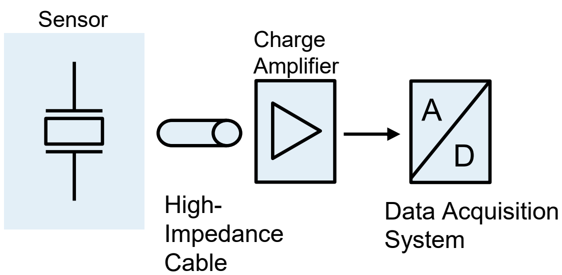
Part 2: Applications (15 October 2020)

- Brief Review of Part 1
- Micro-vibration/ Exported Force and Torque (EFT)
- Force Limited Vibration
- Propulsion Testing
- Summary/Conclusions
- Q&A

PE and IEPE Sensor

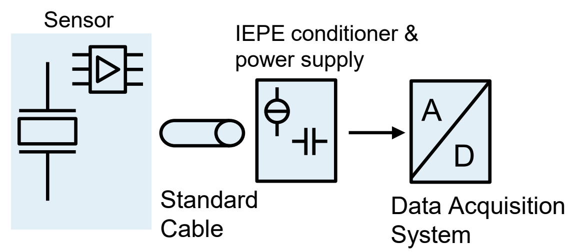
Piezoelectric Sensor Principles

PE (pC/mu)
(**P**iezo**E**lectric)



- Sensor does not contain electronics
- High impedance cable required
- Very wide temperature range
- Externally rangeable with charge amplifier
- Huge measuring range
- Quasi-static (long TC) as well as highly dynamic measurements possible
- Reset/Measure Tares the measurement to remove static loads from the dynamic range

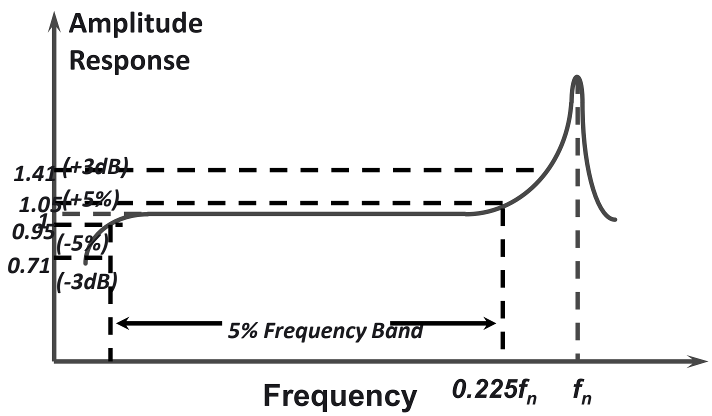
IEPE (mV/mu)
(**I**ntegrated **E**lectronics **P**iezo**E**lectric)



- Sensor contains internal charge to voltage converter – Powered by IEPE Constant current supply
- Standard cable for sensor connection
- Many DAQ systems offer an integrated IEPE power supply required for operation
- Integrated TEDS inside sensor possible
- Only dynamic measurements possible
- Measuring range is fixed
- Temperature range limited with internal sensor integrated electronics
- Not Resettable

PE and IEPE Sensor

Frequency Response



- Most piezoelectric sensors follow the upper frequency rule
  - $f_{+5\%} = f_n/5$;
  - $f_{+10\%} = f_n/3$;
  - $f_{+3dB} = f_{+41\%} = f_n/2$
- Exciting sensor resonances can occur in measurements – Ranging the measuring chain maintains output in the linear region of operation (No Saturation) and the resonances signals can be filtered

High Frequency Relationship

$$\frac{a_o}{a_b} \cong \frac{1}{\sqrt{\left[1-\left(\frac{f}{f_n}\right)^2\right]^2 + \left(\frac{1}{Q^2}\right)\left(\frac{f}{f_n}\right)^2}}$$

f_n = undamped natural (resonant) frequency (Hz)

f = frequency at any given point of the curve (Hz)

a_o = output acceleration

a_b = mounting base of reference acceleration $\left(\frac{f}{fn} = 1\right)$

Q = factor of amplitude increase at resonance

Low frequency Relationship

$$\frac{V_o}{V_{in}} = \frac{2\pi f(\tau)}{\sqrt{1+[2\pi f(\tau)]^2}}$$

$$\text{phase lead (deg)} = \text{arc tan}\ \frac{1}{2\pi f(\tau)} \cong 80\sqrt{\frac{V_{in}-V_o}{V_{in}}}$$

$$f_{-5\%} = \frac{0.5}{\tau}$$

τ = time Constant (sec)

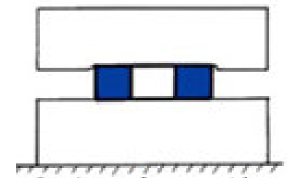
Review: Considerations for Force Dynamometers

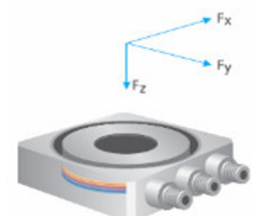
“Make your own” Dynamometer Fixtures or Use off the Shelf or Custom Dynamometers

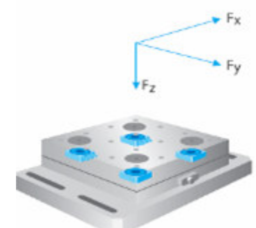
- A Force Dynamometer is comprised of an array of Force sensors between thick metal plates.
  - Off-center forces applied to a single load washer create moment loads that, at best, degrade accuracy and, at worst, can break the sensor
  - Dyno’s absorb moment loads by differential force reactions within the sensor array
  - Force Dynamometers can be of various shapes and sizes square, triangular, rectangular, circular…
    - Moment can be a direct measurement or calculated from a specific geometry

- **Analog Bandwidth Considerations**
  - Charge Amp determines Lowest and highest Frequency Possible
  - Test Article – Required Frequencies of Interest and Resolution
  - Force Sensors == Fixtures
    - Natural Frequency needs to satisfy Test Article requirements and could be the limiting factor
    - Trade off on Amplitude tolerance for wider Bandwidths 5%,10%,3dB or Redesign Fixture

- Considerations
  - Installation and Mounting
  - Size, Materials, Tolerances
  - Load Bearing Surfaces
  - Linearity
  - Sensor Selection & Preloading
  - Sensor Matched height and Sensitivity
  - Ground Isolation/Noise
  - Sensor Alignment /Cross Talk
  - Calibration/ Checkout after Installation
  - 6-Component Force and Moment Equations
  - Mass Loading
  - Fixtures
  - Frequency Response FEA/ Stiffnesses
  - Vacuum Operation
  - Environmental







Moment Calibration: K-Factor Correction

Formula for Calculations

$F_x = F_{x1+2} + F_{x3+4}$

$F_y = F_{y1+4} + F_{y2+3}$

$F_z = F_{z1} + F_{z2} + F_{z3} + F_{z4}$

$M_x = [b \cdot (F_{z1} + F_{z2} - F_{z3} - F_{z4})]\ kM_x$

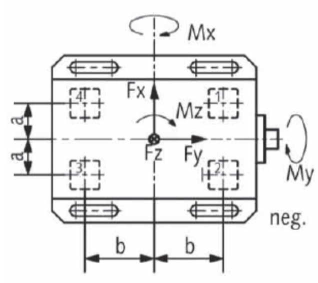
$M_y = [a \cdot (-F_{z1} + F_{z2} + F_{z3} - F_{z4})]\ kM_y$

$M_z = [b \cdot (-F_{x1+2} + F_{x3+4}) + a \cdot (F_{y1+4} - F_{y2+3})]\ kM_z$

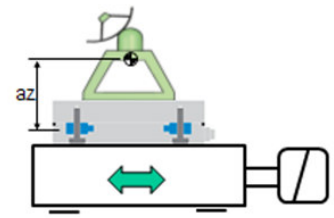
a = Distance of the sensor axis from the y-axis

b = Distance of the sensor axis from the x-axis

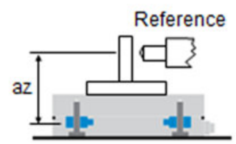
kM_x, kM_y, kM_z = Correction factor of torque calibration



Real world example:
Test on shaker



Calibration



- Deviations occur when measuring moments because a dynamometer is not infinitely stiff. These deviations are corrected by the correction factors, KMx, kMy and KMz and are determined through a special calibration which is as close as possible to real measurement design to prevent measurement inaccuracies.
  - For moments with a lever arm, the non- ideal stiffness of a dynamometer causes an uneven loading over the dynamometer. This results in a virtual increase of sensor distance.

- Real world and calibration should have same force application points as the actual test which is essential for the application of the correct Kfactor. The so called "effective (measured) distance" depends on the actual force distribution which cannot be determined directly. So the moment calibration process is used
  - The known applied force and lever arms, the expected moment is calculated.
  - Using the calibration press, we measure the dynamometer output to get measured moment
  - If the k-factor = 1.0000, then the calculated and measured value is exactly identical (…in-reality never the case).

Sample Calibration Certificate with Moment Calibration

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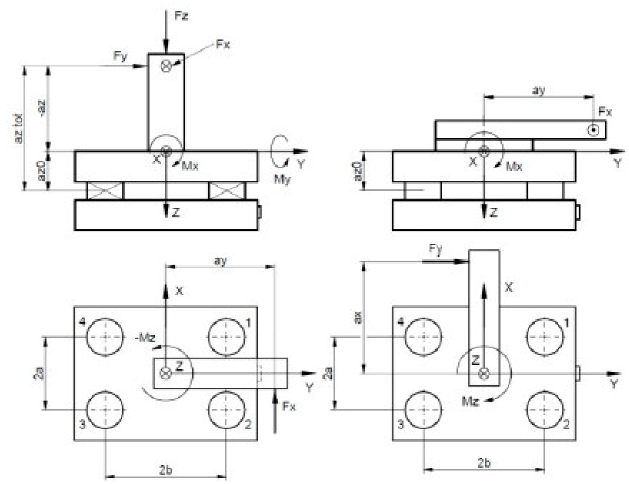
Calibrated Range	Sensitivity	Linearity[1]	CMC[2]
N	pC / N	±%FSO	%
Fx 0 ... 100	-7,779	0,11	0,14
Fy 0 ... 100	-7,772	0,09	0,17
Fz 0 ... 100	-3,789	0,12	0,15

1) linearity including hysteresis

2) The reported expanded uncertainty of measurement (CMC) is stated as the combined standard uncertainty of measurement multiplied by a coverage factor k = 2 and represents the calibration and measuring capability of the calibration system at the assigned measuring point of the calibration range.

Calibrated Range	adjustment coeff.	Linearity[1]
N·m	N·m / N·m	±%FSO
Mx 0 ... 19,5	1,013	0,05
My 0 ... -19,5	1,012	0,04
Mz[3] 0 ... 19,5	1,027	0,14

1) linearity including hysteresis
3) average of multiple loads



Crosstalk	→Fx	→Fy	→Fz	→Mx	→My	→Mz
N	%	%	%	mN·m/N	mN·m/N	mN·m/N
Fx 0 ... 100		0,1	-0,4	-0,699		-0,742
Fy 0 ... 100	0,7		-0,8		-0,256	0,539
Fz 0 ... 100	-0,1	0,0		2,241	-0,603	-0,145
Calibrated Range	→Fx	→Fy	→Fz	→Mx	→My	→Mz
N·m	N/N·m	N/N·m	N/N·m	%	%	%
Mx 0 ... 19,5	0,04		-0,04		-0,1	0,3
My 0 ... -19,5		-0,01	0,02	0,4		0,4
Mz 0 ... 19,5	0,04	-0,01	-0,01	0,4	0,1	

Remarks The adjustment coefficients (k[Mx], k[My] and k[Mz]) are needed to calculate the moments from the individual signals. They can be adjusted in the Multi-Channel Charge Amplifier Type 5017 / 5070 / 5080. The torques were generated with a lever arm of az tot = 195 mm or ax, ay = 200 mm.

EFT Introduction : Measurement Noise Considerations

Electrical Noise

- Ground Isolated Measuring Chains – Avoid Ground Loops
  - One common ground for the measurement chain
- Avoid strong Electromagnetic fields (ex. EMI) in the area of the instrumentation/cables
  - Use 360° Shielded Cables
- Battery Power of signal conditioner can often show an improvement
  - AC power is converted into DC power which is not a perfect process
- Bandwidth is directly proportional to rms noise

Other Environmental Noise Error sources (ex. Micro-vibration Applications)

- Transmissibility of seismic inputs to the Sensors performing measurement
- Structural response of Test Rig
- Acoustic Borne Noise
- HVAC inputs with Airflow on structures under test

Noise – Time and Frequency Domain View

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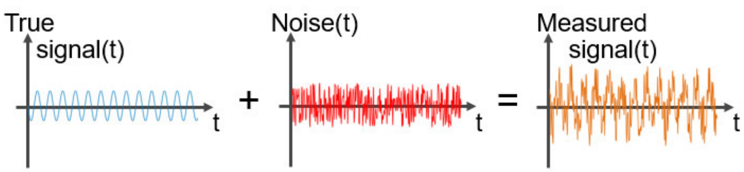
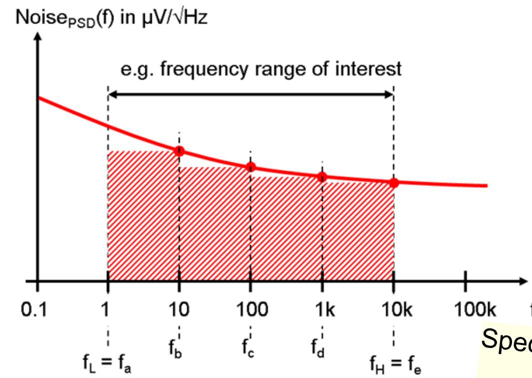


- Noise is unwanted, random signal fluctuation which degrades signal
  - Noise limits the minimum signal level that can be measured
  - For many random (white) noise sources : σrms = SQRT($\sigma^2_1 + \sigma^2_2 + \ldots + \sigma^2_N$)
  - Appropriate filtering reduces noise and enhances the signal quality
- **Power spectral densitiy** describes the noise in specific frequency ranges. It allows one to estimate the noise as a function of bandwidth/ filtering.
  - FFT is effectively Narrowband filtering of the signal of interest.
    - Narrowband FFT processing can support higher resolution and SNR on a frequency bin basis
  - Frequency Bin width is related to the number of FFT points and Sample Rate



Spectral noise (1 Hz) 5.0 µV/√Hz
Spectral noise (10 Hz) 1.6 µV/√Hz
Spectral noise (100 Hz) 1.3 µV/√Hz
Spectral noise (1 kHz) 1.1 µV/√Hz
Spectral noise (10 kHz) 1.0 µV/√Hz
Spectral noise (100 kHz) 1.0 µV/√Hz

Convert noise PSD to Mechanical Units(MU) via Sensitivity mV/MU

For the range between f_L and f_H:

$$\text{Noise}_{RMS} = \sqrt{\int_{f_L}^{f_H} [\text{Noise}_{PSD}(f)]^2 \, df}$$

Example: DC Power Charge Amplifier/DAQ - RMS Noise and SNR

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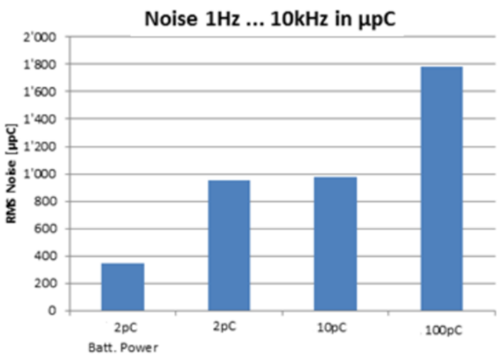
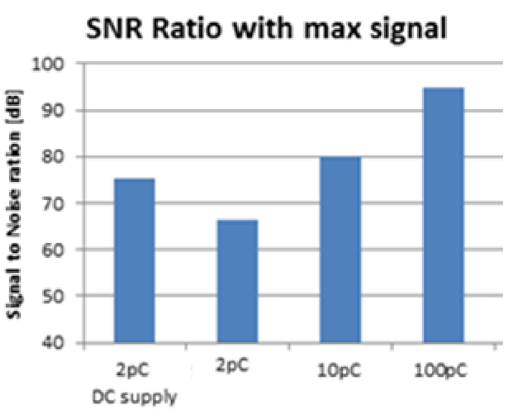
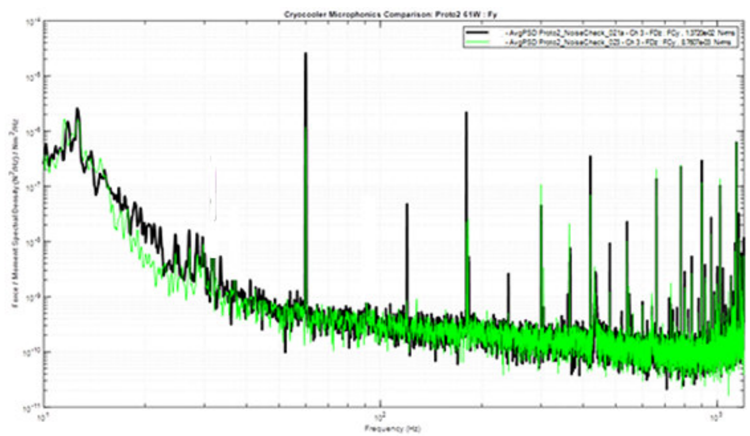


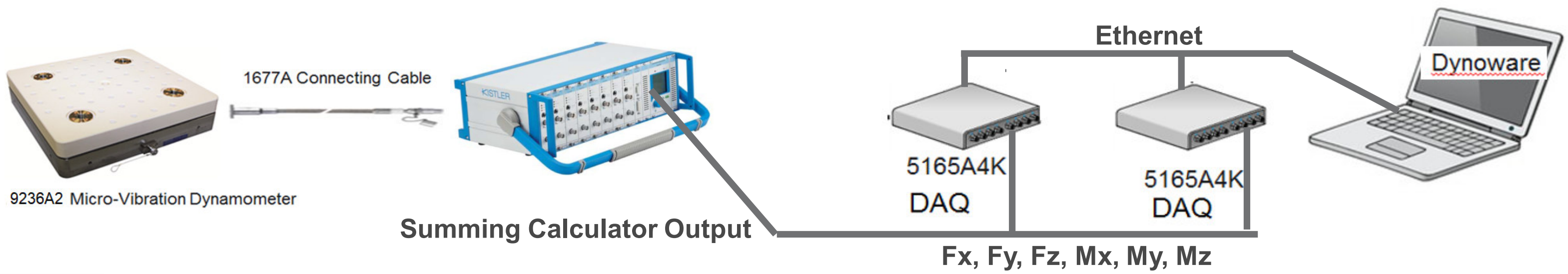


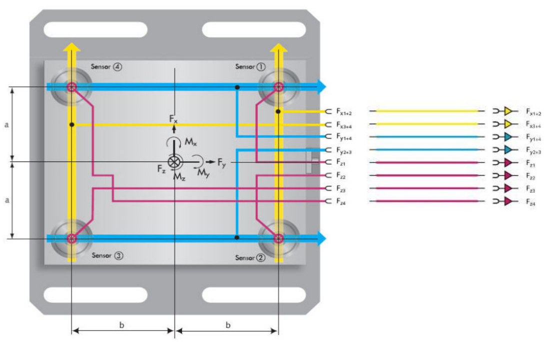
- Conversion of AC power to DC power to power the internal circuitry of an Amplifier results in residual noise.
- Example: S= 8pC/N sensitivity results a rms noise of 0.000032Nrms in a Broadband 1Hz…10KHz band for the 2pC Full Scale Range
- Using a DC powered 5080A Charge Amp with DC Bench Supply provides future flexibility to use Battery if needed. Green Trace – Battery Power Charge amp – Harmonics reduced – DAQ is powered with AC-DC Converter. Power with Battery as well to reduce harmonics



~100pC Range

Other Considerations to Minimize Electrical Noise (ex. EFT)





Calculation of the three forces F_x, F_y, F_z and the three moments M_x, M_y, M_z

$$F_x = F_{x1+2} + F_{x3+4}$$

$$F_y = F_{y1+4} + F_{y2+3}$$

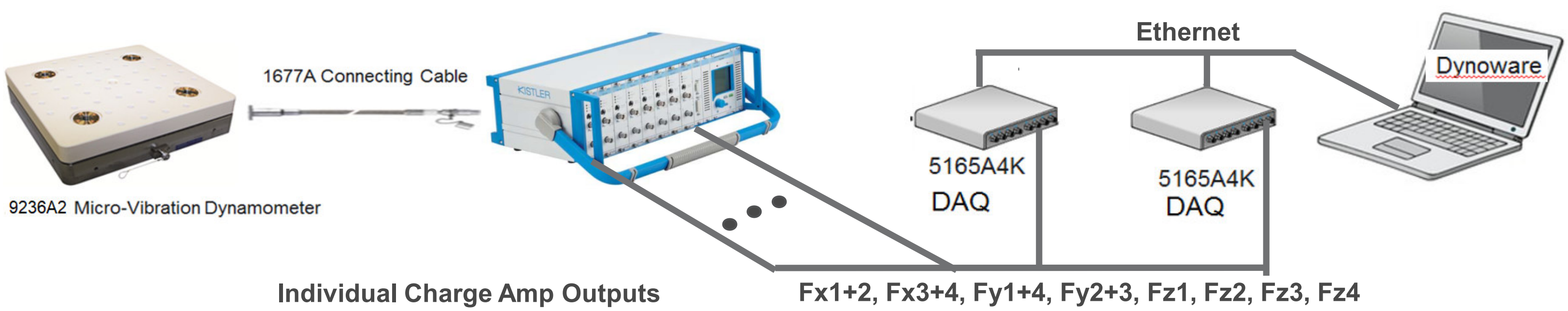
$$F_z = F_{z1} + F_{z2} + F_{z3} + F_{z4}$$

$$M_x = b\,(F_{z1} + F_{z2} - F_{z3} - F_{z4})$$

$$M_y = a\,(-F_{z1} + F_{z2} + F_{z3} - F_{z4})$$

$$M_z = b\,(-F_{x1+2} + F_{x3+4}) + a\,(F_{y1+4} - F_{y2+3})$$

- Multi-Channel Amps with Summing Calculators have some additive Electrical noise
- Noise floor required is Application dependent.
- Use Software (Ex. Dynoware) to compute the 6-Components from component signals (No Additive Electrical Noise)



Harmonics - Increases the Frequency requirements on Dynamometer

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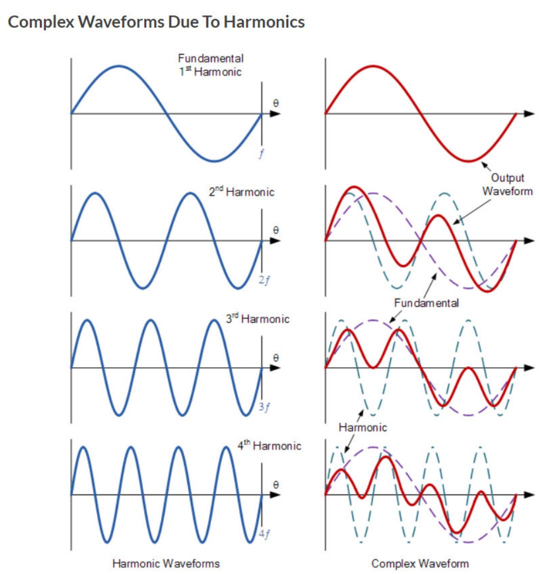
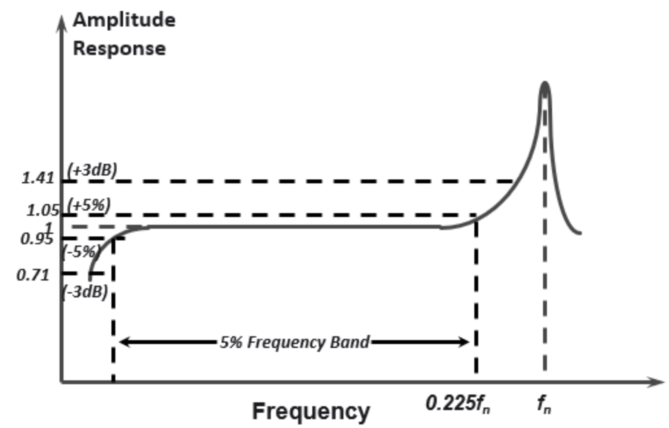
- Harmonics are unwanted higher frequencies which superimposed on the fundamental waveform creating a distorted wave pattern
- “Harmonics” are multiples of the fundamental frequency and can therefore be expressed as: $2f$, $3f$, $4f$, etc. as shown.





- Most piezoelectric sensors follow the upper frequency rule
  - $f_{+5\%} = f_n/5$;
  - $f_{+10\%} = f_n/3$;
  - $f_{+3dB} = f_{+41\%} = f_n/2$

Environmental Considerations: Vacuum Measurements

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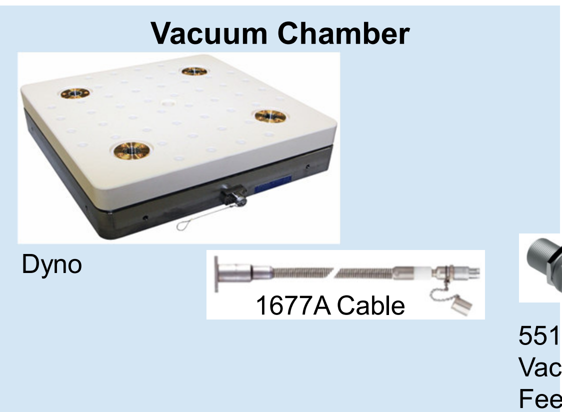
- **Cryo Coolers--** Sound transmission does not travel through a vacuum. Acoustic excitation of structures under test are minimized in a vacuum. Develop Vibration Control Algorithms
- **Thrusters/Propulsion--**Expansion of gases passed by the nozzle exit is very important in deciding the thrust produced. In normal atmosphere, pressure of the gas at the exit is under-expanded for minimum thrust. In vacuum, it is over-expanded which produces higher thrust.



- Vacuum Compatibility / Outgassing
  - Hard Vacuum conditions can cause materials to releases gasses which could contaminate sensitive electro-optics and impair the mission.
- Hermetic sensors can have a natural low outgassing qualities (Gross and Fine Leak Check) . Low outgassing cables are designed without materials known to outgas
  - Test/by Analysis for example per NASA Guidelines “Outgassing Data for Selecting Spacecraft Materials having a TML (Total Mass Loss) of ≤ 1.0 % and CVCM (Collected Volatile Condensable Mass) of ≤ 0.10 % or Less https://outgassing.nasa.gov/)
  - Potential areas of Sensor Leakage: Welds and hermetic connectors on sensors. Thermal Vac Bake Out (ex. MSFC-SPEC-1238)

Micro-vibration Installation Guidelines

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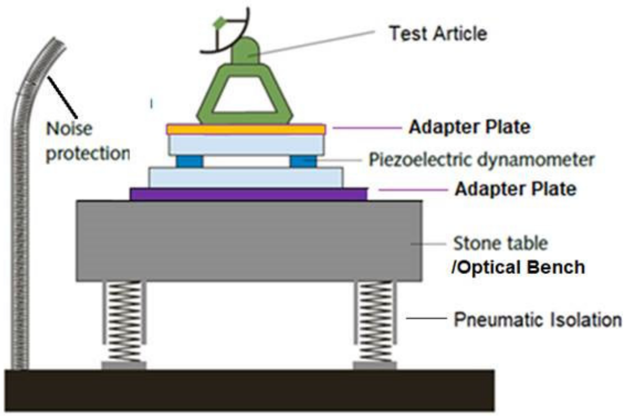

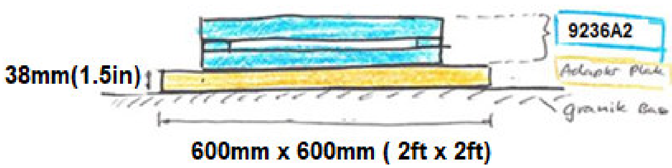

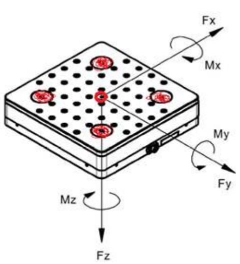

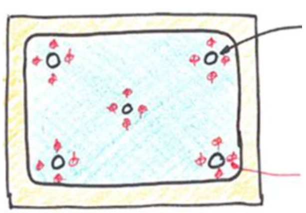

5 Mounting Holes
in adapter plate
to mount dyno

Atleast 4 mounting holes to
the table around each of the
5 Dyno mounting locations

- Pneumatic Isolation acts as a mechanical Low pass filter attenuating ambient inputs to the table
- Granite Table/Optical Table - Provides a stiff and rigid mounting surface with a goal that resonances are minimized and ideally outside the measurement frequencies of interest.
- General rule is that mass mounted to the granite table is <10% Mass of Table.
- The background vibration(noise) for the facility/table setup can be determined by running an ambient noise test once the dyno is connected and the overall set-up is completed.
- Adapter plates to the Table are typically made of stainless steel and ground flat and parallel. The plate is hard mounted to the table using as many fasteners as possible and the dyno is hard mounted to the adapter. Adapter plate from the Dyno to Test Article are typically aluminum

Example: Anechoic Chamber. Granite Block vs. Clean Room – Optical Bench with Primary Air Handler Turned off (other Noise sources present)

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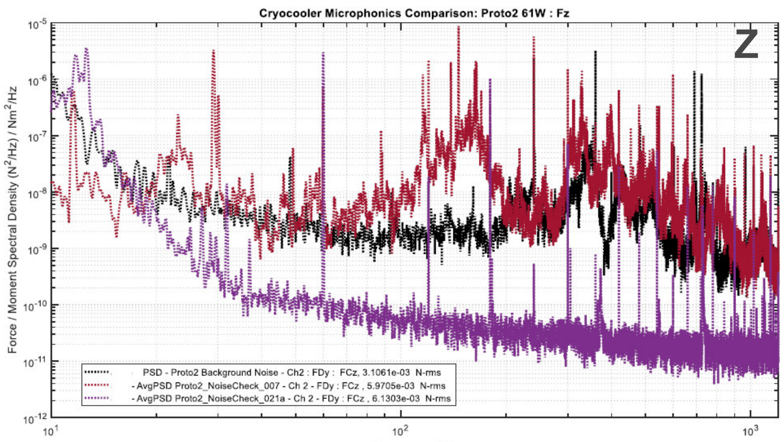
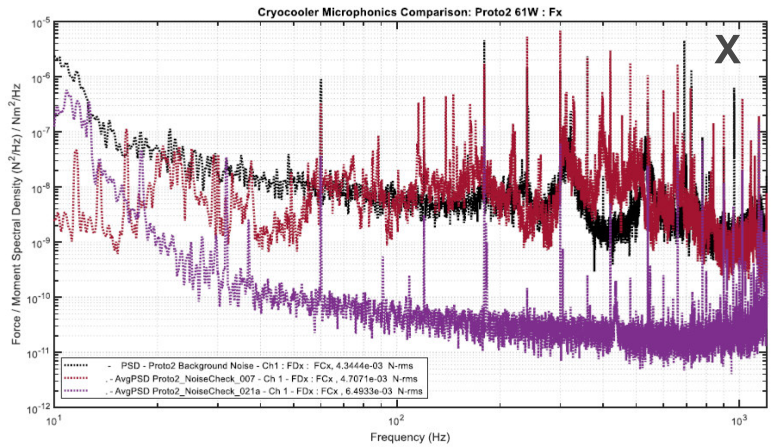
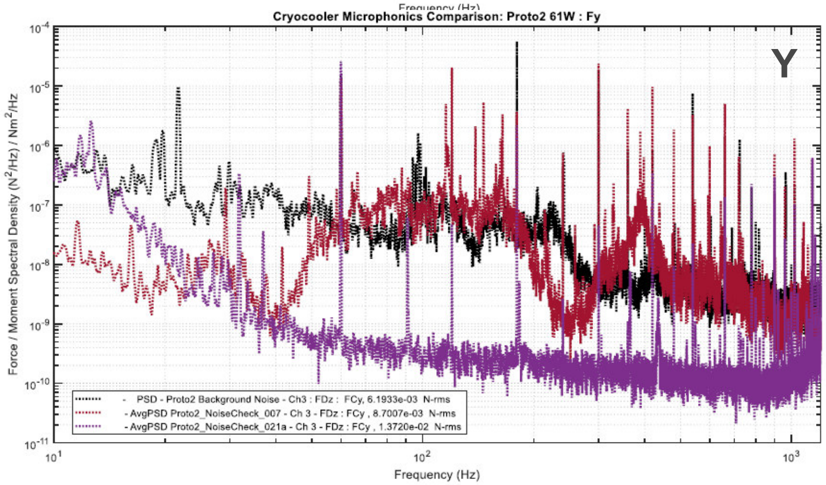
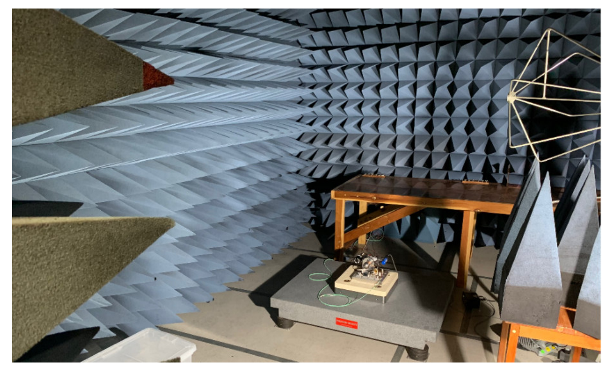






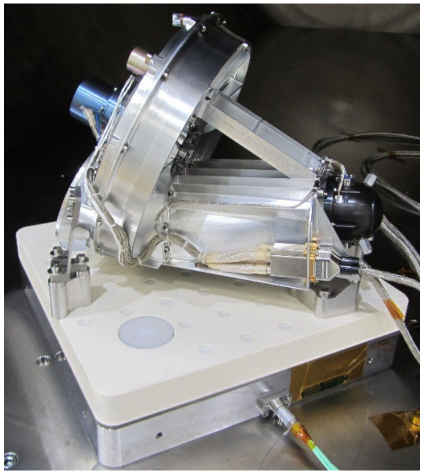
- Granite Block in Anechoic chamber provides nearly 2 orders of magnitude reduction of Noise Compared to Large Optical Bench in Clean Room
- Large Optical Bench appeared more sensitive to acoustics than Granite Block
- Perform Background Noise Checks in the installation



Typical Mechanisms Exported Force and Torque Testing – Micro-vibration Applications

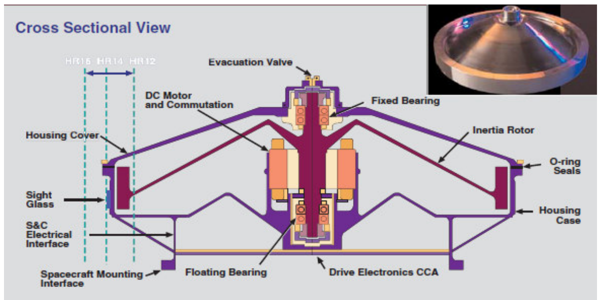
- Mechanism Testing/Exported Force and Torque
  - Cryocooler & EO/IR Imaging
  - Positioners/Antennas
  - Reaction Wheels /Attitude Control
  - Control Moment Gyro/Attitude Control
  - Momentum Wheel Systems/Attitude Control
  - Latches/Clamps/Reaction force/moments Docking
  - Actuators/Motors
  - Booms/Deployable structures/Erectable structures
  - Bearings
  - Dampers/Brakes
  - Deployment devices/Hinges/Linkages
  - Drives/Gearing/Speed Reducers
  - Gimbals/Pointing/Servomechanisms
  - Scanner/Chopper/Mirror/Instrument Mechanisms
  - Release mechanisms (Transient Events, Optical Shutters etc)
  - Robotics
  - Solar-array related mechanisms
  - Soil and particle collection mechanisms
  - Separation/Ejection/Satellite Despin
  - Utility (power, data, fluid) transfer/Umbilical's

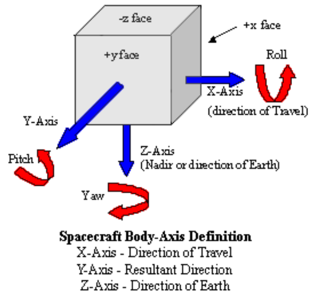
Vibratory and/or transient events (e.g. Release Mechanisms, Optical Shutters, etc). Goal: characterize exported disturbances



Example: Reaction Wheel Mounted on Force Dynamometer Fx,Fy,Fz, Mx,My,Mz

Reaction Wheel – Attitude Control System





Example: 4 reaction wheels in tetrahedral configuration

- Reaction wheels control the satellite attitude (roll , pitch , yaw) without the use of thrusters, which reduces the mass needed for fuel.
- The electric motor attached to a flywheel (Rotor) which, when its rotation speed is changed, causes the spacecraft to counter-rotate proportionately through conservation of angular momentum.
- Reaction wheels rotate a spacecraft only around its center of mass and are not capable of moving the spacecraft from one place to another -- Thrusters are used for this
- Temporary changes in its speed result in small changes in angle. The wheels therefore permit very precise changes in a spacecraft's attitude (roll, pitch, yaw).
- Wheels are often used to aim spacecraft imaging cameras , radars or telescopes. Imbalances in the rotor and bearing vibrations cause “Exported Force & Torque” to the satellite which can affect the mission.
- Example ---3–Axis arrangement +1 spare for a total of 4 reaction wheels to control Attitude Control

Disturbance Induced by a Reaction Wheel Can affect the Mission

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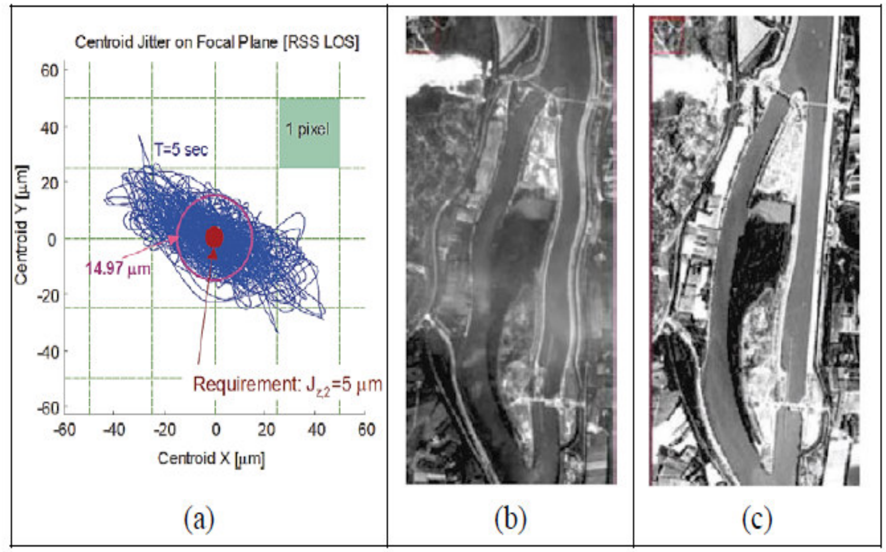
- Reaction Wheels correct for Attitude position without using Fuel
- Dynamic forces induced by Attitude Determination and Control System (ADCS) generates micro-vibration which affects the satellite pointing.
- Characterization of ADCS and related components is required to manage disturbance sources.
- Micro-vibration usually causes problems for optical imaging systems onboard Earth Observation satellites. The major effect of micro-vibration is the excitation of the support structures for the optical elements during imaging operations **which can result in severe degradation of image quality** by smearing and distortion.

Exported Force and Torque (EFT) Testing

- Mount the Mechanism on Fixture/ Dynamometer.
- Characterizing mechanism disturbances influences the design, compensation, balancing and/or isolation/ damping methods to reduce the effects on the satellite mission.



Satellite Pointing (blue line), which is worse than requirement (red dot), resulting in image distortion (b); image without distortion (c)

Example: Reaction Wheel Test

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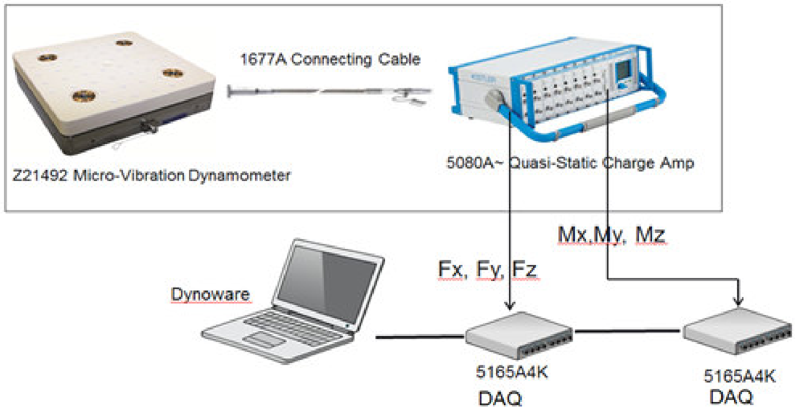
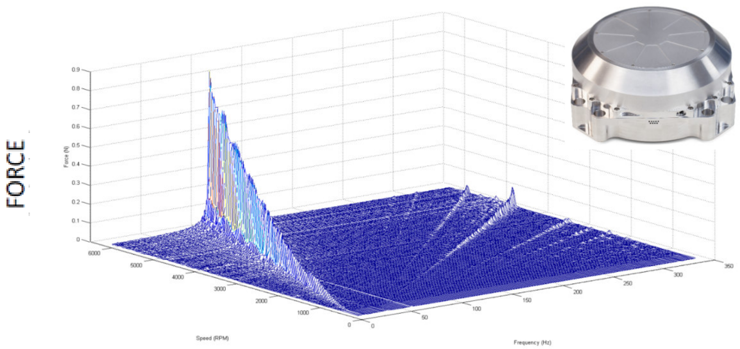
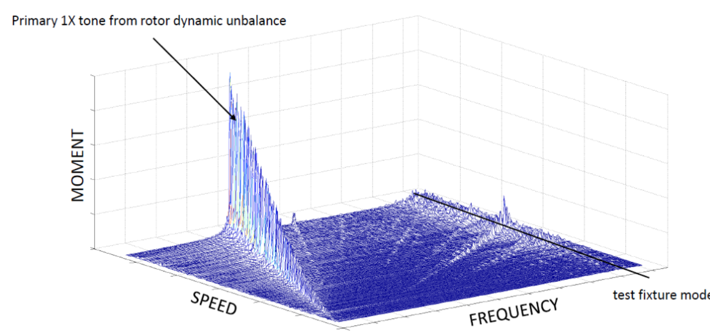


			9236A1	9236A2
Noise RMS (1 Hz ... 10 kHz)[1]	F_x, F_y	N	≈0,7 * 10^{-3}	≈0,7 * 10^{-3}
Broadband	F_z	N	≈1,5 * 10^{-3}	≈1,5 * 10^{-3}
	M_x, M_y, M_z	N·m	≈4,0 * 10^{-4}	≈4,0 * 10^{-4}

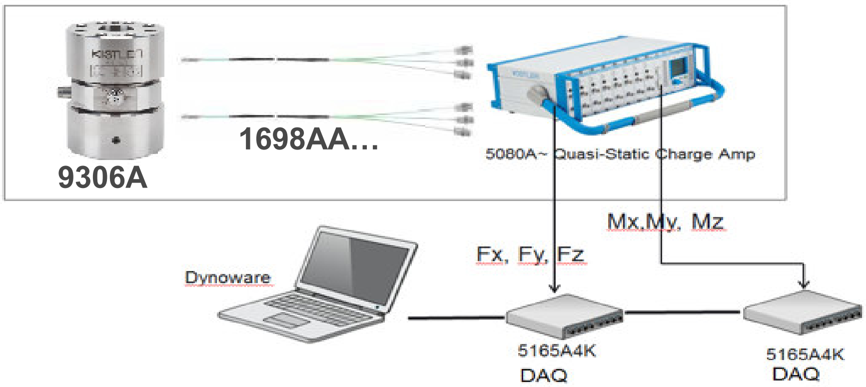


- Waterfall plot of radial force output from a reaction wheel. This is a typical shows how the micro-vibration force output from the wheel varies with speed vs frequency.
  - Static: The primary ridge on the graph is created from the static unbalance of the rotor, where the force shown is equal to **F = m*r*ω^2** and the **m*r** term in that equation is the rotor's static unbalance. The smaller ridges showing in the higher frequencies tend to be running harmonics of the bearing/rotor system.
  - Dynamic: The primary ridge on the graph is created from the dynamic unbalance of the rotor, where the Moment shown is equal to **M = m*r*d *ω^2** and the **m*r*d** term in that equation is the rotor's dynamic unbalance. The smaller ridges showing in the higher frequencies tend to be running harmonics of the bearing/rotor system.

- Spacecraft designers use this information to create math models of the disturbance output from the reaction wheels to evaluate the effects of that jitter on their instruments.
- Microvibration Measurements down to 0.01mN (narrowband 1Hz band).possible
- EFT is used to both characterize and balance wheel to minimize Jitter

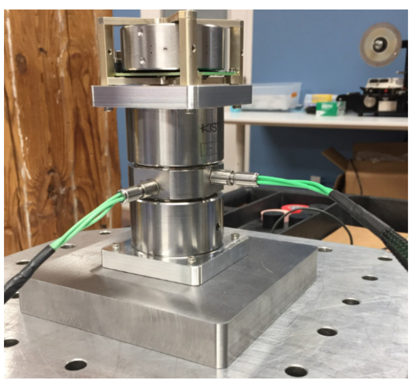


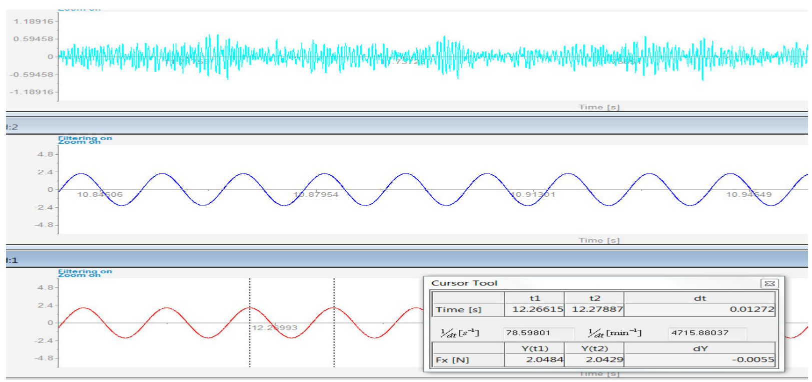
9306A 6-Component Sensors: Exported Force and Torque Testing of Reaction Wheel



f_n (F_x, F_y, F_z)	kHz	≈18
f_n (M_x, M_y, M_z)	kHz	≈11

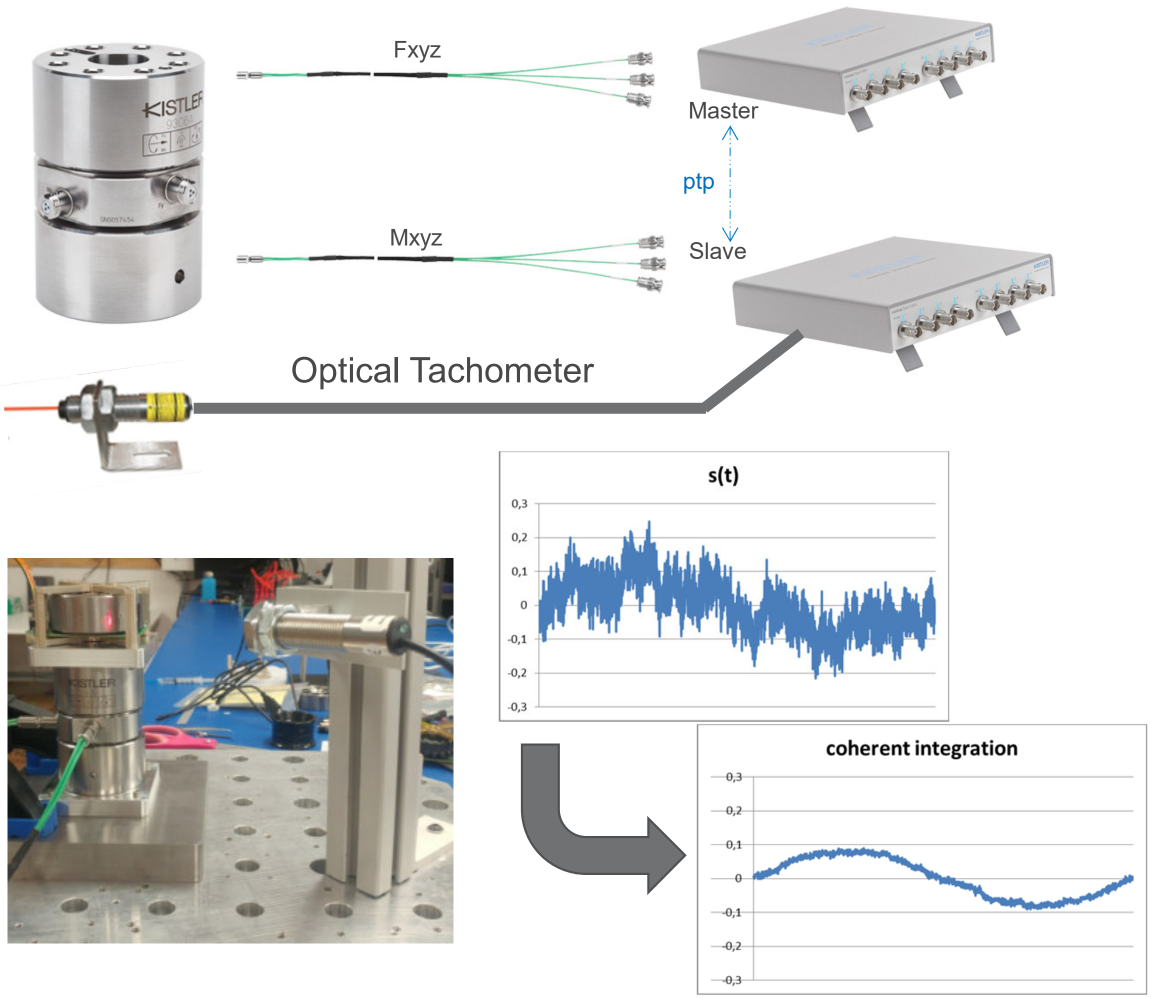
- 6-Component Force/Torque Link
- 9306A Specifications:
  - Fx,y ≤ +/- 5 kN (±1124 lbf)
  - Fz ≤ -5 … 10 kN (-1124 … 2248 lbf)
  - Mx,y,z ≤ +/- 200 Nm (±147 ft·lb





500r/s (80Hz)
Typical Range:
50r/s to 600r/s

Exported Force and Torque Set-up: Coherent Integration



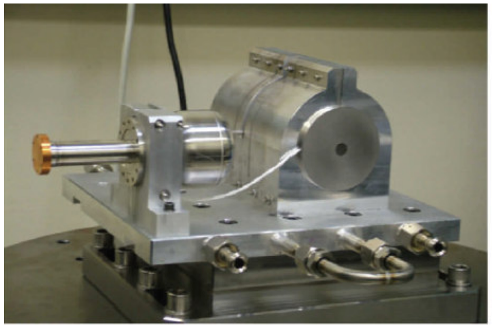
- At the lower rotational speeds(ex. 50r/s) , the rotor imbalance disturbance is small where the resulting signal to noise ratio is lower compared to higher speed characterization.
- A fixed rotational speed gives the opportunity to sample the signal always at the same starting point by the use of an optical tachometer which will be the key to synchronize each time domain block.
- Then, an angular coherent integration can be done to improve SNR by averaging of nondeterministic signal
- Coherent angular averaging helps to reduce by roughly 5 the noise level and helps to minimize effect of vibration source non coherent with the reaction wheel (Environment)

Satellite Cryocoolers

- Active Cryo Coolers (ex. Stirling, Pulse Tube, Joule Thompson) exhibit different efficiency,/temperature/vibration and use closed thermodynamic cycles to achieve lower cold-end temperatures at the cost of electrical input power.
- Cool Detectors IR, Gamma-Ray, X-Ray, Imaging Systems etc
- Vibration Disturbances mainly caused by compressor and cryogen (ex. Helium/Hydrogen) liquid to gas transitions for the cooling cycle
  - Employ moving parts to cycle the Cryogenic media around a thermodynamic cycle. The fluid is typically compressed at room temperature, precooled in a heat exchanger, then expanded at some low temperature
  - Active vibration suppression reduces unbalanced forces to levels inline with the mission requirements.
  - Passive vibration suppression protects the equipment from damage due to Launch loads and improves operational performance .

- The key sensitivity is the extent to which the cooler's vibration **harmonics** excite spacecraft resonances and prevent on-board sensors from achieving their operational goals with respect to resolution and pointing accuracy. Blur Image

- **Exported Force and Torque(EFT)**
  - Characterizing mechanisms disturbances and determining design and / or compensation methods to reduce the effect on the satellite mission are of interest
    - Vibration based on operational conditions for example with different compressor or displacer strokes, cold-block temperatures, and drive frequencies.
    - For space coolers with closed-loop vibration suppression systems, characterizing the effectiveness is an objective



Active Thermal Architecture (ATA) 6U CubeSat Cryocooler System

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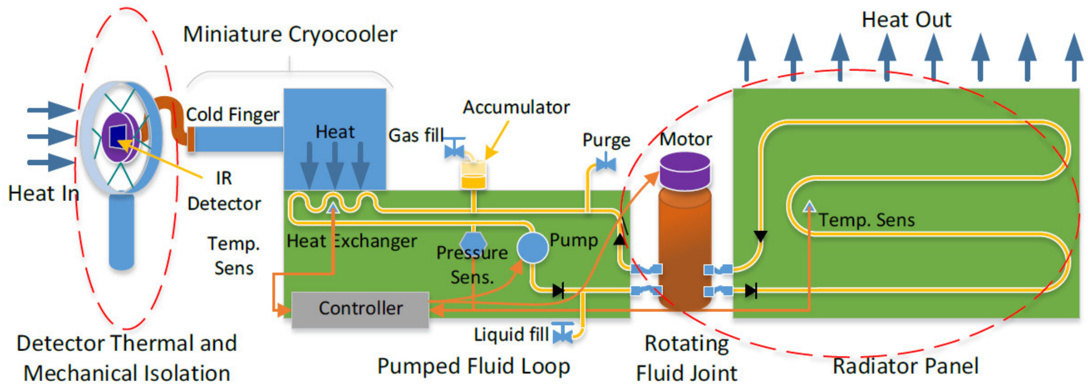
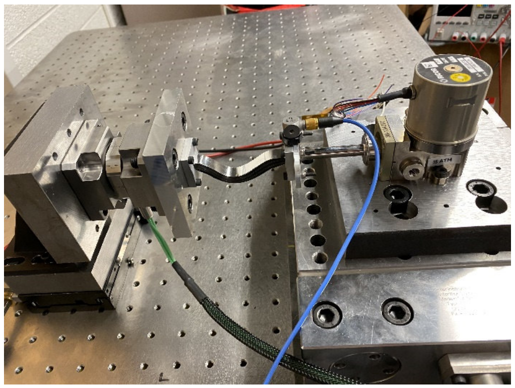


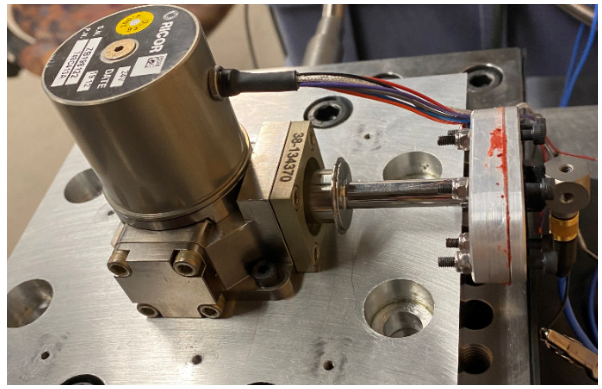
Utah State University- Center for Space Engineering

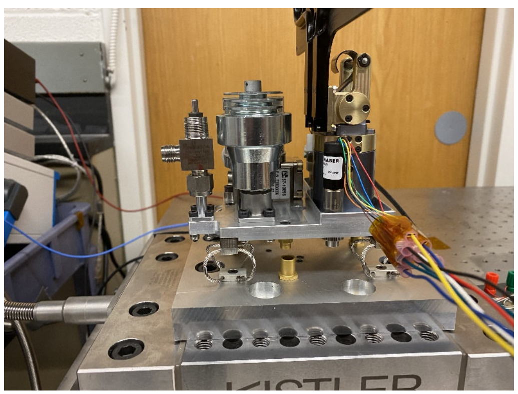
- Dr. Charles Swenson, Director
- Dr. Luke Anderson, R&D
- Joel Mork, R&D

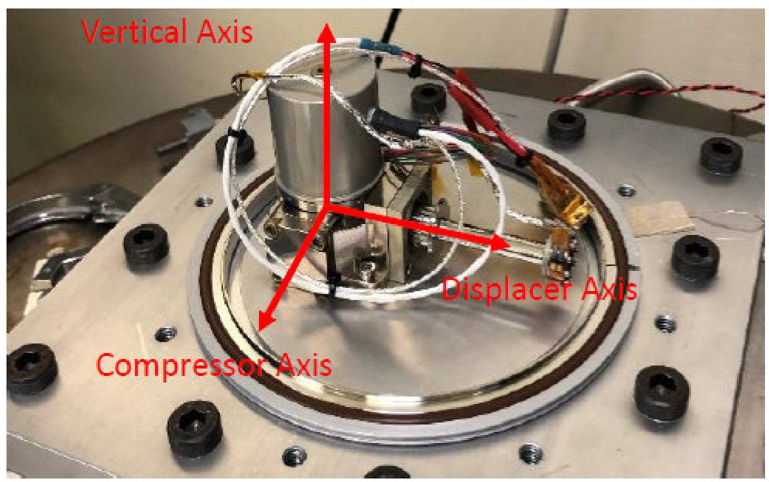
- Cryocooler- Closed lop Circulation of Helium Gas to cool cold finger
- Thermal Strap- Pyrolytic Graphite Sheet (PGS) – provides High Thermal Conductivity and high flexibility
- Optical Detector – Cooled by Thermal Strap/ Cryocooler
- Wire Rope Isolators – Passive Cryocooler assembly mounts used to reduce exported vibration (Braided Stainless Steel)
- Heat Exchanger + Pump+ Rotating Fluid Joint + Radiator Panel.
  - Circulates Novak 7000 Heat Transfer Fluid @ 60-75psi (4-5 Bar) though closed loop system. Pumps typically noisy
- Particle Damper – Mounted at Cold tip to lower operational vibration as well as launch survivability
  - 300micron Stainless Steel Particles allowed to freely move in a reservoir
- Radiator Panel – Motorized assembly to radiate heat to space – Typically “edge on” to sun to minimize heat loading

Active Thermal Architecture (ATA) 6U CubeSat Cryocooler System









Active Thermal Architecture (ATA) 6U CubeSat Cryocooler System

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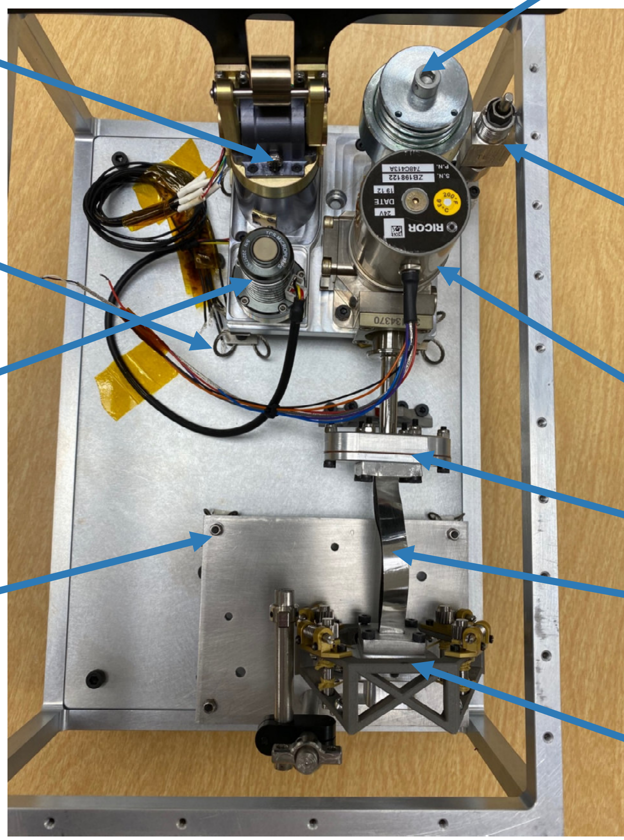
Rotary Union and radiator. With micro stepper motor hidden behind

Floating on wire rope isolators

Micro Pump. Pumping Novec 7000

Floating on wire rope isolators



Accumulator for Novec 7000 in pumped fluid loop.

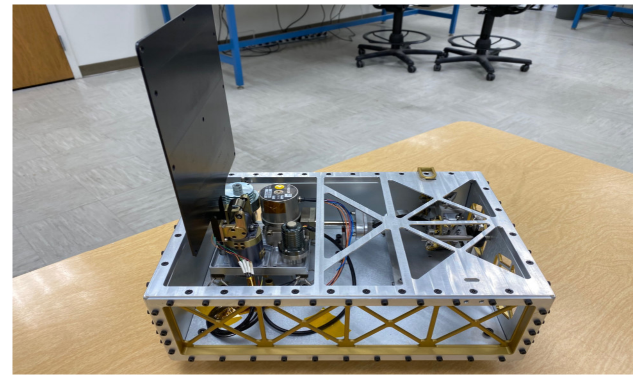
Purge and Fill Valve. Not realistic for an actual flight. You would want a smaller one

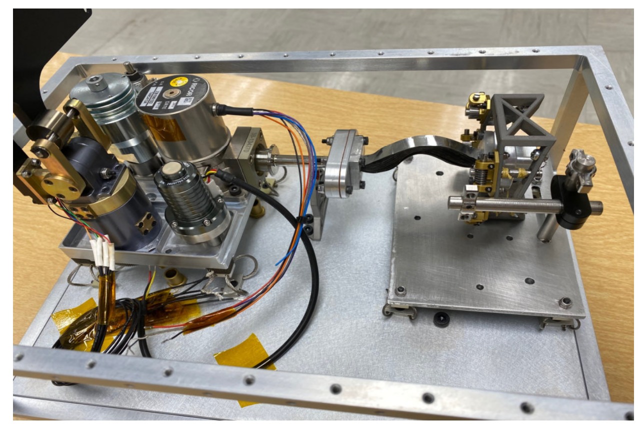
Cryocooler. Closed loop with Helium Gas

Cold tip and particle damper

Thermal Link

Kevlar Isolation Mount + Optical Detector





Total Cryocooler Assembly: Cumulative Exported Force transferred to the body of the CubeSat (Kistler 9139AA)

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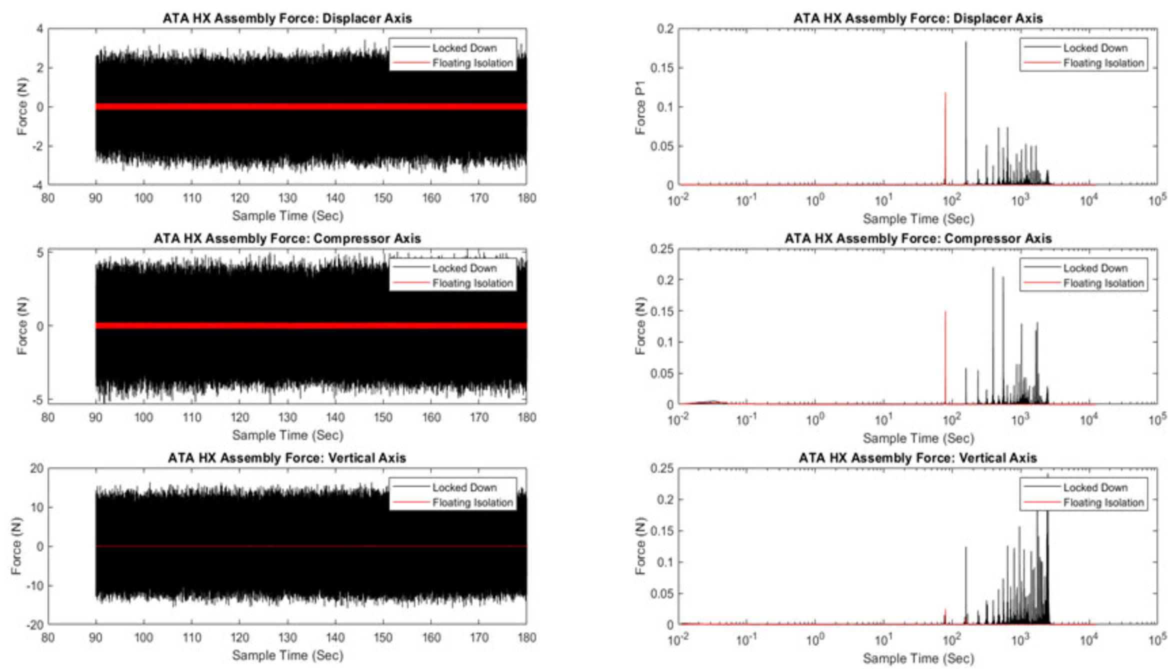
- Combined forces of the pump and cryocooler.
- Cryocooler is in full power “cooldown” mode
- The pump is the MGD1000F micro-gear pump operating at 40% capacity with a working fluid of IPA
- The stepper motor is not on, but it was determined that for a regular operating mode as shown above (Rpm’s between 50 and 100) the stepper motors contributions are negligible
- Notice that wire rope isolators reduce the exported forces and moments of the combined and fully operational ATA system.



Total Cryocooler Assembly: Cumulative Exported Moment transferred to the body of the CubeSat (Kistler 9139AA)

KISTLER
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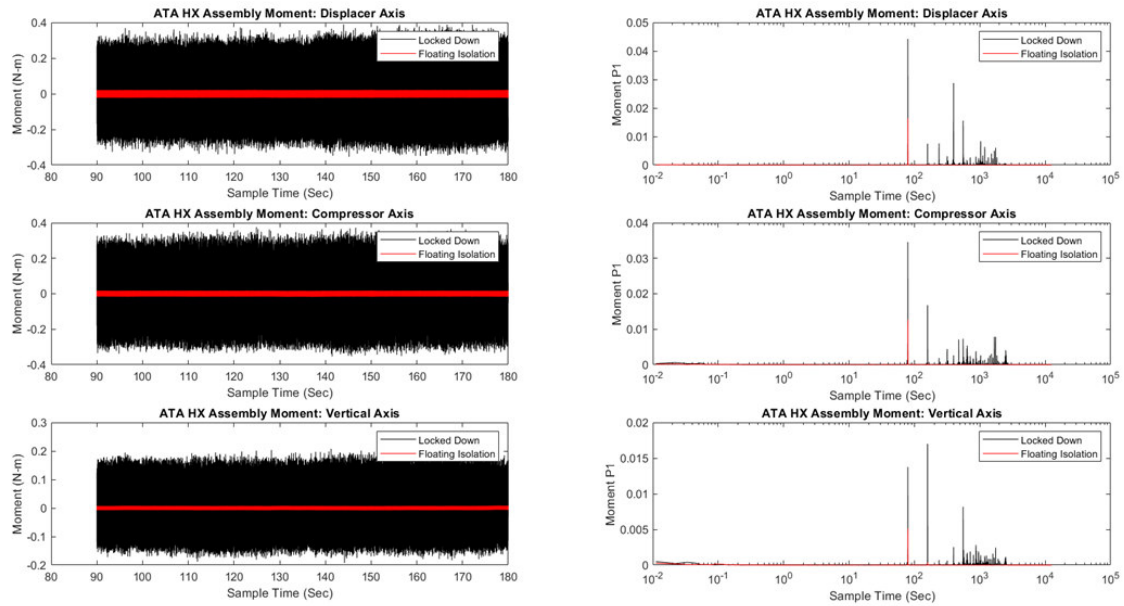
- Combined forces of the pump and cryocooler.
- Cryocooler is in full power “cooldown” mode
- The pump is the MGD1000F micro-gear pump operating at 40% capacity with a working fluid of IPA
- The stepper motor is not on, but it was determined that for a regular operating mode as shown above (Rpm’s between 50 and 100) the stepper motors contributions are negligible
- Notice that wire rope isolators reduce the exported forces and moments of the combined and fully operational ATA system.



Total Cryocooler Assembly: @ Cold Tip (Kistler 8763B) Acceleration

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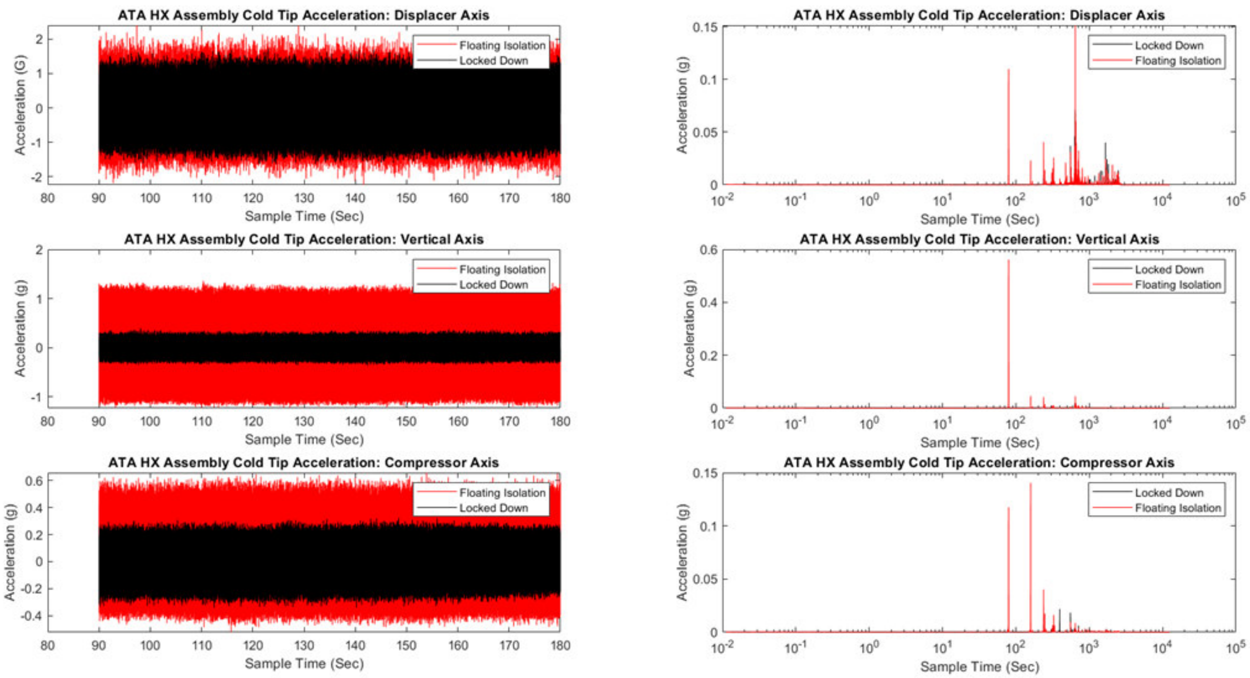
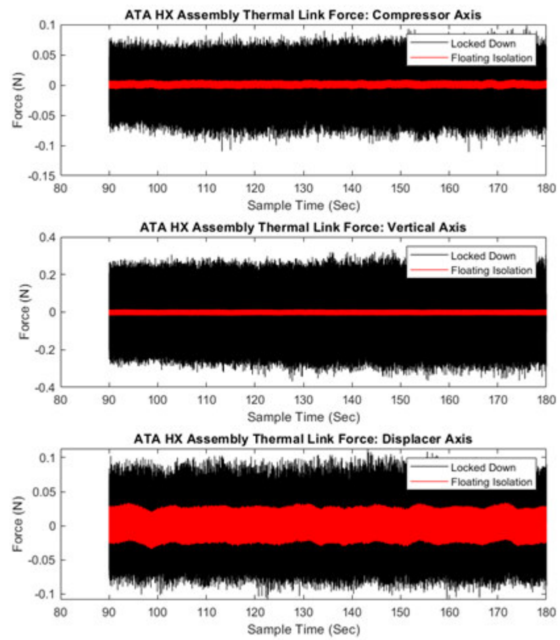
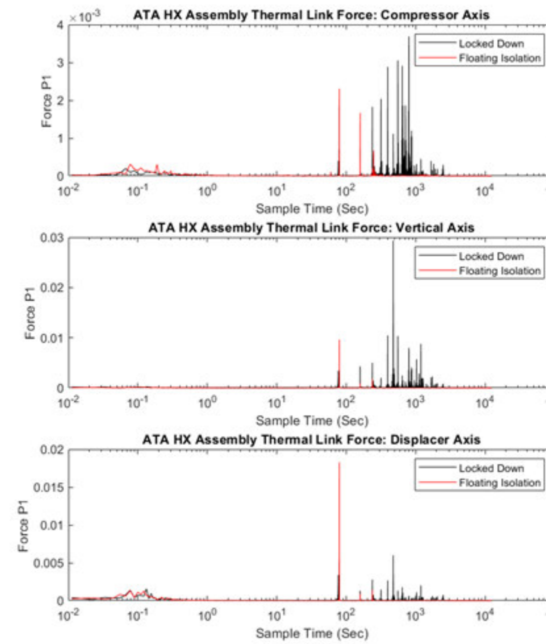
- Combined forces of the pump and cryocooler.
  - Cryocooler is in full power “cooldown” mode
  - The pump is the MGD1000F micro-gear pump operating at 40% capacity with a working fluid of IPA
  - The stepper motor is not on, but it was determined that for a regular operating mode as shown above (Rpm’s between 50 and 100) the stepper motors contributions are negligible
  - It should be noted however, that for cold tip acceleration the wire rope isolators increase the relative acceleration value.
    - Cryo cooler has a 79 Hz driving frequency.
    - Observed that Wire Rope isolators amplify <~100Hz and attenuate at higher Frequencies.

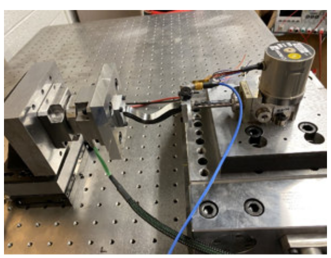


Total Cryocooler Assembly: Exported Force (Kistler 9347C) @ Thermal Link

- Combined forces of the pump and cryocooler.
  - Cryocooler is in full power "cooldown" mode
  - The pump is the MGD1000F micro-gear pump operating at 40% capacity with a working fluid of IPA
  - The stepper motor is not on, but it was determined that for a regular operating mode as shown above (Rpm's between 50 and 100) the stepper motors contributions are negligible
  - Notice that wire rope isolators reduce the exported forces and moments of the combined and fully operational ATA system.
  - Forces at the Thermal Link Reduced by the wire rope isolators







Satellite Precision Pointing Mechanism

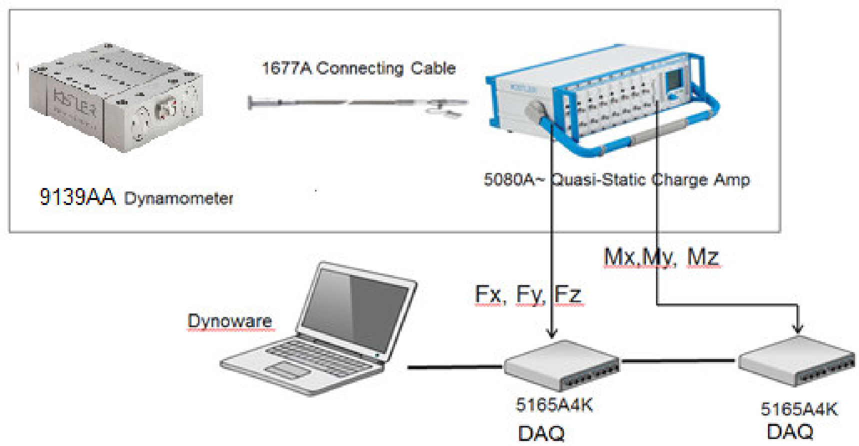
- Positioners/ Gimbals/Stepper Motors
  - Antenna / Solar array positioning, Hold-down and release mechanisms
  - Disturbances caused by motor/shaft resonances, and potential interactions/ structural response
  - Stepper motors- are electromagnetic devices that converts digital pulses into mechanical shaft rotation.
    - Advantages of step motors are low cost, high reliability, high torque at low speeds and a simple, rugged construction that operates in almost any environment.
      - Precise positioning and repeatability of movement since good stepper motors have an accuracy of 3–5% of a step and this error is non-cumulative from one step to the next.
      - Excellent response to starting/stopping/reversing.
      - Very reliable since there are no contact brushes in the motor. Therefore, the life of the motor is simply dependent on the life of the bearing.
    - A disadvantage in using a stepper motors can be a resonance effect often exhibited at low speeds and decreasing torque with increasing speed.

Exported Force and Torque

  - Characterizing mechanisms disturbances and determining design and / or compensation methods to reduce the effect on the satellite mission are of interest.

Satellite Antennas/Positioners

- A Satellite constellation can provide voice and data coverage to satellite phones as well as other commercial functions such as imaging, weather etc..
- Antennas may generate a high-gain Tx/Rx beam, enabling a tracking link to a ground station. Antennas can downlink data and/or be used for Inter Satellite Link antennas for example. Includes Actuators, Gimbals, Precision positioning systems etc..
- Antenna solution, is capable of steering the beam over a given scan range
- A design goal is that the mass of this steerable antenna is very low considering that it includes gimbals, a rotary joint and reflectors. (ex< 3.6Kg (8lb))
- If antenna/positioner disturbances are high they can affect the mission. Desire to have low jitter solutions. Characterizing the disturbances in 6DOF can be accomplished through a Dynamometer Plate



Typical Antenna Positioning Measurements

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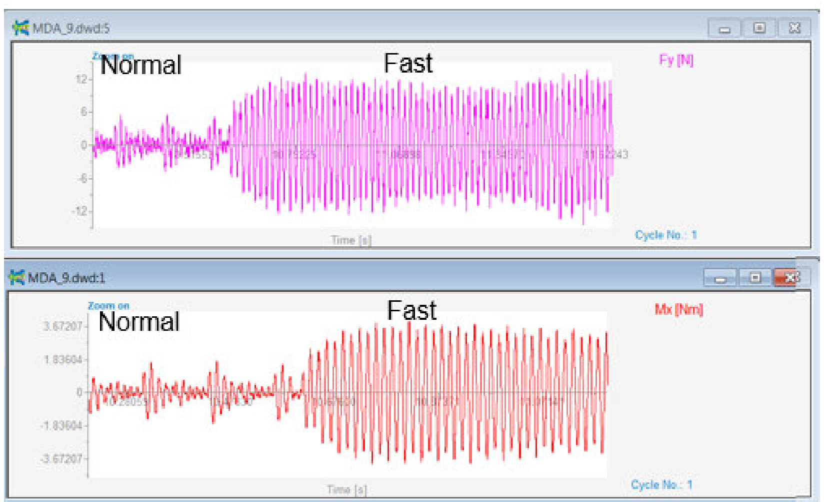
- ‘Normal’ mode has lower Motor RPM compared to ‘Fast’ mode is the higher
- For a ‘stepper’ motor, each step sends an impulse or shock to the structure of the antenna. the natural frequency of the Fast mode, in steps/second, is close to the natural frequency of the antenna.
- There is coupling of the motor excitation with the natural frequency of the antenna that was amplifying the forces. That is why the forces generated in Fast mode were bigger that the ones generated in normal mode
- 6DOF measurements provide design inputs for structural analysis and dynamic response of Antenna. Mounting Mechanisms to large force plates with high frequency capability – are used for such evaluation



Satellite Release Mechanisms - -Transient Event Considerations

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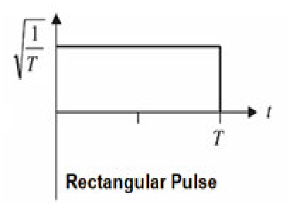
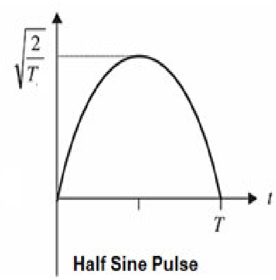
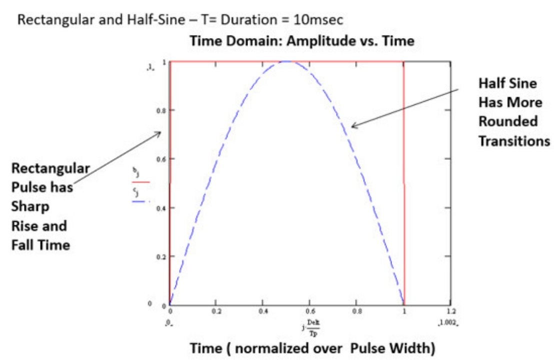
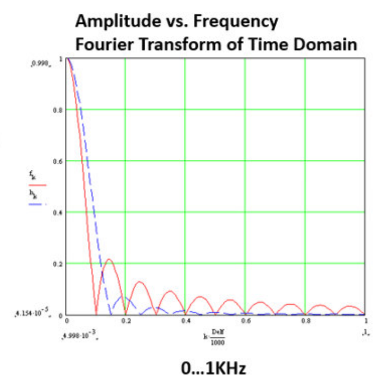
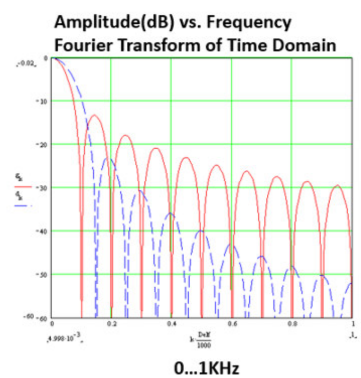
- Analog Bandwidth (Hertz, Hz, 1/sec) – Defines the acceptable bandwidth definition to represent the signal of interest. Insufficient analog bandwidth leads to distortion of the desired signal.
- The required analog bandwidth is the portion of signal frequency extent that contains most of the signal energy to represent the signal of interest.
- For example, the frequency extent at which the signal bandwidth contains 50%, 90% or 99% of energy. The decision on what rule to use to define analog bandwidth is critical where typically the essential bandwidth is between 90% to 99% of the energy.
- The energy is the integral of the energy spectral density. Short duration transient events have frequency bandwidth that is inversely proportion to the duration T
- Example
  - Rectangular Pulse (Red); 90% = 0.85/T; 99% ~10.3/T
  - Select 99% as the required analog bandwidth definition = 10.3/T
  - Half Sine Pulse (Blue); 90% = 0.78/T; 99% = 1.18/T
  - Select 99% as the required analog bandwidth definition = 1.18/T











Release Mechanisms - -Transient Event Considerations

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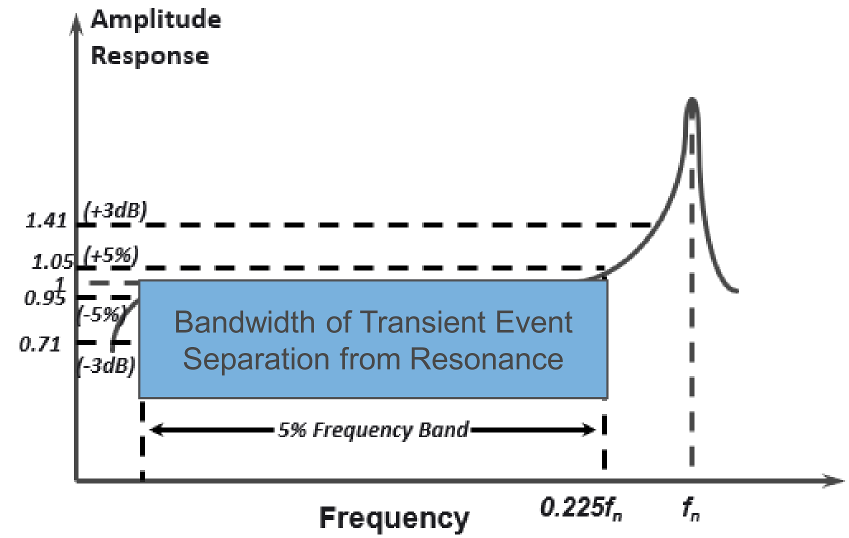
- Need Frequency Separation between required bandwidth needed and the Natural Frequency of the Dynamometer
- Range the dynamometer appropriate to keep response in the linear range (No Saturation)
- Use Low Pass Filtering to remove the resonance from the measured response.
  - Often this can be a post processed solution
- Remember Relationships of Natural Frequency to usable frequency of dynameter



- Most piezoelectric sensors follow the upper frequency rule
  - $f_{+5\%} = f_n/5$;
  - $f_{+10\%} = f_n/3$;
  - $f_{+3dB} = f_{+41\%} = f_n/2$

FLVT: Environmental Testing for Launch and Space Vehicles

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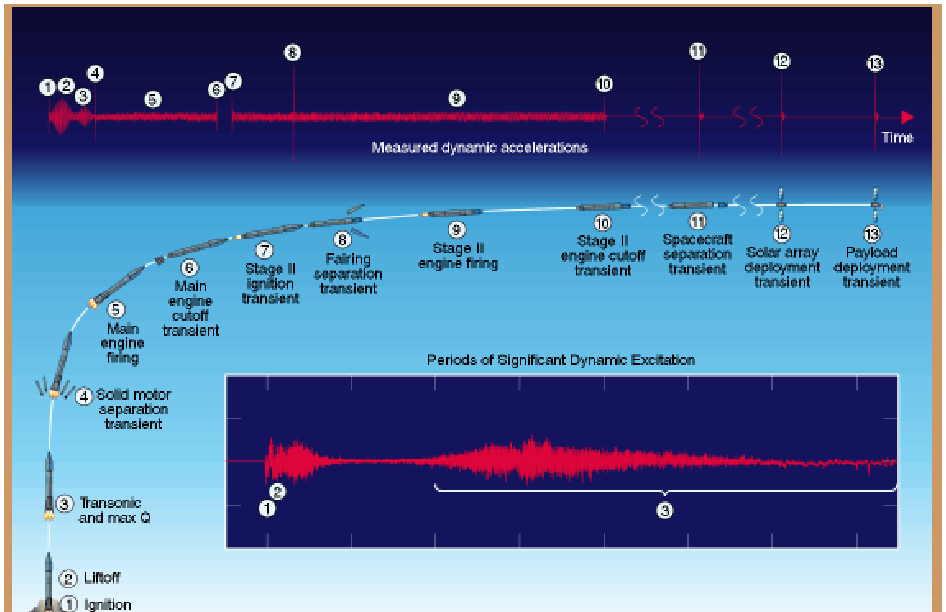
- Space systems must endure a physically stressful journey from the launch pad to their final destinations. Adequate testing can help ensure they survive the trip.



A typical Delta II mission profile and the associated accelerations due to acoustic, vibration, and shock environments during liftoff, transonic and maximum-dynamic-pressure (max Q) flight, main engine cutoff, secondary engine cutoff, stage separation, payload fairing separation, and spacecraft separation. The acceleration time history is processed for each significant dynamic event and transformed into frequency plots representing acoustic-pressure levels, vibration, and shock

Ref: Environmental Testing for Launch and Space Vehicles, E. Perl, T.Do, A.Peterson, J.Welch

Forces During Launch and Flight

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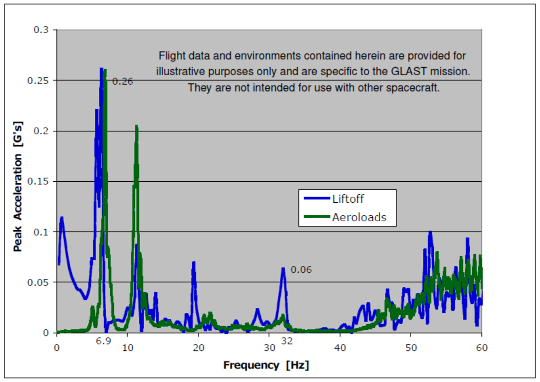


Figure 24—GLAST Spacecraft Z-Axis (Thrust) Interface Flight Accelerations

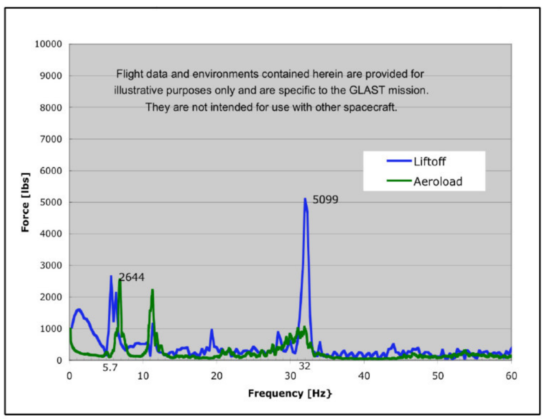


Figure 25—GLAST Spacecraft Z-Axis (Thrust) Flight Base Forces

- Acceleration and forces during lift off and flight can reach considerable levels
- These results were captured with a specially prepared satellite with force sensors and accelerometers (GLAST mission- Gamma-ray Large Area Space Telescope)
- The first axial mode of the spacecraft is 32Hz. Lower frequencies are caused by the launch vehicle

Environmental Testing

- Environmental Stress Screening (ESS)/ Workmanship Screening includes a wide variety of Testing

- Testing Includes Components, Subsystems and Spacecraft/Payloads. Testing Includes
  - Vibration Testing (e.g.. Sine, Random, Transient)/**Force Limited Vibration***
  - Shock Testing (Pyro, Separation, Mechanical)
  - Vibroacoustics
  - Electromagnetic Compatibility/Interference
  - Thermal Vacuum Chamber

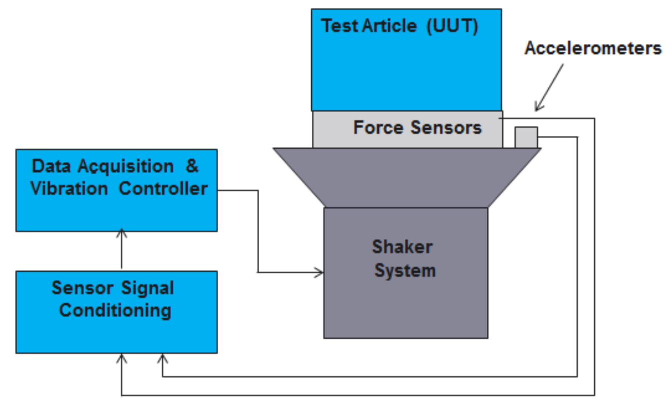
* NASA-HDBK-7004C, Force Limited Vibration Testing

Force Limited Vibration

Ref: NASA-HDBK-7004C, Force Limited Vibration Testing

- Traditional vibration testing controls the input acceleration to the frequency envelope of the flight data. Limiting the test acceleration responses to those predicted for flight is highly dependent on analysis & usually requires limiting the acceleration responses at many locations - large test items. Could result in over-testing, destruction, overdesign and/or cost/schedule impact if the UUT is broken.

- Alternately, limiting the input force at the fixed base resonances of the UUT is less dependent on analytical models and provides automatic notching w/o over-testing. Force limiting automatically notches the acceleration at a test item's resonances, by measuring and limiting the reaction force between the test item and the shaker table.



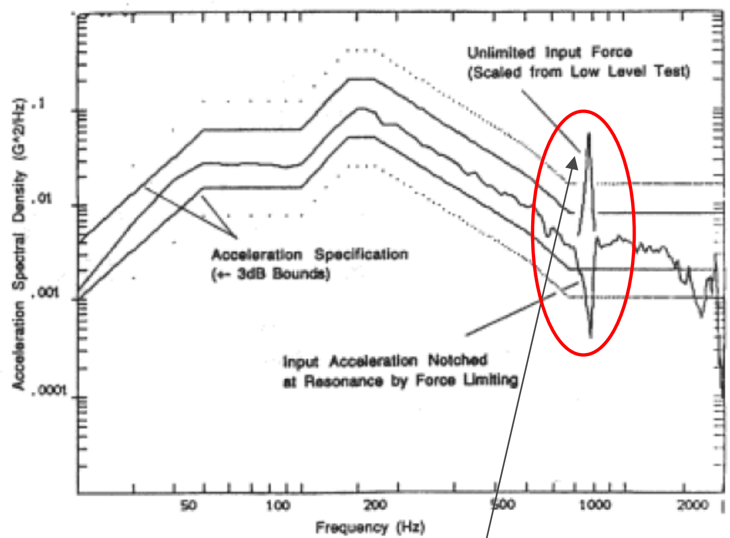
- Force Limiting replicates the test article resonant response for the actual flight mounting condition. Flight equipment is typically mounted on a relatively lightweight structure, which has a mechanical impedance comparable to that of the mounted equipment (Shakers have near infinite mechanical Impedance).

- Real time "Extremal Control" - controls UUT vibration based on the maximum of several inputs (e.g. F, A)
  - At frequencies other than the test item resonances, the acceleration test specification usually controls the test level. However, at the test item resonances, the base reaction force increases where the force control specification limits the input force.
  - Force Control Limits – are based on legacy flight data, analysis and added safety margins.

FLV Example: Z-axis Random Vibration Test

- With force limiting, the controller automatically notches the acceleration input by the amount the unlimited force signal would have exceeded its specification, i.e. about 10 dB.
- The notch is very sharp and approx. the mirror image of the force peak.
- It is impractical to manually apply sharp notches. Also without the force sensors to detect the frequency of the force peak, it would be difficult to place the notch at the correct frequency.
- Force limiting is automatic and less dependent on analytical models and is more convenient.

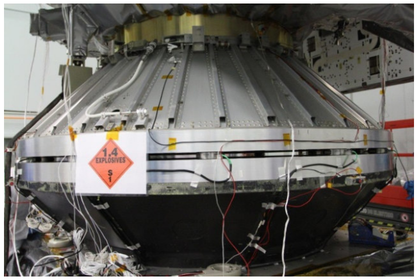
Ref NASA- Report1403



Force would have been in the full level test if the Force were not limited

Example Global Precipitation Measurement (GPM) Satellite

- GPM Monitor rain and snow activity worldwide
- Payload mass approx. 7000 lbs. (3,175kg)
- The force ring approx. 350 lbs.(158.8kg)
- Frequency range of interest 5Hz to 70Hz
- 3 inch (76.2mm) thick top and bottom plate
- Ring Diameter ~102 inch (2.6m)
- Qty 12, Type 9077C load Cells
- Preload to 60,000lb (267kN) , star pattern, 4 step preload (25%, 50%, 75% and 100%)
- Custom 1in (25.4mm) diameter bolts with Delran spacers to center Force sensor



Example: 12 Sensor FLV Equation Implementation

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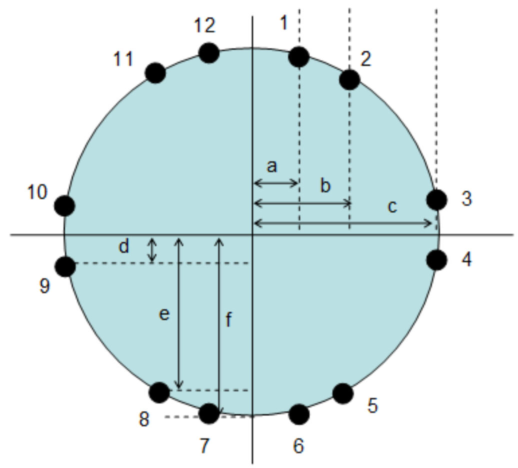

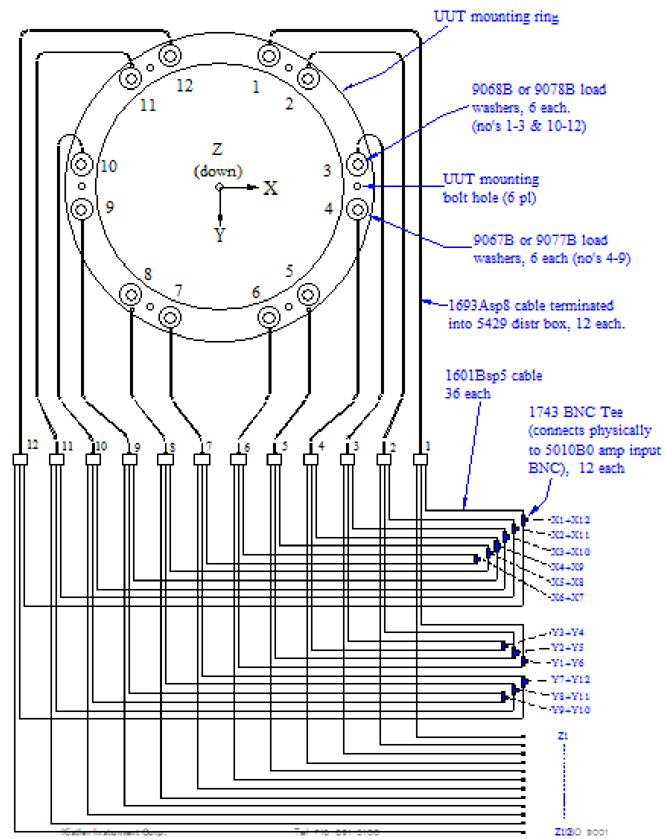

$Fx = \Sigma\, Fx_i \;\; i = 1\ldots12$

$Fy = \Sigma\, Fy_i \;\; i = 1\ldots12$

$Fz = \Sigma\, Fz_i \;\; i = 1\ldots12$

$Mx = d\,[(Z_4+Z_9)-(Z_3+Z_{10})] + e\,[(Z_5+Z_8)-(Z_2+Z_{11})] + f\,[(Z_6+Z_7)-(Z_1+Z_{12})]$

$My = a\,[(Z_7+Z_{12})-(Z_1+Z_6)] + b\,[(Z_8+Z_{11})-(Z_2+Z_5)] + c\,[(Z_9+Z_{10})-(Z_3+Z_4)]$

$Mz = a\,[(Y_1+Y_6)-(Y_7+Y_{12})] + b\,[(Y_2+Y_5)-(Y_8+Y_{11})] + c\,[(Y_3+Y_4)-(Y_9+Y_{10})] + d\,[(X_9+X_4)-(X_3+X_{10})] + e\,[(X_5+X_8)-(X_2+X_{11})] + f\,[(X_6+X_7)-(X_1+X_{12})]$

Force Limited Vibration Estimates Allowable Force and Moment

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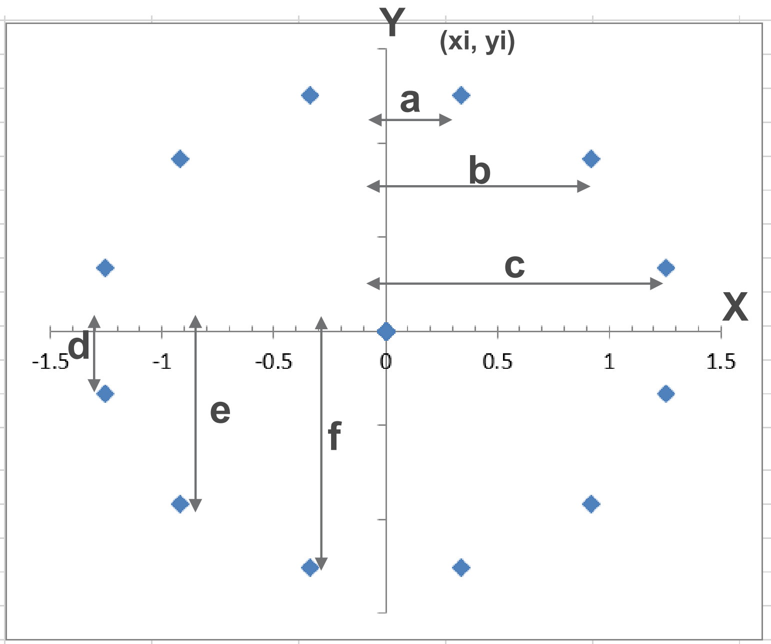

a = 0.336m   d = 0.336m
b = 0.919m   e = 0.919m
c = 1.256m   f = 1.256m

- N=12 Sensors
- Safety Factor = SF= 2
- Max Shear Force-x = Fs-x = N * Fx /SF
- Max Shear Force-y = Fs-y=N * Fy/SF
- Max Axial Force = Fz= N Fz / SF
- Max Moment-y = My= (Σ Fzi * yi)/SF
- Max Moment-x = Mx = (Σ Fzi * xi)/SF
- Max Bending (Overturning) Moment = √ (Mx^2 + My^2)
- Example 9077C
  - Fz max = 150KN
  - Fx max = Fy max = 75KN
- PE Force as mentioned previously is a rangable solution.
- Sensors are selected for measuring range as well as Stiffness for naural frequency considerations (ex. FEA) .
  - 3-Component sensors with more capacity are stiffer

FLV Guidelines: Preload

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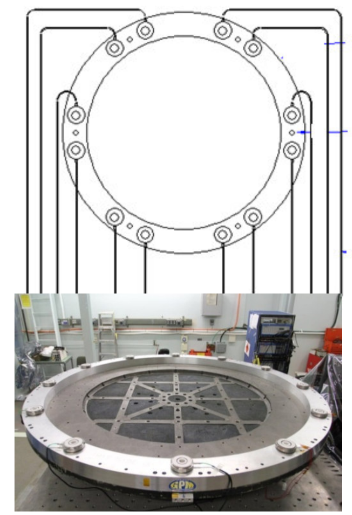
- For 3-Component force sensors are preloaded to 70%FSO
  - Preloaded to 70% FSO, Integral Ground Isolation for improved signal quality – Also provides a 0.2 frictional Coefficient ; Force Shunt with Preload Bolt (6-9% lower Sensitivity). Low inherent cross talk , High Rigidity/higher natural frequency, Check Out Instrumentation , Ring Only , Ring + Mass Simulator
  - Linearity
  - Preload is sufficient to carry the shear loads via friction, without slip (5:1 ratio of Preload to Shear Force)
  - Preload is sufficient to prevent unloading related to the dynamic forces and moments, e.g., tensile forces and heel-to-toe moments

- PE Force sensors are used to measure the bolt preload while the bolts are being torqued by connecting to a quasi-static charge amp in long time constant to the force the preload force readings for the bolt torqueing sequence.

- Calibration certificate provide two sets of calibration values one for the transducer itself and one for the transducer with their standard preloading hardware. For FLV usually preferable to utilize a preloaded bolt configuration that is tailored to the test item.

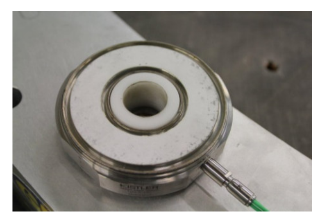


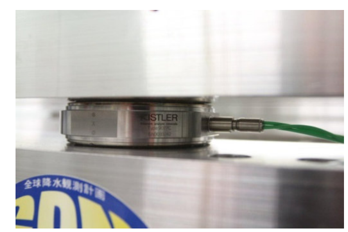
Preloading force sensors in ring typically uses a star pattern

Results of Measurement

Calibrated Range kN		Sensitivity pC / N	Linearity ≤ ± %FSO	Cross talk	%		%
Fx	0 ... 75	-4,201	0,15	Fx → Fy	0,3	Fx → Fz	-0,1
Fy	0 ... 75	-4,189	0,14	Fy → Fx	-0,3	Fy → Fz	0,2
Fz	0 ... 150	-1,999	0,16	Fz → Fx	-0,2	Fz → Fy	0,2
Fz*	0 ... 500	-2,128	0,37				

* without preload



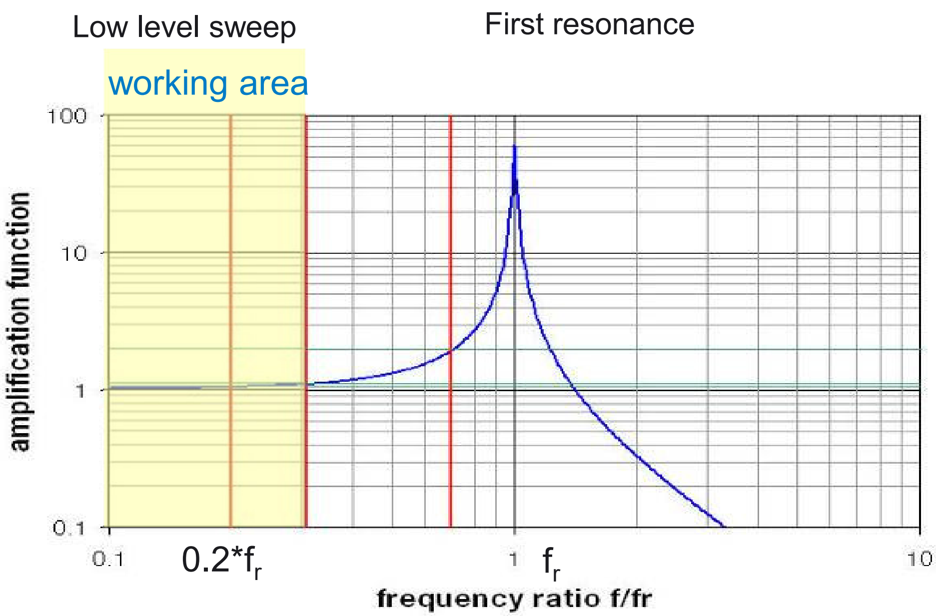


Ref: NASA-HDBK-7004C, Force Limited Vibration Testing

In-Situ Calibration and Checkout

Low level sweep according NASA-HDBK-7004C

- Calibration can be done with a low level sine sweep sufficiently below the first resonance as a simple way for a calibration.
- Also recommended as a functional test to check if everything is working with mass simulator.
- The low-frequency (below first resonance of the test item) of the apparent mass is compared with the known total mass of the test item. The relevant apparent mass is the ratio of total force to the input acceleration in the shaker direction.

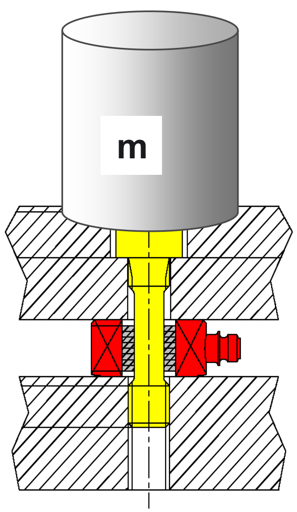


In-Situ Calibration and Checkout

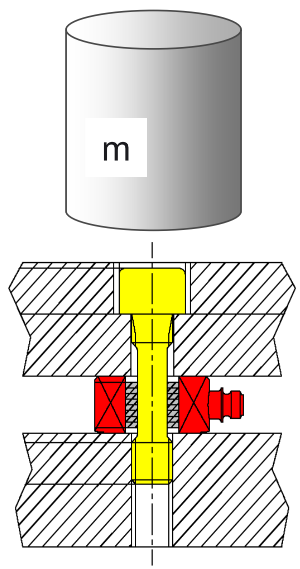
Static calibration according NASA-HDBK-7004C

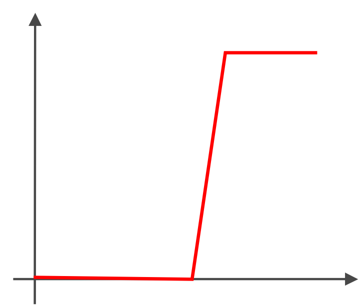
- Calibration can also be done with known weights
- Reset charge amplifier, place weight on force sensor set up, switch to operate and lift weight carefully
- The load step can be used to calibrate force sensors. Difficult with large loads, as weights become very heavy and difficult to handle.

Weight on sensor



Charge amp «operate» and lift weight





Example: M+P VibRunner + Rack + Vibcontrol – Control Requirements – Resolution of Forces and Moments

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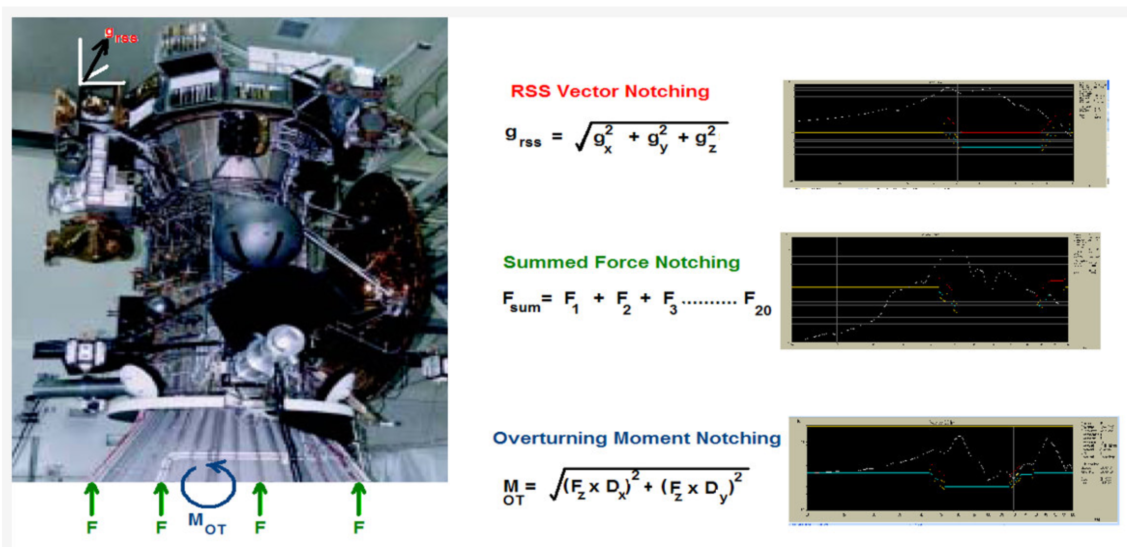
- Real Time Calculations for Control
- Limit to force input in axis on structure
- Reduce the overturning Moment to a safe level
- Standard notching to limit values on substructures.
- Off axis notching for non-square parts
- RSS notching to limit total acceleration to a point (RSS) notching.



Example: Fx, Fy, Fz ,Mx, My

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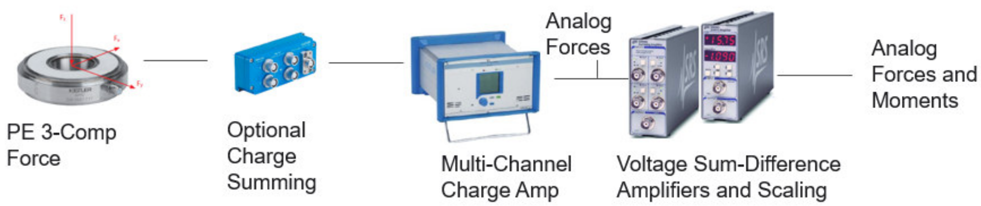
- Integrated System Solutions (ex. LMS, M+P Controllers..etc for real time calculation of Forces and Moments)
- When controller cannot calculate forces and moments , or when independent check on Integrated system is required
  - Analog Signal Conditioning: Stanford Research /Configurable Commercial Solution



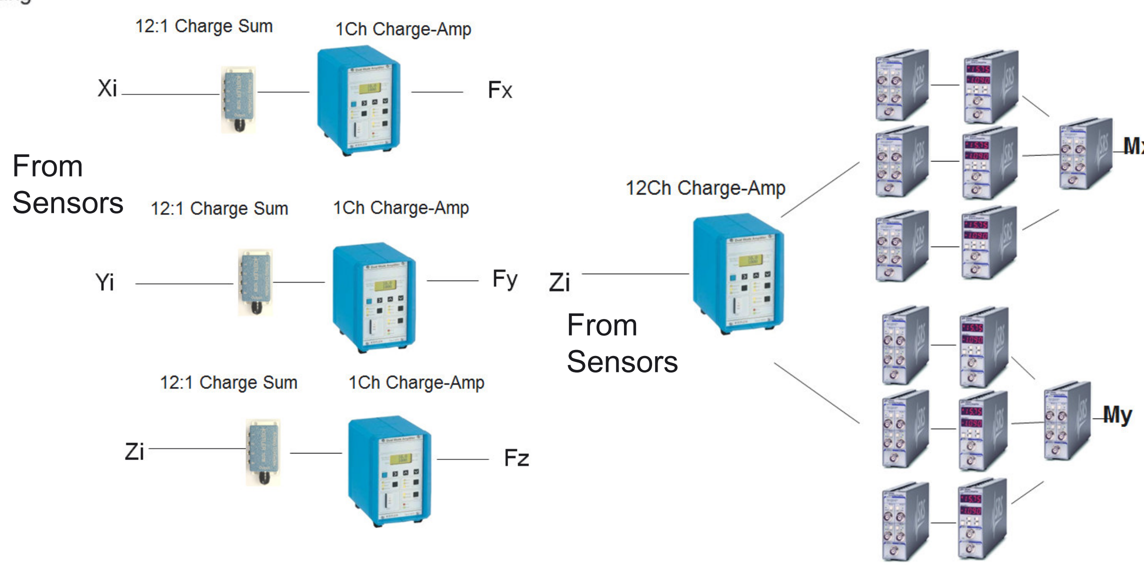
- $Mx = d\,[(Z_4+Z_9)-(Z_3+Z_{10})] + e\,[(Z_5+Z_8)-(Z_2+Z_{11})] + f\,[(Z_6+Z_7)-(Z_1+Z_{12})]$
- $My = a\,[(Z_7+Z_{12})-(Z_1+Z_6)] + b\,[(Z_8+Z_{11})-(Z_2+Z_5)] + c\,[(Z_9+Z_{10})-(Z_3+Z_4)]$

SIM 980

Sum-Diff Amp

SIM 983

Scaling Amp



Application – Force Limited Vibration Testing

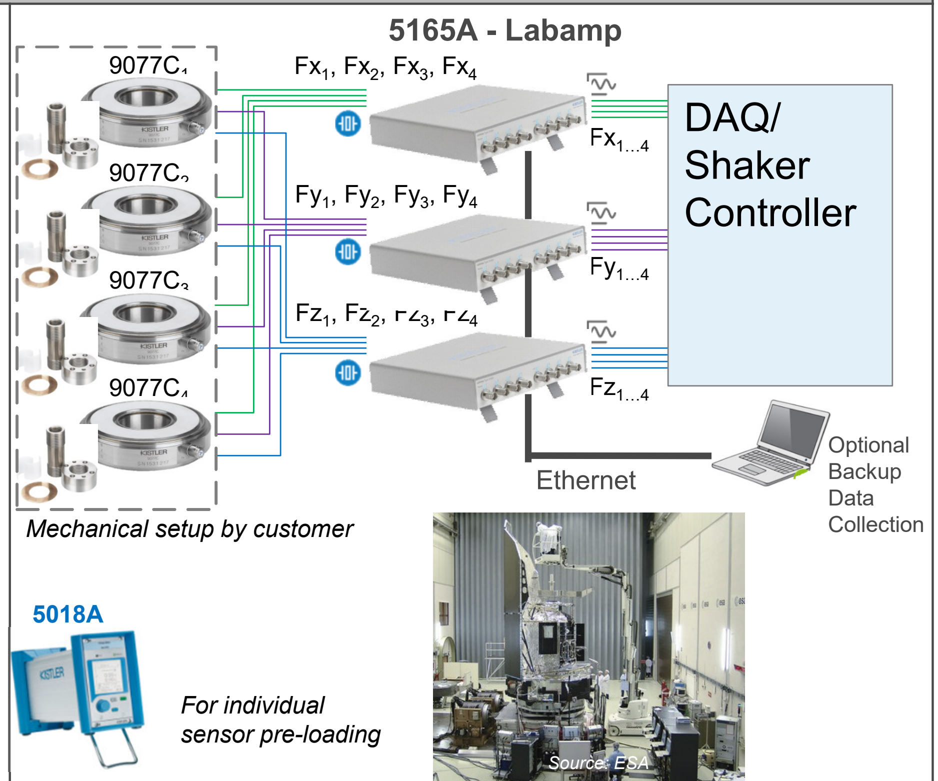
Application Description

Application needs:

- Space payload is tested on a shaker to simulate launch environment
- Forces are observed to prevent damage to the payload during test due to overload (to limit test inputs near fixed Base resonances)
- Backup Data Recording/High Fidelity Analog inputs to Controller

Setup:

- Four 3-comp force sensors mounted between customer designed top and base plate. Preloading is accomplished using a quasi-static amplifier (e.g. 5018A)
- FLV is a dynamic test – Signal conditioning of all individual X, Y, Z forces is performed by three LabAmp 5165A4K
- LabAmp 5165A4K Analog output signals are acquired by a 3rd-party Vibration Controller/DAQ system to perform FLV shaker control



Thrust Testing---Propulsion Systems – Examples

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Space launch propulsion, or in-space propulsion applications

Designers generally discuss spacecraft performance in amount of change in momentum per unit of propellant consumed also called specific impulse. The higher the specific impulse, the better the efficiency.

- Chemical rockets have a lower specific impulse (~300s) but high thrust.
- Ion propulsion engines have higher specific impulse (~3000s) and low thrust.

Chemical Propulsion: Systems that operate through chemical reactions that heat and expand a propellant (or use a fluid dynamic expansion as in a cold gas) to provide thrust.

- Earth Storable (Hydrazine, Green Propellants, ADN, HAN, …)
- Cryogenic - Liquified Gases at Low Temp (LOX, Methane, Liquid Hydrogen (LH), …)
- Solids (premixed oxidizers and Fuels)
- Hybrids (solid fuels and liquid oxidizer)
- Gels
- Cold Gas (Store inert gases to increase thrust)
- Warm Gas (Heated Gas to create thrust of increase pressure)

Electric Space Propulsion: Converts electric energy to interact with and accelerate a reaction mass to generate thrust. (Some have firing duration of months to years at low level thrust)

- Electrostatic – uses electrostatic fields to ionize and accelerate a propellant (e.g. Ion engines, Hall thrusters, Electrospray propulsion)
- Electromagnetic – propulsion which interacts with a reaction mass using electromagnetic fields (e.g. Pulsed inductive thruster, Magnetoplasmadynamic (MPD) thruster, Electrodynamic launch, e.g. double-sided linear induction motor (DSLIM)….)
- Electrothermal – Propulsion heats propellant prior to expansion through a nozzle (e.g. Resistojets, Arcjets….)

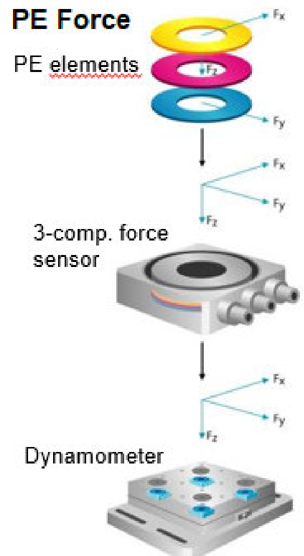
Propulsion Testing

- Characterization of thrust includes efficiency, fuel mixture, nozzle design and specific impulse
  - Ignition needs to be fast as possible to achieve operation without consuming excess fuel.
  - Shut off should be quick to burn residual propellants.
  - During Operation thrust fluctuations could indicate operational issues
- Pressure monitoring of combustion process
  - Static/Dynamic Pressure : Piezoresistive -40C (-40F) to 120C(250F) , use Standoff for high temp
  - Dynamic Pressure: PE up to 700C (1300F) – Flush or Passage with Ablative Coating
- Vibration : PE up to 700C (1300F)
- Thrust Measurement : Piezoelectric Force or Stain Gauge
  - Vacuum Measurements covered earlier -- Expansion of gases passed by the nozzle exit is very important in deciding the thrust produced. In normal atmosphere, pressure of the gas at the exit is under-expanded which produces minimum thrust. In vacuum, it is over-expanded which produces higher thrust.
  - Thrust Misalignment also a consideration in some cases
  - Vertical or Horizontal Orientation of Rocket Motor /Bending Moments and Cross talk
  - Thermal Isolation

PE Pressure

PR Pressure

PE Force

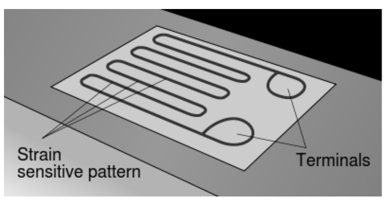


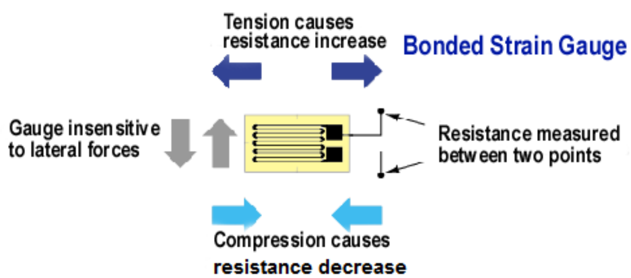
PE Acceleration

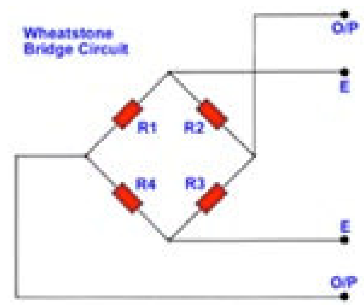
 02.12.2021

Bonded Foil Strain Gauge

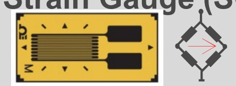
- The strain gauge sensors, including pressure sensors, load cells, torque sensors, position sensors, etc.
- Foil types, consist of a pattern of resistive foil which is mounted on a backing material.
- When foil is subjected to stress, the resistance of the foil changes in a defined way.
- If these stresses are kept within the elastic limit of the metal strip (so that the strip does not permanently deform), the strip can be used aa a measuring element for physical force, the amount of applied force inferred from measuring its resistance
- “Bonded gauge" are strain gauges that are glued to a larger structure under stress
- As stress is applied to the bonded strain gauge, a resistive changes takes place and unbalances the Wheatstone Bridge. The resistance change proportional to the applied force.







Example: Comparison PE and Strain Gage Technology

Main characteristics of force sensors0.	Piezoelectric (PE) 	Strain Gauge (SG) 
Static measurements	✓ Quasi-static force measurement/Drift	✓ Ideally for static force measurements
High dynamic measurements	✓ Very stiff, ideal for dynamic meas.	✓ Limited due to stiffness.
Wide measuring range	✓ Range 1:1,000,000 Rangable with C/A	✓ Range 1:10,000 Not Rangable
Measure small forces at high Initial load	✓ C/A "Tares" initial load to optimize on low level	✓ initial load + small Forces- Lower Resolution
Small sensor dimensions	✓ Sensitivity, threshold and resolution indep.of the sensor range/size	✓ Different sensors sizes have different performance
Cycle lifetime	✓ Solid state, no glued bonding used	✓ Fatigue/Creep effects possible
Overload	✓ Typically 20%-50% overload possible	✓ higher range for overload – lower Resolution
Temperature effects	✓ Preloading makes temp compensation difficult	✓ Very good temp compensation possible
Operation at high temperatures	✓ -196°C to +200°C	✓ -269°C to +250 °C Chrome Nickel/Polymide
Harsh cable environment	✓ High insulation cabling needed.. Durable	✓ No need for high insulation cables
Accuracy	✓ Typically 0.1%...1% FSO	✓ Typically 0.01%...1% FSO

- PE Requires a Charge Amp;
- Strain Gauge requires a Bridge amplifier to provide a voltage representative of the applied load or change in resistance
- Strain Gauge Technology is known for Long Duration constant thrust measurement
- Decision to use Strain Gauge or PE technology is application dependent where historic experiences of user and/or R&D facility are a factor

Typical PE Thrust Measurement considerations relative to Strain Gauge

Based on feedback from users--

- **Natural Frequency** - Strain Gauge has much lower natural Frequency and inherently noisier (mechanical noise) data which is believed to be related to low stiffness of Strain gauge compared to PE. Test Article mass further reduces natural frequency
- **Response Time** – PE has much faster response time especially important for fast acting short burn tests – PE were more accurate at capturing the complete thrust as some of the other strain gauge devices seem to mechanically filter the waveform.
- **Test Stand Adaptability** - Universal PE 6DOF stand for many product lines– offers a rigid platform which Is rangable to the device being testing.
    - Calibrate the stand to very low ranges and maintain good signal integrity and maintain a very acceptable signal to noise ratio especially with 5080A. Successful calibrate same stand for 6700N(1500lbf) to 670N(150lbf). Rangeability of PE
        - Significant advantage to use one common test stand helps performing testing with available budgets.
    - Dynamometers can off the shelf or configured on site using force sensors/links to record multicomponent forces and moments
    - Easily adapted to a multitude of different applications but they really shine in multi-axes, multi degree of freedom platforms that require reading forces in all three dimensions as well as moments about all three axes simultaneously.
        - The low inherent crosstalk allows these devices to be easily integrated into test stands
    - The PE Sensors allow users to build 6 Degree of Freedom test stands that are rigid and offer a very high response rate as well as being a simple bolt together design without the complicated use of flexures or linkages.
    - Cleaner Data with PE

Thrust Measurement: PE Force sensors Mechanically in Series

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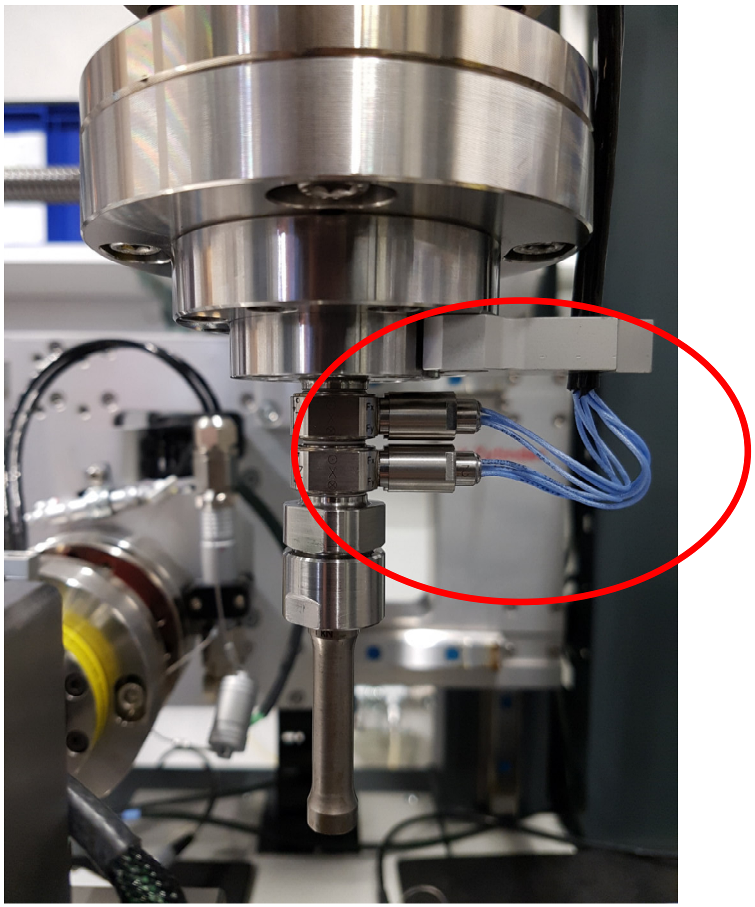
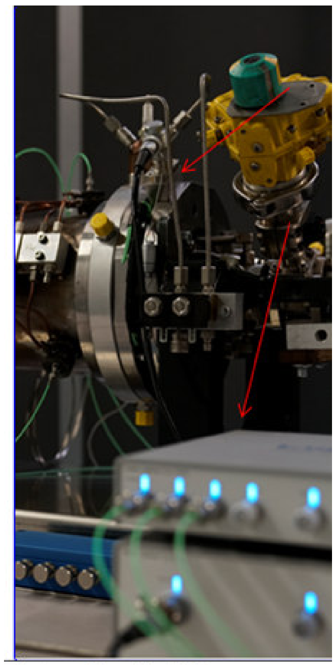


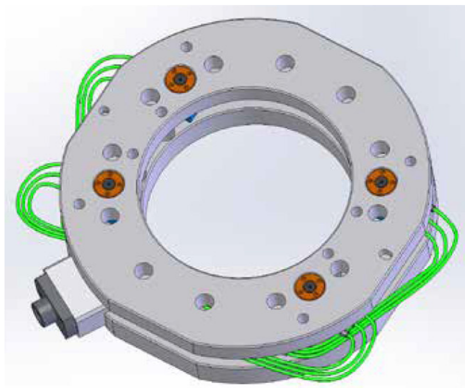
2x 9317C
Piezostar
3-Component
Force Sensor

- Dual Redundant Force sensors for thrust measurement---Single or multi-component
- Strain Gauge offers Dual Redundant as well as Shunt Calibration (not possible with PE)
- Increased Sensitivity
  - Directly Sum sensor outputs in Charge increases the sensitivity by a factor of 2.
  - Higher sensitivity complements higher precision

Example: Fully Instrumented Rocket Engine Test



- Custom PE Multicomponent Force Dynamometer
- Quasi-Static LabAmp for Thrust Characterization and Optimization



Custom PE Multicomponent Force Dynamometer

Calculation of the three forces F_x, F_y, F_z and the three moments M_x, M_y, M_z

$$F_x = F_{x1+2} + F_{x3+4}$$

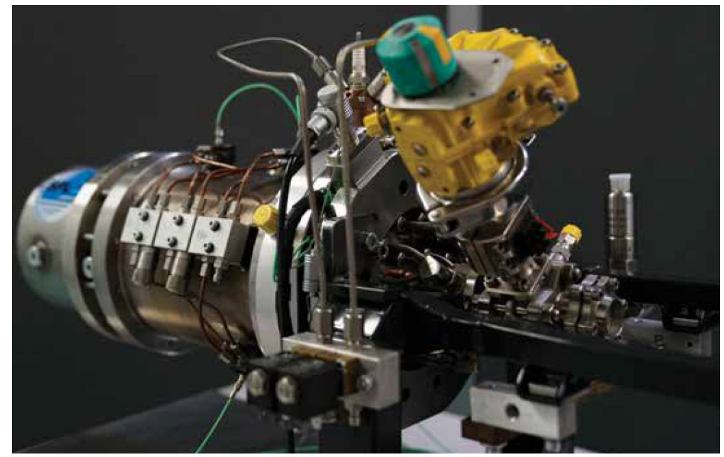
$$F_y = F_{y1+4} + F_{y2+3}$$

$$F_z = F_{z1} + F_{z2} + F_{z3} + F_{z4}$$

$$M_x = b\,(F_{z1} + F_{z2} - F_{z3} - F_{z4})$$

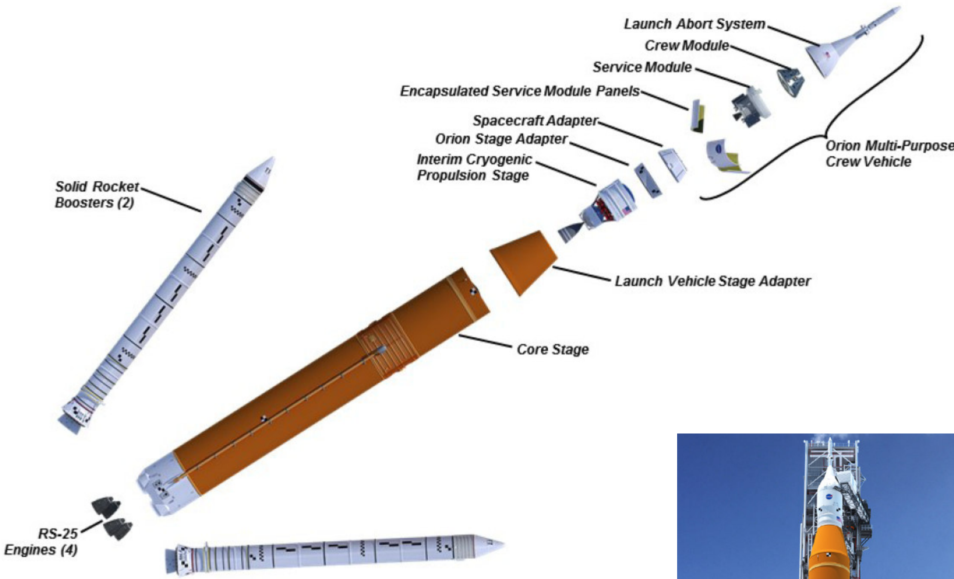
$$M_y = a\,(-F_{z1} + F_{z2} + F_{z3} - F_{z4})$$

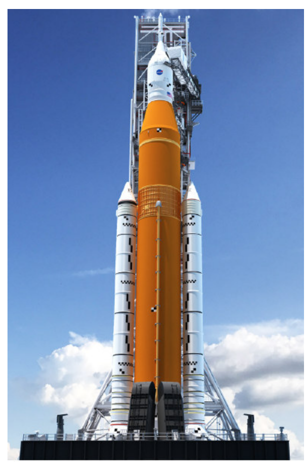
$$M_z = b\,(-F_{x1+2} + F_{x3+4}) + a\,(F_{y1+4} - F_{y2+3})$$

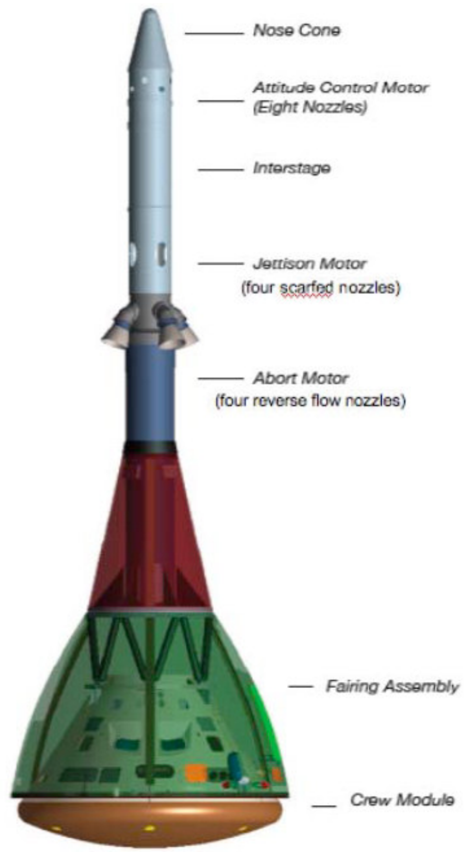


- Force dynamometer for thrust measurement,
- High temperature pressure and acceleration for combustion instabilities,
- Static Piezoresistive pressure of control of propellant

NASA Orion /SLS Heavy Lift



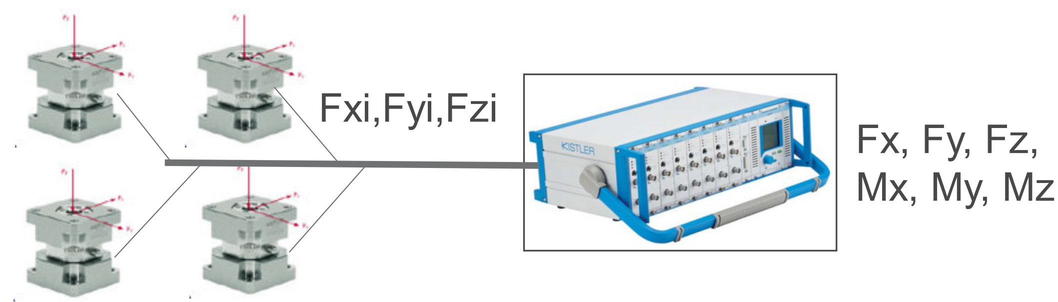




NASA Orion Attitude Control Motor (ACM) Test

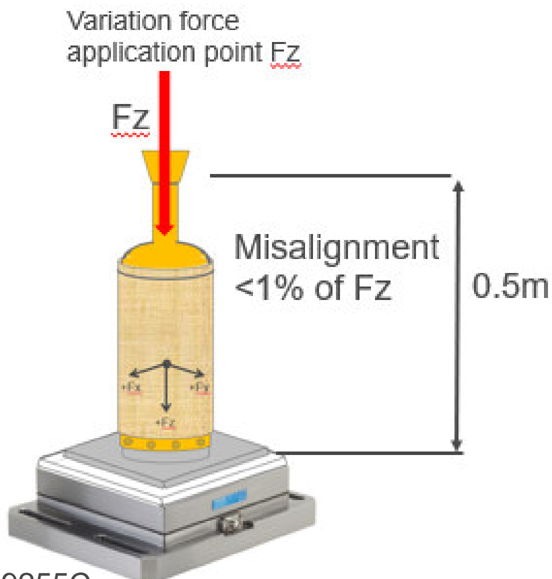
Video Link: https://www.youtube.com/watch?v=6AO4kwmpUZk

- ACM consists of a solid propellant gas generators with 8- proportional valves equally spaced around the circumference of the motor
- ACM has 2 functions
  - Steer Orion's abort system and crew module away from the launch vehicle in the event of an emergency
  - Orients the capsule for parachute deployment once cleared from hazards
- 4 x 3-component Force Links (9367C) and 5080A to resolve 6-components Fx, Fy, Fz, Mx, My, Mz



Example: Considerations for Thrust Misalignment Measurement

- Inherent alignment of rocket motors or Thrust Vectoring Applications
- 9255C common off the shelf solution – but many other custom solutions possible
- Each Application different – requiring separate design evaluation



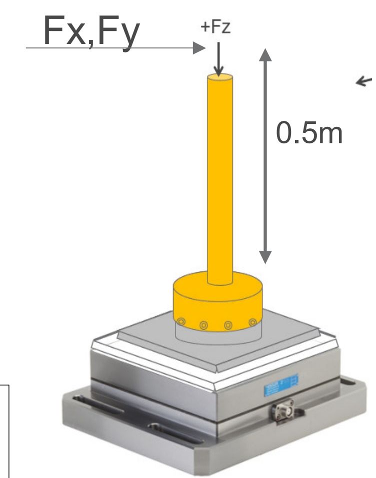
9255C

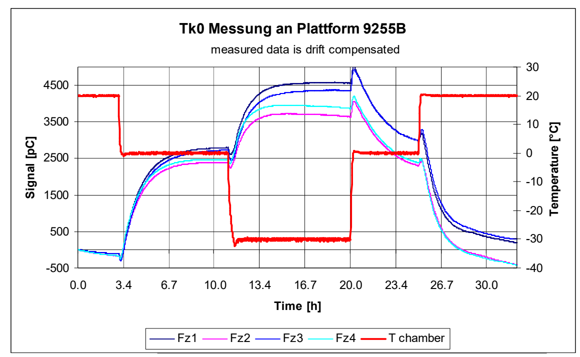
- Misalignment can be measured with two methods (Fz = 10000N):
  - Side Forces : Fx, Fy
    - Fx,Fy = 1% * 10000 = 100N
    - Fx,Fy = 0.3% * 10000 = 30N (max measurement uncertainty for Fx,Fy)
  - Moments : Mx, My
    - Mx, My = 100N * 0.5m = 50Nm
    - <u>Problem:</u> Variation of force application point of Fz also creates a Mx, My
    - For 25mm variation, Mx,My = 10000N * 0.025m = 250Nm
    - => 5x larger than Mx, My by misalignment – So Moment should not be used for misalignment where Fx, Fy will be used.
- For misalignment, Fx,Fy should be measured with an uncertainty allocation of 30N – Estimated Uncertainty is ~23N

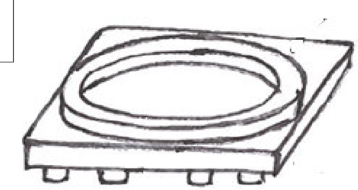
Measurement Uncertainty: Considerations

What affects measurement uncertainty of Fx, Fy?

- Cross talk Fz => Fx, Fy : Select 9255C with low cross talk Fz => Fx, Fy ~ 0.15 %FS or Fz (~15N)
- Linearity Fx, Fy: Select a 9255C with that is highly linear , most have a linearity of ≤± 0.04%FSO
- Sensitivity Fx,Fy with long lever arm (0.5m): Sensitivity is ~5% Lower-- but Calibration with a similar long lever arm compensates sensitivity resulting in error allocation of 0.3% of Fx,Fy
- Effect on cross talk Fz => Fx, Fy by variation of force application point of Fz
  - Force application point of Fz assumed in a rectangle of 25mm which leads to an uneven loading of 390N. Select cross talk of each sensor ≤± 0.3%FSO; results in 1.2N Error dur to crosstalk
- Sensor individual sensitivity variation due to Fz force application point
  - Force application point of Fz assumed in a rectangle of 25mm which leads to an uneven loading and Sensitivity deviation between sensors: ≤± 1.5% which results in 5.85N error
- TC0 caused by heat flux from thruster: Ceramic Plate or Protective Shroud
  - Error Assumed ~0.1% of Fx,Fy
- Flatness of mounting base 9255C – Ground Surfaces
  - Error Assumed ~0.1% of Fx,Fy
- Interface 9255C and rocket thruster - Low Surface area for low conductive effects
  - Rocket thruster and calibration fixture must have the same interface
  - The interface should be stiff to minimize deflection of top plate.
  - Error Assumed ~0.1% of Fx,Fy







Dynamometer System Considerations - Review

- Measurement Requirements/Analysis
  - Force and/or Moment Range
  - Noise and Resolution
  - Frequency Response
  - FEA/Simulation

- Frequency Response
  - Installation and Mounting
  - Added mass of Test Article and Fixtures acting on the force sensors
  - Response requirements often vary depending on type of rocket engine
  - Quasi-static Operation
  - Fixtures

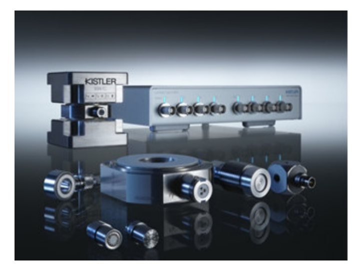
- Vacuum Operation
  - Forces and Moments expected @ Vacuum
  - Hermetic Feedthru's
  - Low Outgassing Cables and Sensors
  - Installation and Mounting in Vacuum Chamber

- Noise/Resolution
  - Installation
  - Ground Isolated Measuring Chain
  - Bandwidth
  - Vibration Isolation /Vibration Damping of test platform
  - Power Supply (Charge Amp/DAQ)

- Partial Range Calibration
  - Defines Linearity
  - Sensitivity
  - Cross Talk

- Thermal Isolation of Instruments
  - Exhaust gasses
  - Temperature transfer from UUT (Cold/Hot fires)

- Special Calibration
  - Moment Correction Factors
  - Large Lever Arms – Calibration and Cross Talk



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Thank You
Questions?