A Perspective on Dynamic Force Metrology

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M. Feng (**NIM, China**)
R. Oliveira (**INMETRO, Brazil**)

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Outline

Overview and (some) History

Application Examples

- Charpy Impact Testing
- Unsteady Aerodynamics

NMI Facilities and Activities

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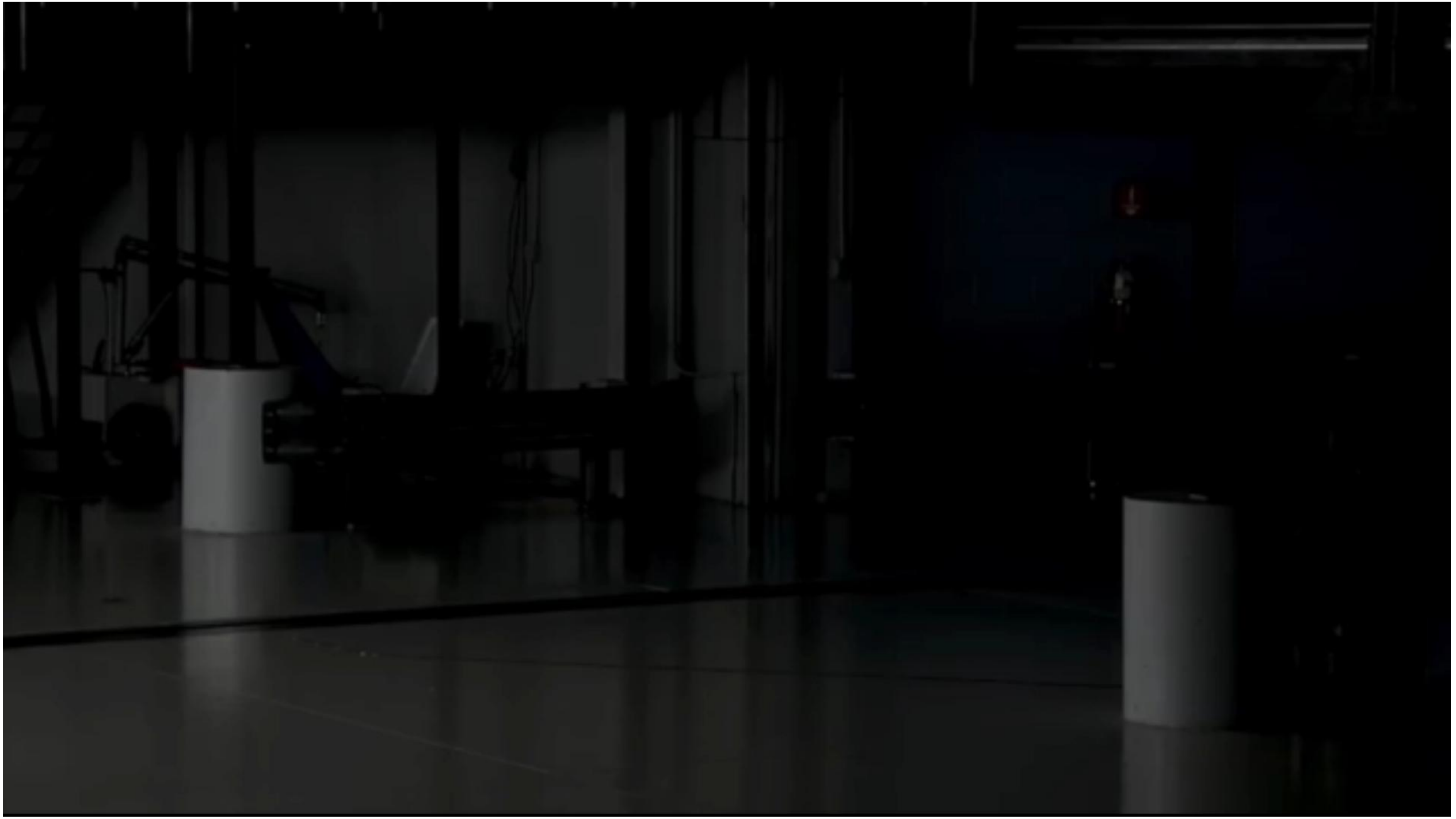
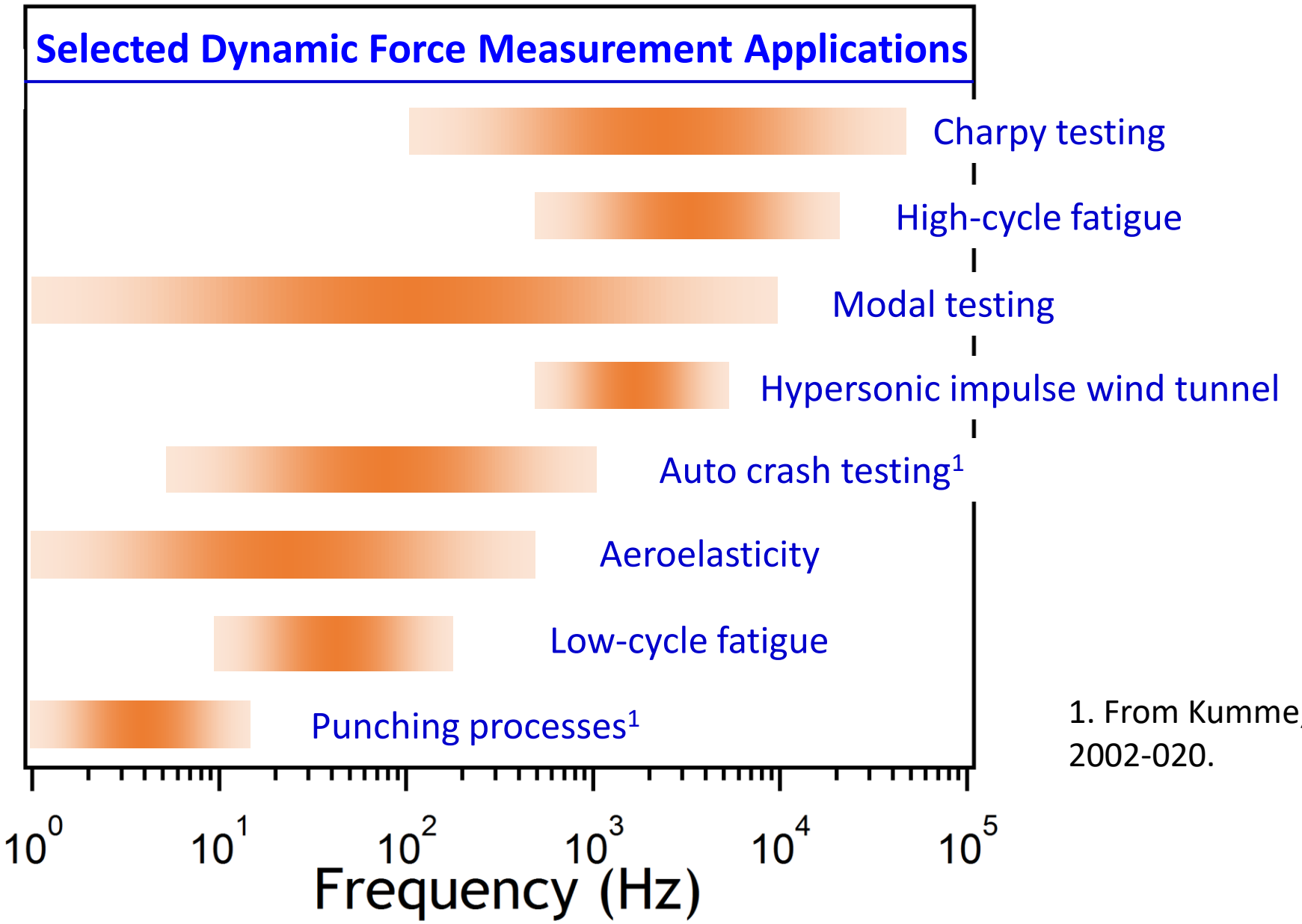


Dynamic Force Application Frequency Ranges



1. From Kumme, R., et al. IMEKO TC3 2002-020.

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Dynamic (Force) Measurement

A dynamic (force) measurement is one in which the force is changing sufficiently rapidly that the dynamic behavior of the measuring system must be taken into account in order to achieve the desired accuracy.

So whether a measurement must be treated as dynamic depends on:

- The properties of the measuring system
- The desired accuracy

A dynamic (force) **calibration** is a determination of the output signal of the measurement system resulting from defined dynamic (force) inputs, with specified uncertainty.

Ideally this would allow you to determine an unknown force input that produced a given sensor output .

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120 years ago

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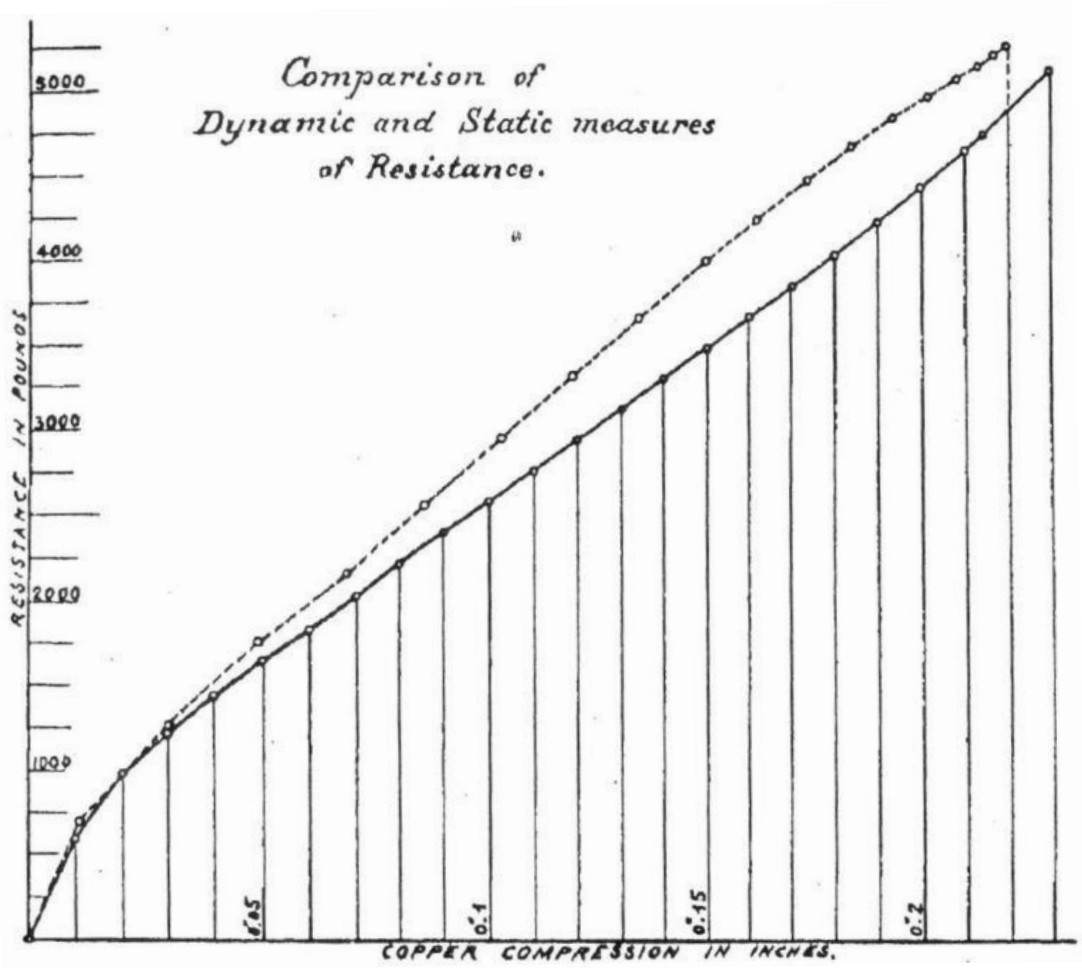
A PHOTOGRAPHIC IMPACT TESTING MACHINE FOR MEASURING THE VARYING INTENSITY OF AN IMPULSIVE FORCE.

BY B. W. DUNN,
Lieut. Ordnance Department, U. S. Army.



Impulse duration: **3 ms**, Timing resolution: **2.3 µs**

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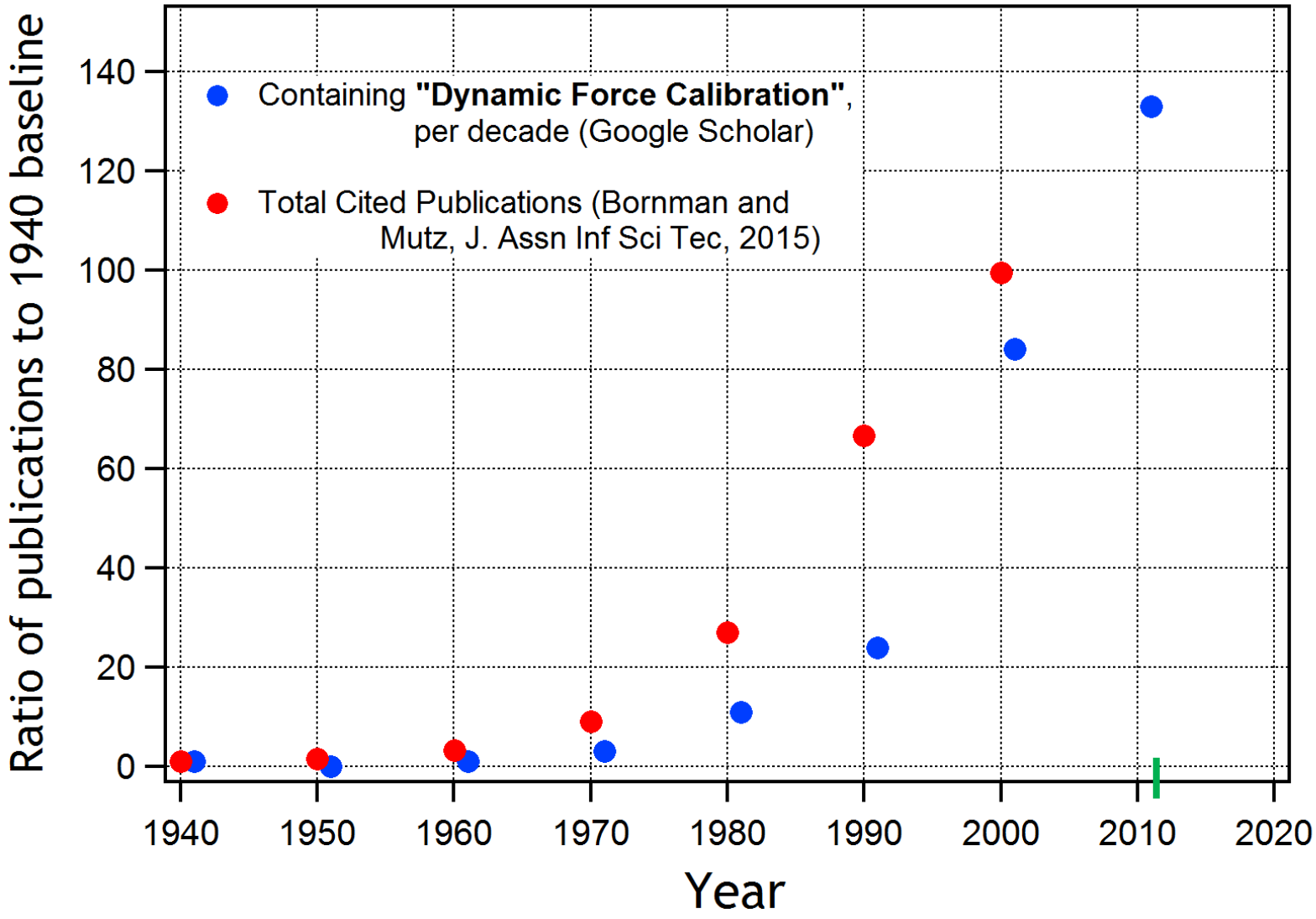
More-recent activity

Number of articles per decade containing the phrase “dynamic force calibration” from Google Scholar search

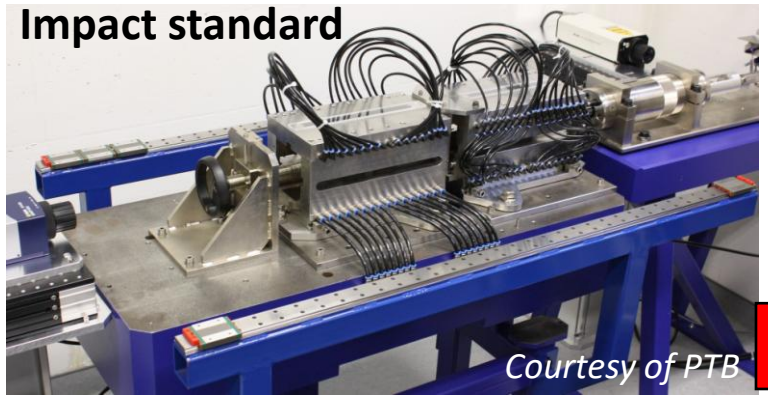


C. Schlegel, G. Kieckenap, B. Glöckner, A. Buß and R. Kumme, *Traceable periodic force calibration*, **Metrologia 49**, 2012.

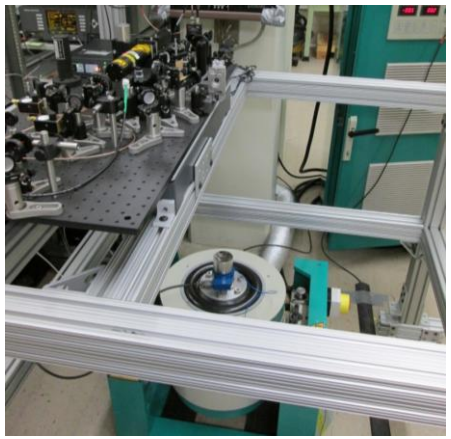
Low-uncertainty SI-traceable Dynamic Force

Standards

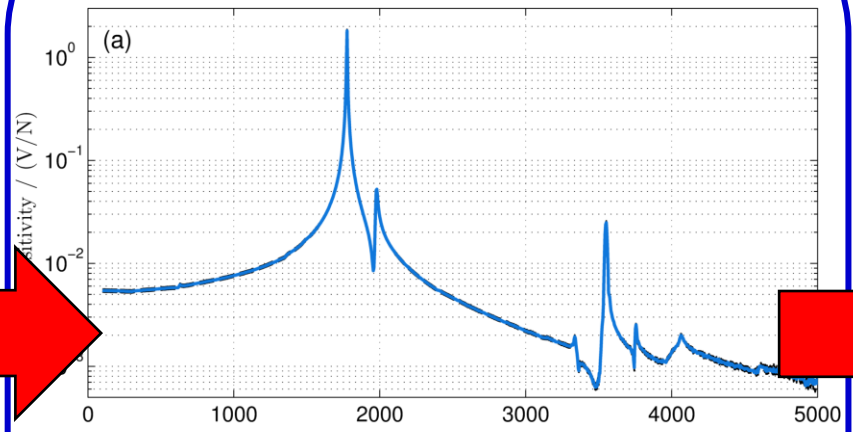
Impact standard



Shaker standard

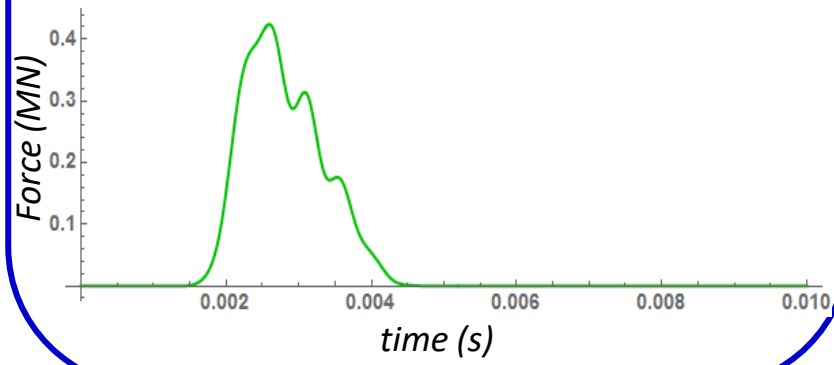


Calibration



- Transfer function / impulse response (linear system)
- Model parameters describing dynamic response of the system
- Response to particular force-time profile of interest

Measurement



Transducer dynamic response in general changes from one setting to another, requiring (at least one of):

- In-situ calibration
- Model parameter calibration

Regularization is often required as the inversion is ill-posed

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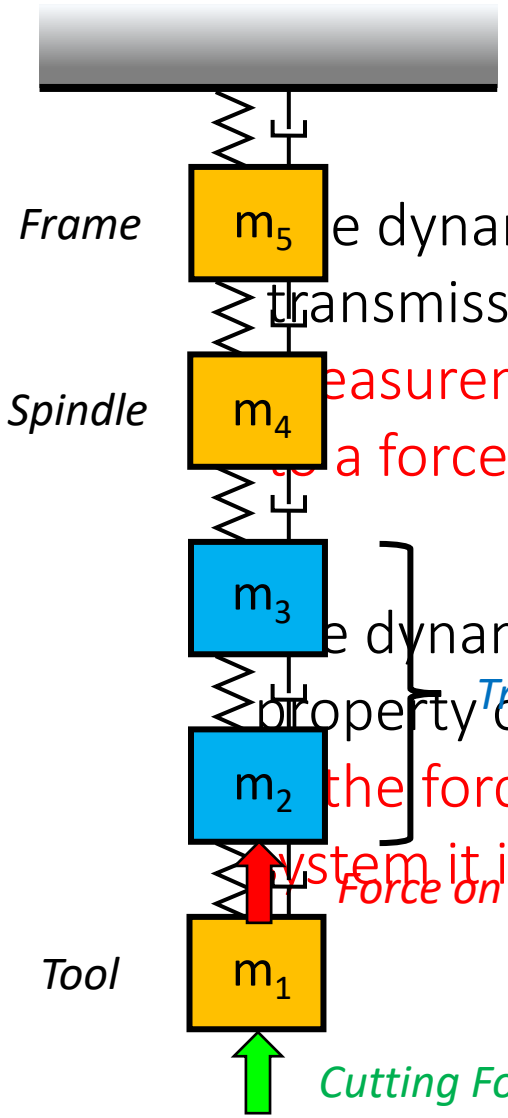
Challenges in Dynamic Force Measurement



e dynamic force is a function of location in the transmission chain → The sensitivity of the easurement system must be known with respect a force applied at the location of interest.

e dynamic sensitivity of a force transducer is not a property of just the force transducer. It is a property the force transducer together with the mechanical ystem it is coupled to.

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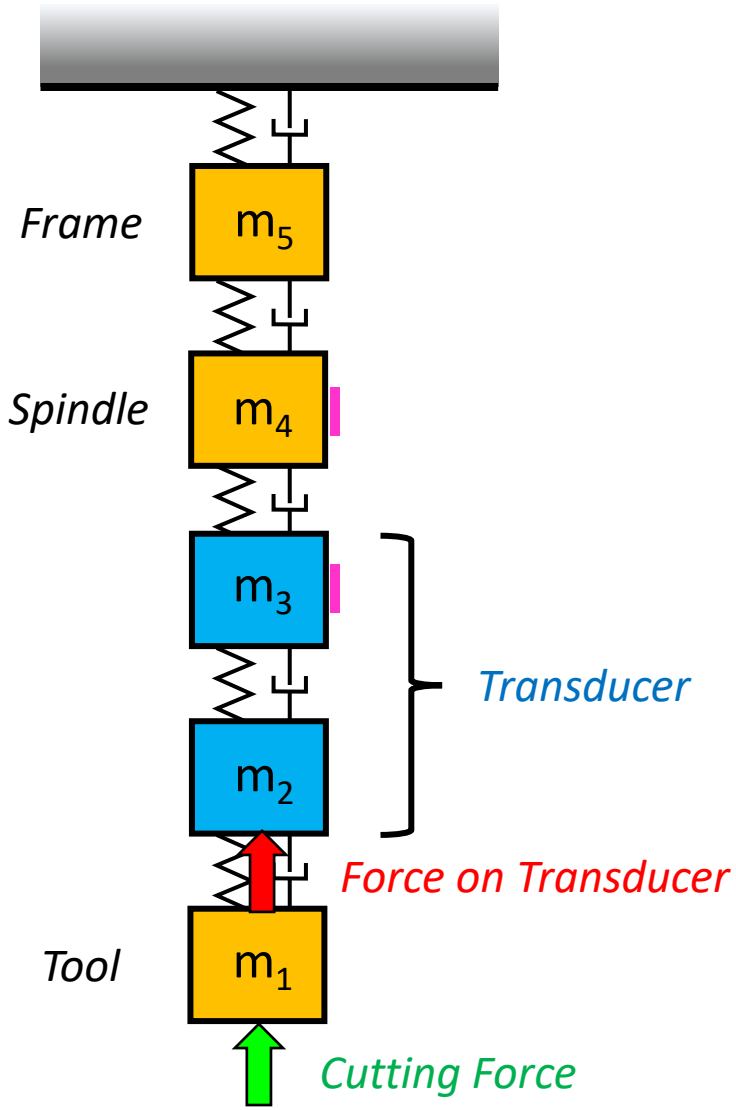
One approach: Give up on using a Force Sensor



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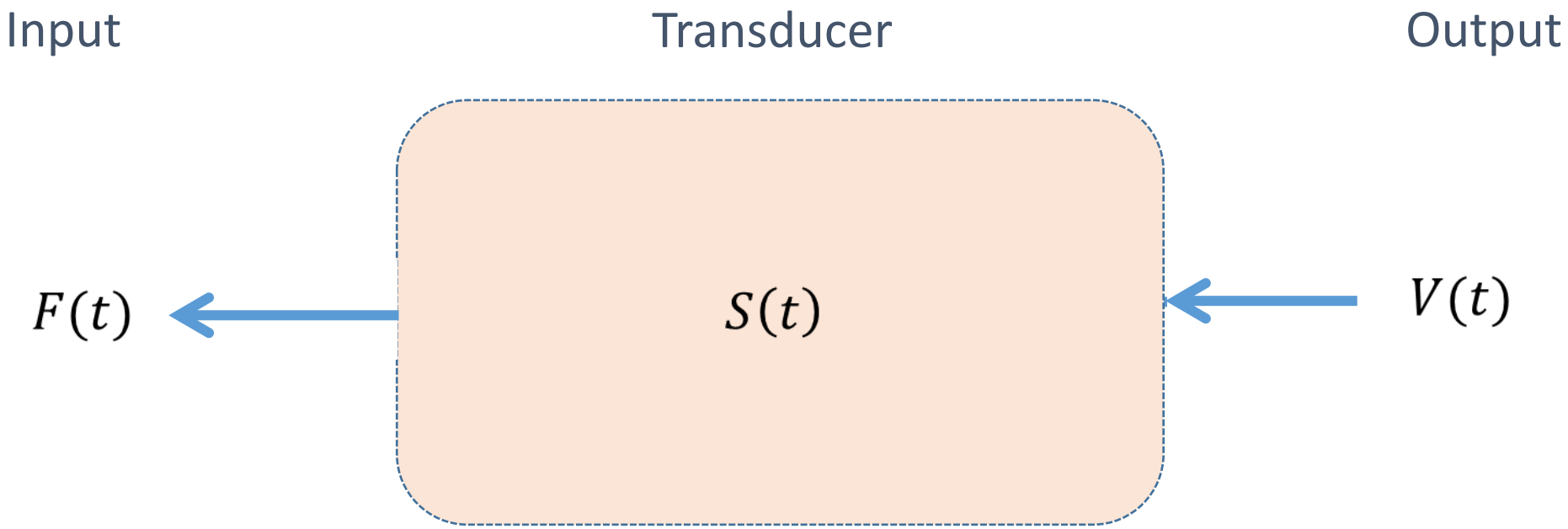
Dynamic (Force) Measurement



$$V(t) = \int_{-\infty}^{\infty} F(\tau)S(t-\tau)d\tau$$

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Comparison to metrology of “fixed” mechanical quantities

Some universal similarities

- The uncertainty achieved in a calibration depends on the device being calibrated
- The uncertainty achieved in use of the device can be significantly larger than the calibration uncertainty
- Conditioning amplifiers contribute to achieved measurement uncertainty

Static force and torque metrology (differences)

- The force/torque applied to the device is essentially the same through the loading (train)
- Transducer sensitivity is essentially independent of the mechanical system it is used in

Mass metrology (similarities)

- Dynamic *methods* are used in mass metrology
- In dynamic weighing applications, there is strong overlap with dynamic force metrology
- Dynamic mass metrology in weighing of mass-changing systems (e.g. container filling)

Hardness metrology (similarities)

- Dynamic *methods* in hardness metrology

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Comparison to metrology of other dynamic mechanical quantities

Dynamic pressure

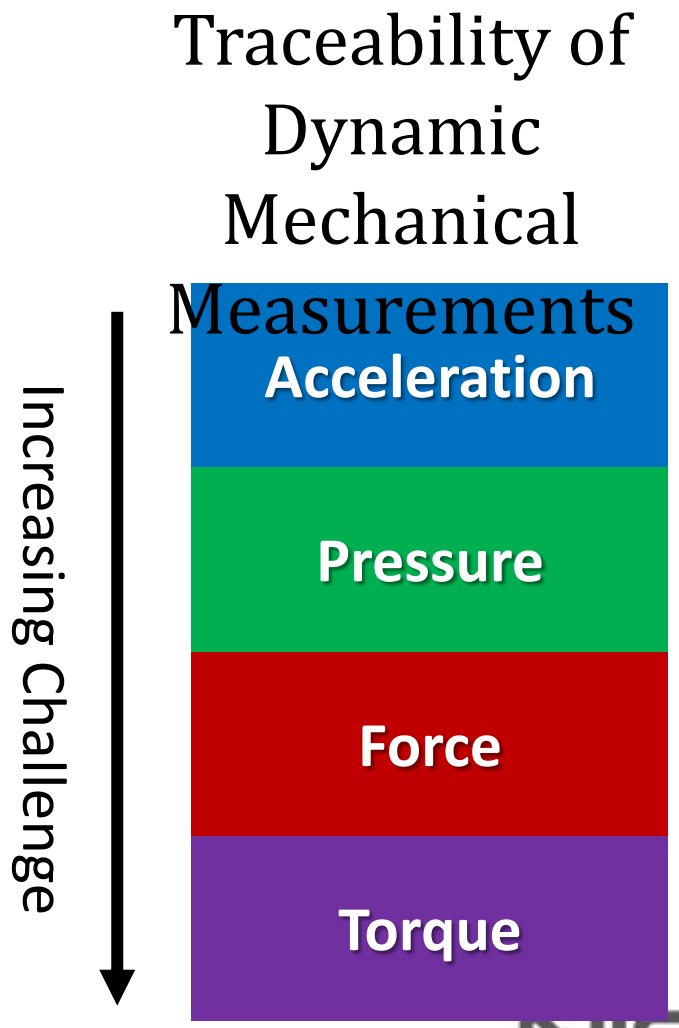
- Similar needs in calibration, modeling, and measurement uncertainty
- Need traceable standard of a generalized force variable
- The field is probed locally; the sensor does not necessarily become a critical link in the structure

Acceleration (vibration, shock)

- Similar needs in modeling and measurement uncertainty
- For shock: Similar needs in dynamic calibration
- Vibration calibration well established
- Generalized displacement variable

Dynamic torque

- All the same considerations as for dynamic force calibration apply, with the additional complications of a moment arm.



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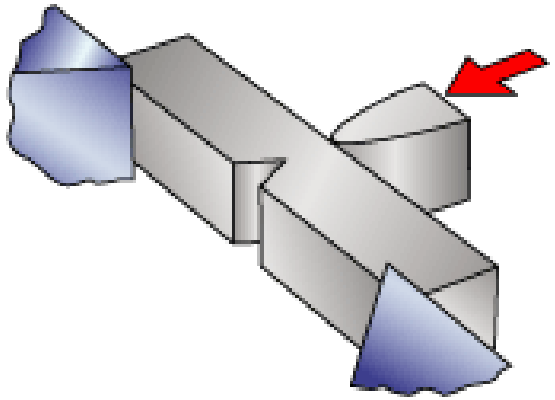
Charpy Impact Testing

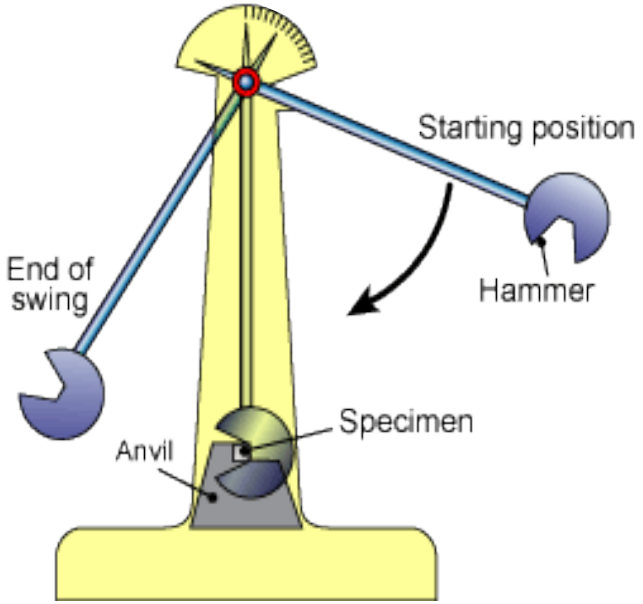
Primary method used to qualify notch toughness of metals

Automotive, ship, rails, nuclear reactor containment, cryogenic containers, aerospace, buildings…

- Attributed to S. B. Russell (1898) and M. G. Charpy (1901).

Measures the energy absorbed in fracturing a notched specimen





Images courtesy of TWI

- NIST Charpy Machine Verification Program has established tightest agreement among any population of Charpy machines in the world

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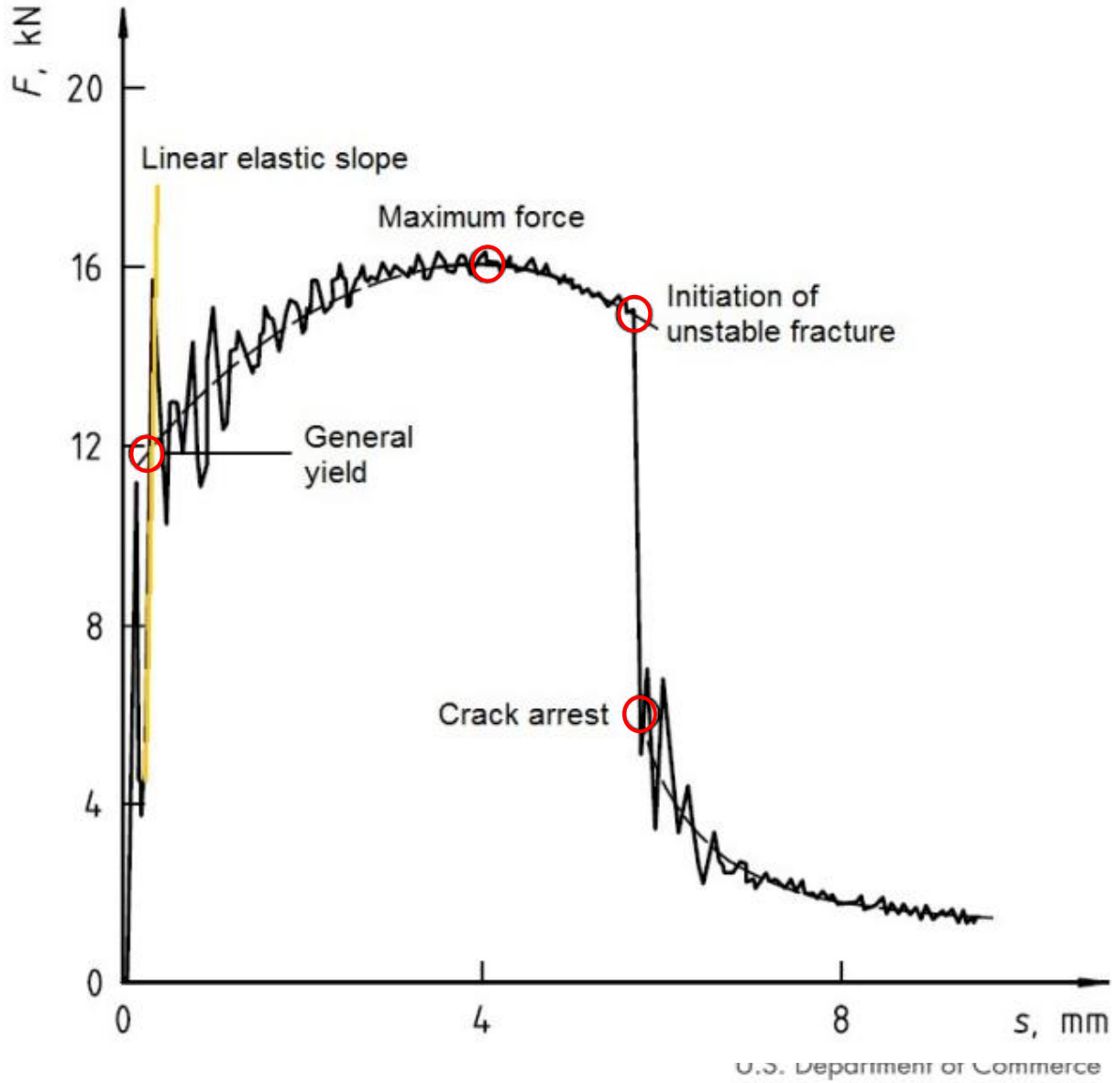
Instrumented Charpy Impact Testing

From the early days of Charpy testing, it has been desired to measure not only the absorbed energy but also the applied force profile, but the latter is significantly more challenging than the former.

Extracted information

- Dynamic yield strength
- Dynamic tensile strength
- Dynamic fracture toughness
- Fracture arrest load



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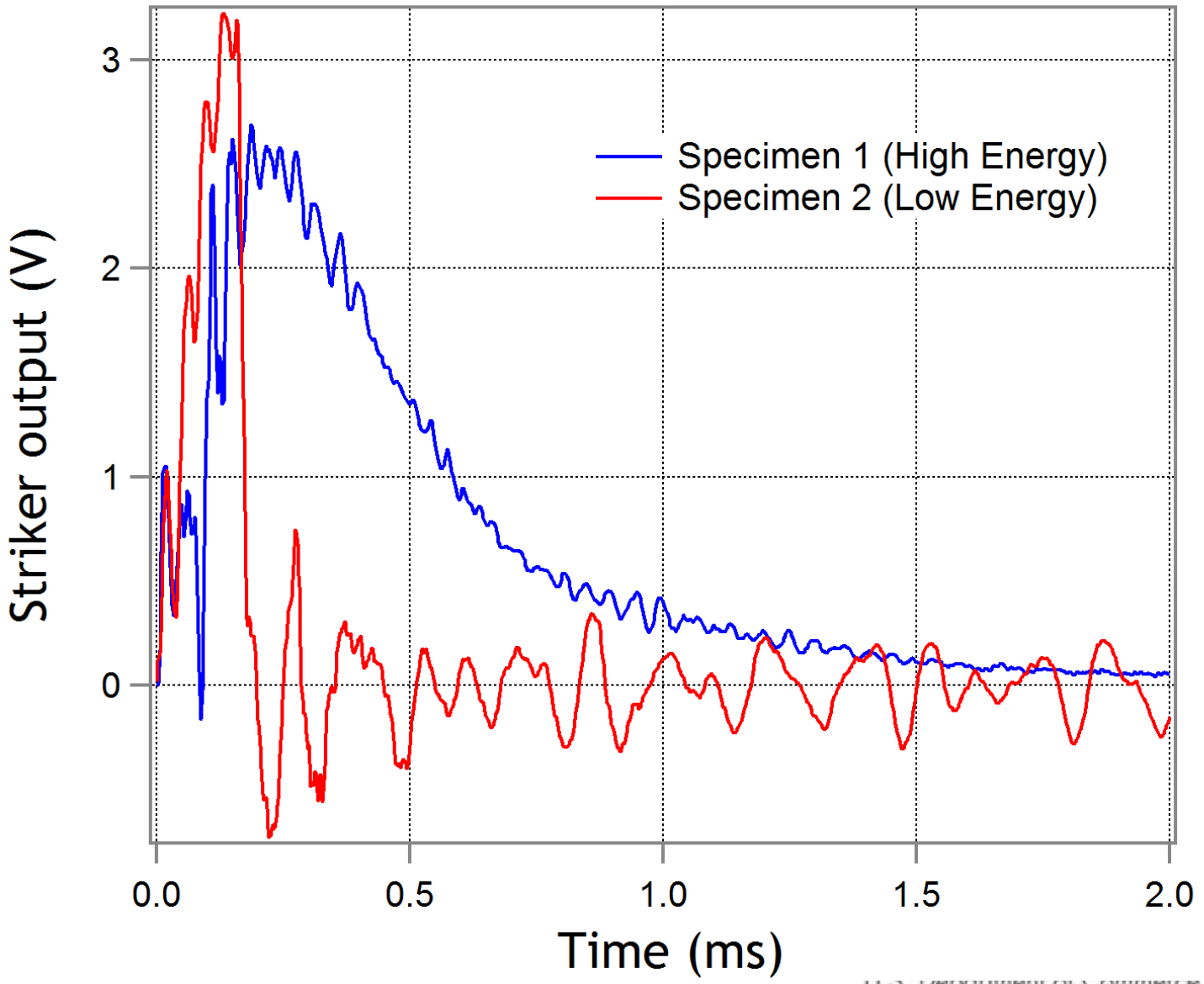
Instrumented Charpy Impact Testing – Striker Calibration

Static Calibration (usual)

Ex-situ or In-Situ

Dynamic methods investigated

- Integrate **force-displacement** to get **energy**, and scale the force values to give agreement with the absorbed energy measurement.
- Calibrate by impact with a mounted force transducer (low blow)
- Instrumented hammer
- Impacting mass



Unsteady Aerodynamics

Image courtesy of NASA Ames Research Center

- Buffet oscillations
- Aeroelastic Flutter

  Frequency range: Hz – 100's of Hz

  (*Springer Handbook of Exp. Fluid Mechanics*)

- Hypersonic impulse testing

  Frequency range: 100's of Hz – several kHz

  (*Cite source?*)

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Unsteady Aerodynamics

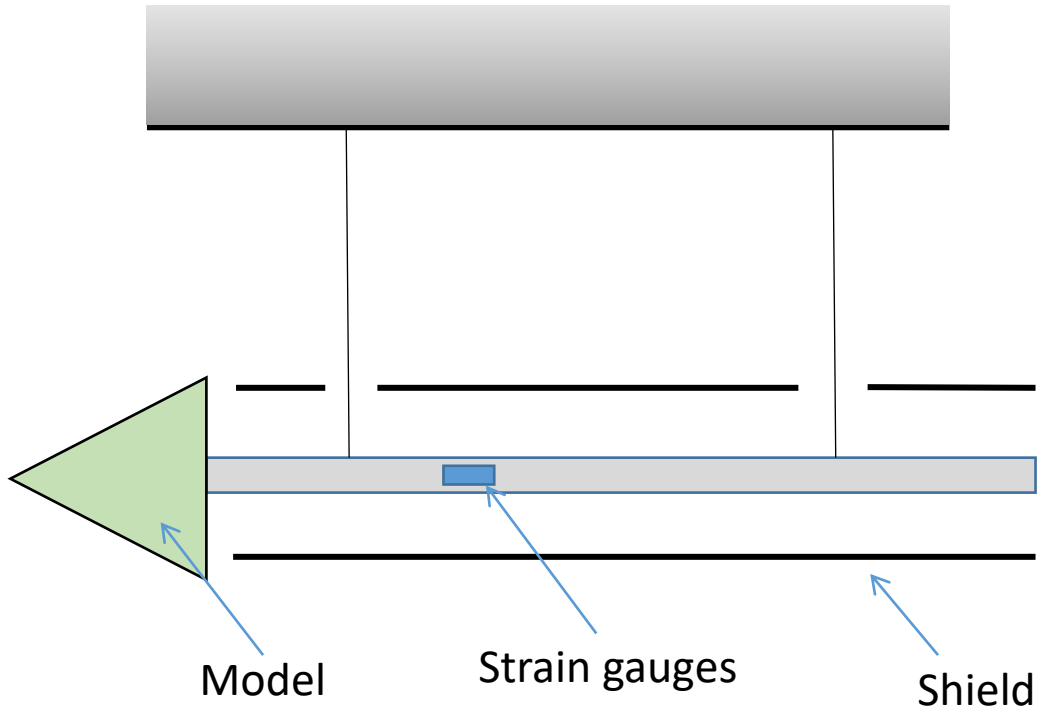

Image cou

Stress wave force balance

Internal strain gauge force balance

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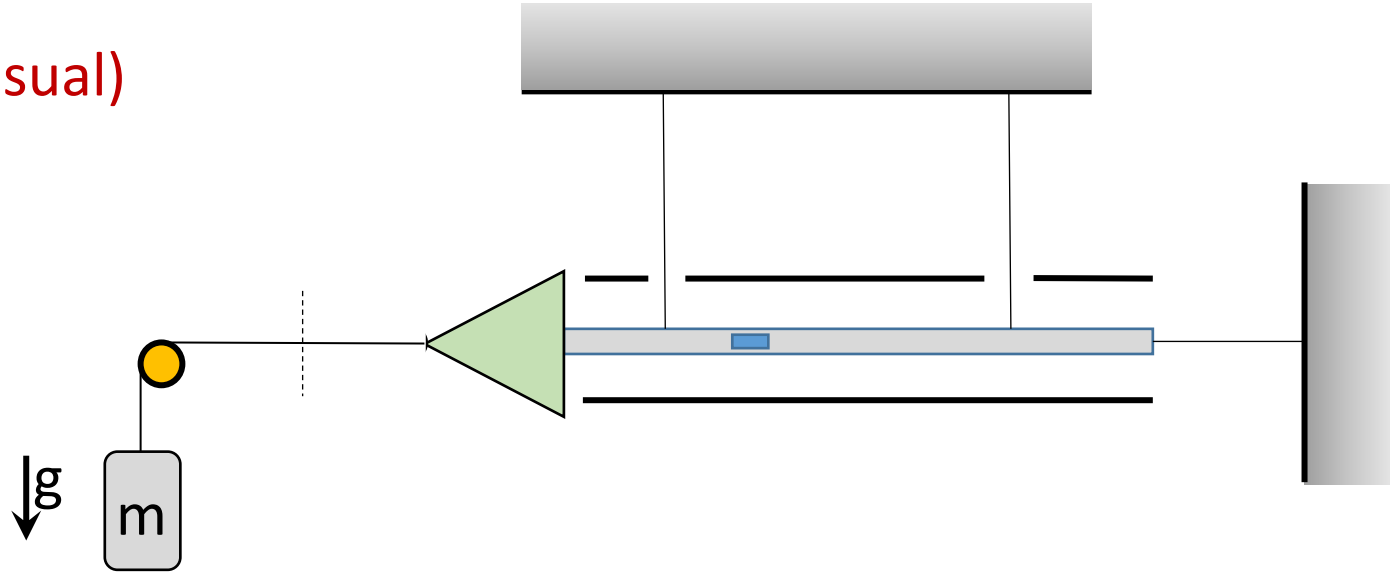
Aerodynamic Force Balances - Calibration

Standard Balances: Static Calibration (usual)

- Deadweights
- Reference transducers

Standard Balances: Dynamic Calibrati

- Instrumented hammer



Stress Wave Balances: Dynamic Calibration

- Instrumented hammer
- Cut wire

See D. J. Mee, *Shock Waves* 12, (2003), pp 443-455

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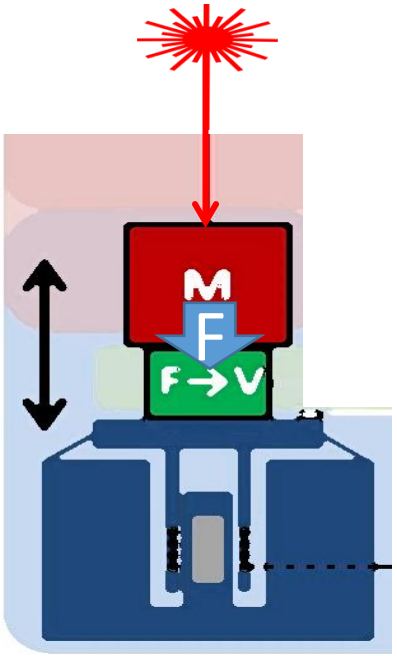
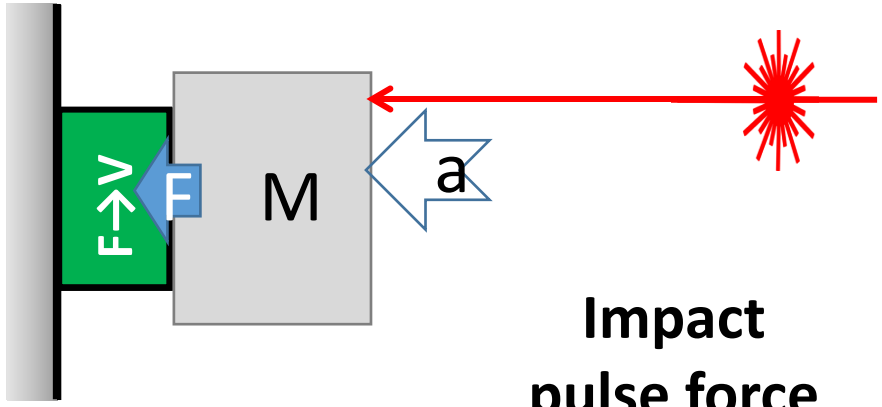
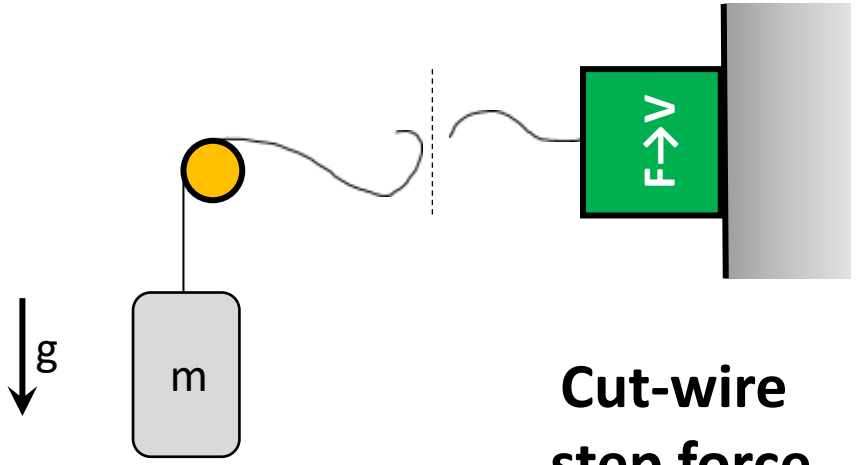
Some Types of Demonstrated Dynamic Force Standards



Shaker-driven
sine force



Impact
pulse force



Cut-wire
step force

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“Calibration” without dynamic force standards

Modeling, in the form of some assumptions, is a feature of most dynamic calibrations, and provides

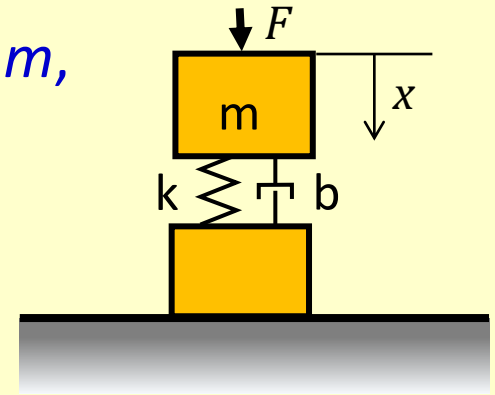
- communication of calibration results and incorporation of them into a larger system
- reduces the requirement on the force standard
- means of inversion and determination of measurement uncertainty

In general the uncertainty depends on both the uncertainty of the model parameters and the degree of applicability of the model.

It can be the case that a model (e.g. parameter values) are not determined using known dynamic forces applied over the range of interest.

Example: Simple harmonic oscillator model with parameters *m*, *k*, *b* determined by static loading (*k*) and by a tap test (*m*, *b*).

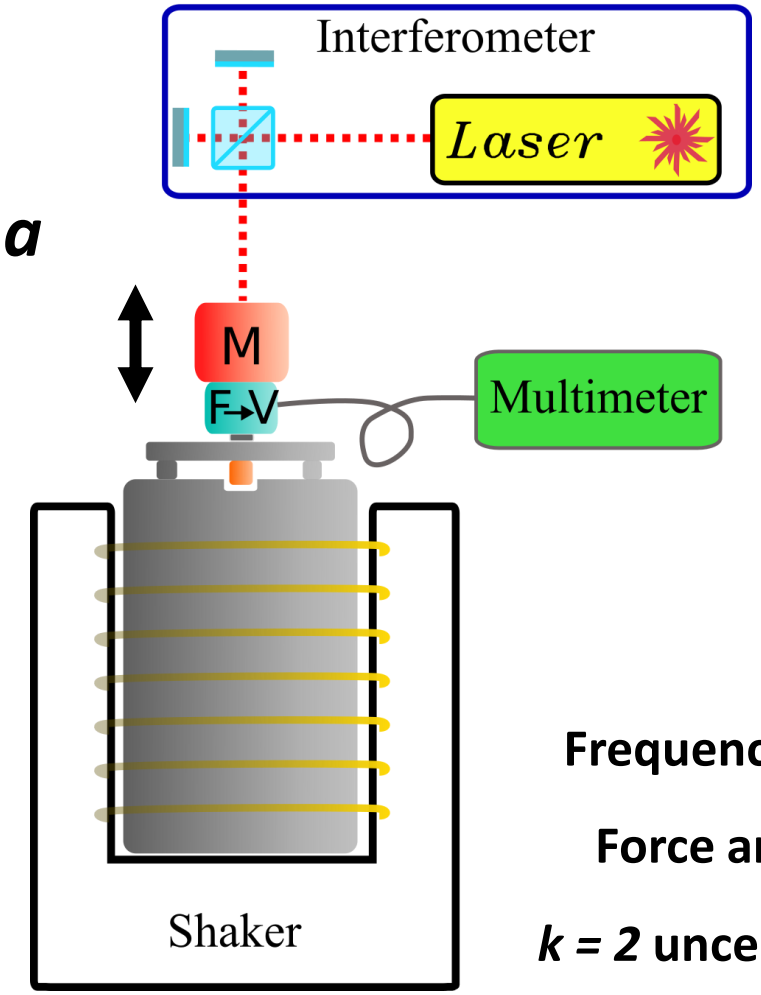
$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = F(t)$$



If the validity of the developed model is not tested by applying known dynamic force inputs adequately covering the range of interest, then I would not call it a calibration.

NIST Shaker-driven dynamic force standard

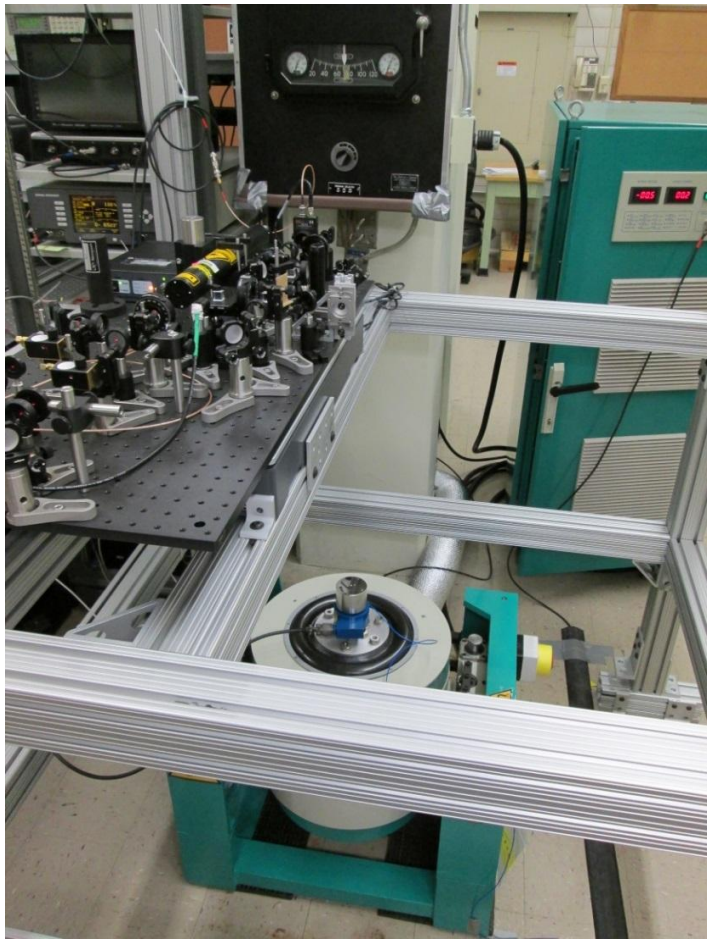
$F = m\,a$



Frequency (sinusoidal) up to 2 kHz

Force amplitude up to 1.5 kN

***k* = 2 uncertainty range 0.10 % - 3.0 %**



Force application from 100 Hz - 2 kHz with *k* = 2 uncertainty < 1.5 %

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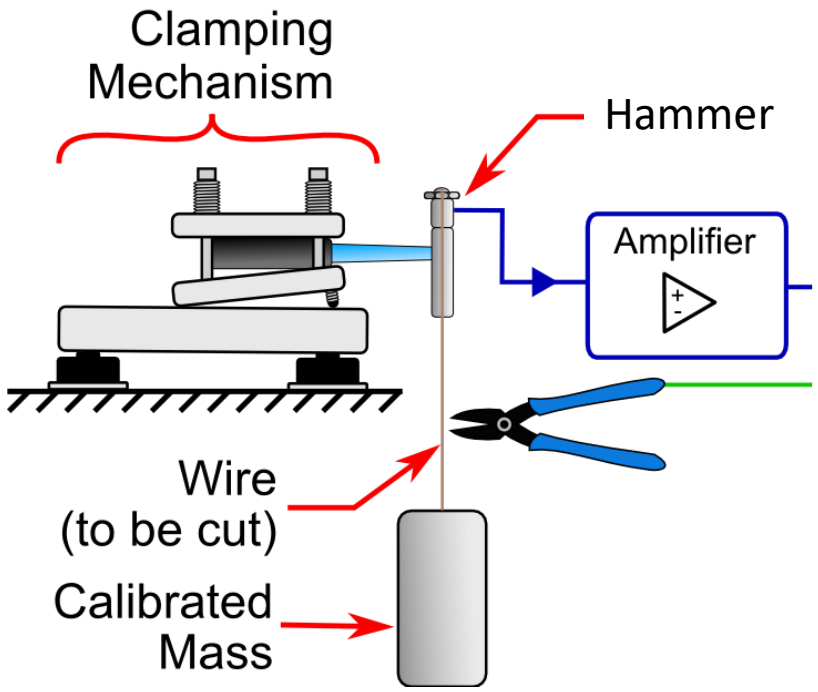
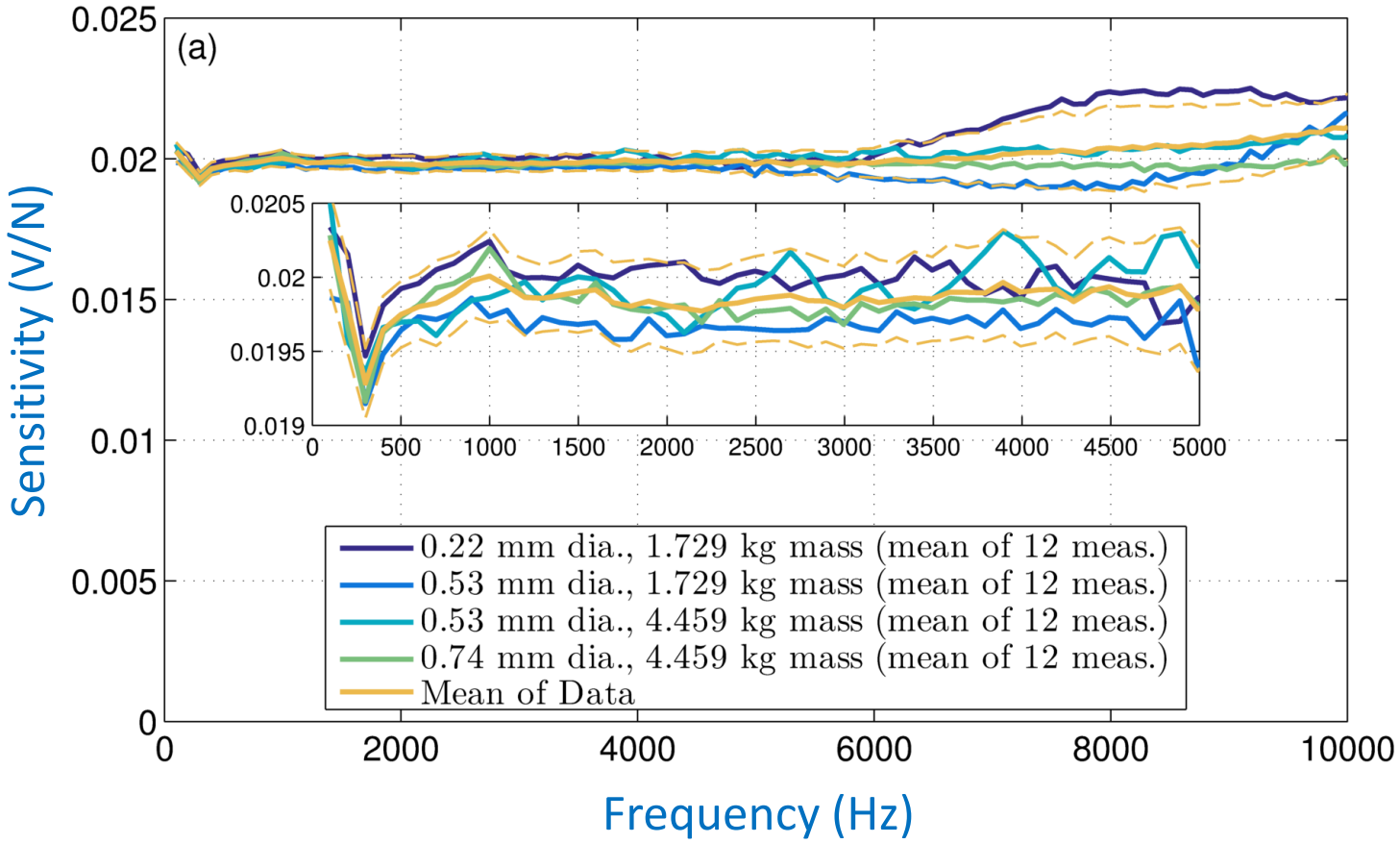
NIST Instrumented Hammer Calibration Test





k = *2* uncertainty < 2.1 % up to 5 kHz

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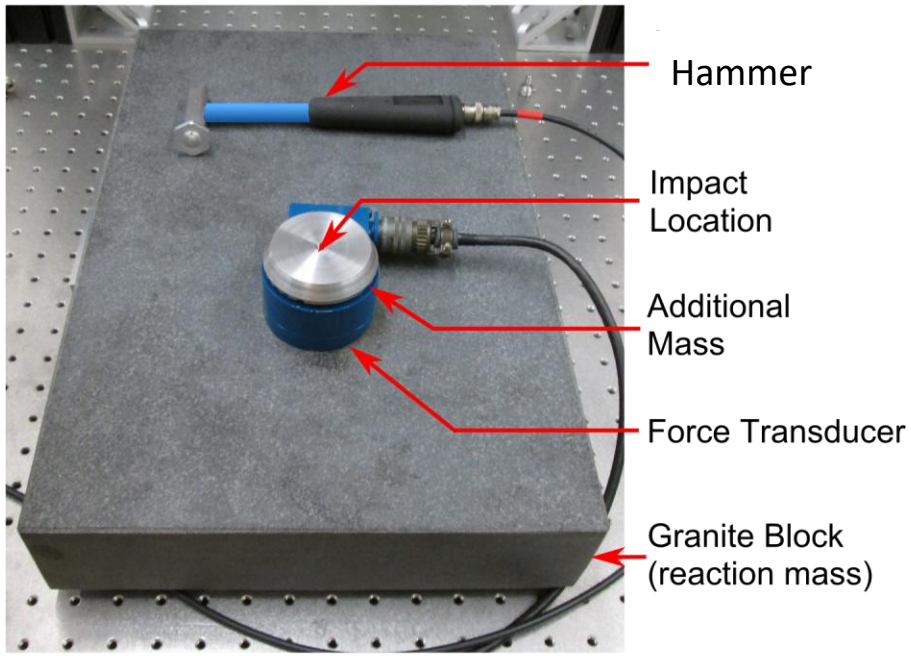
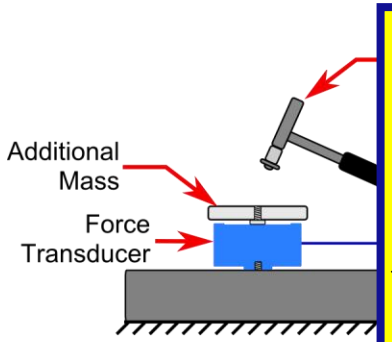
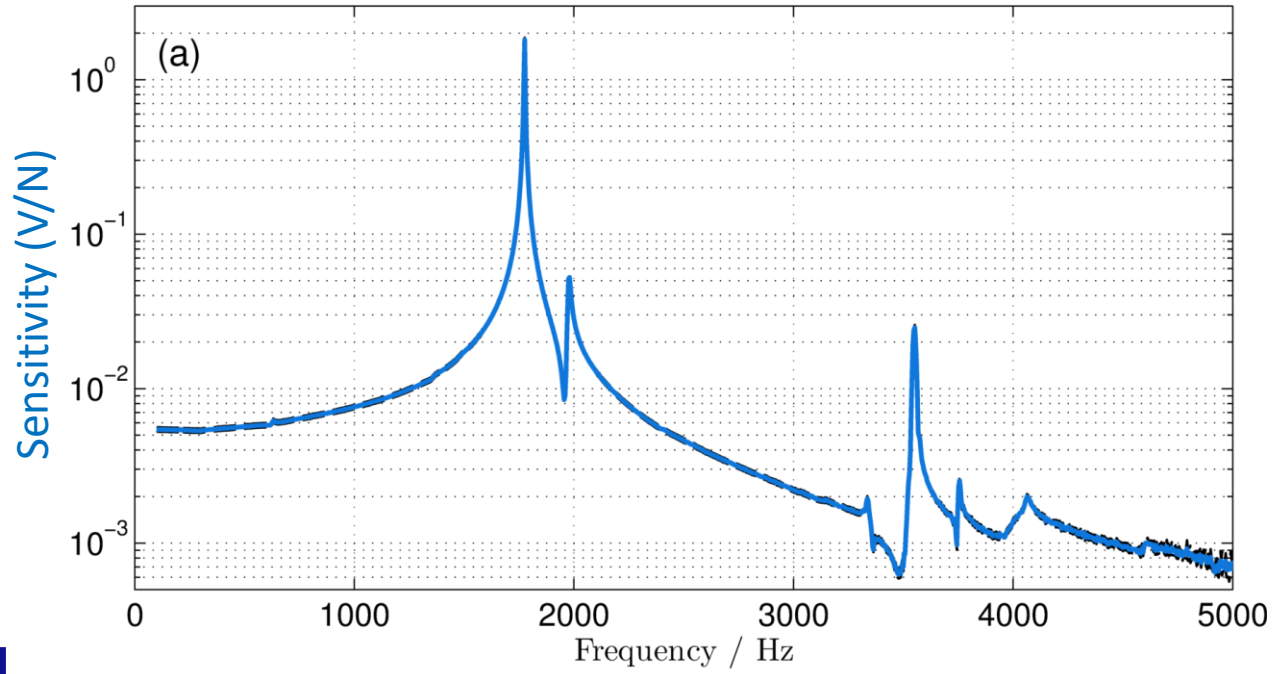
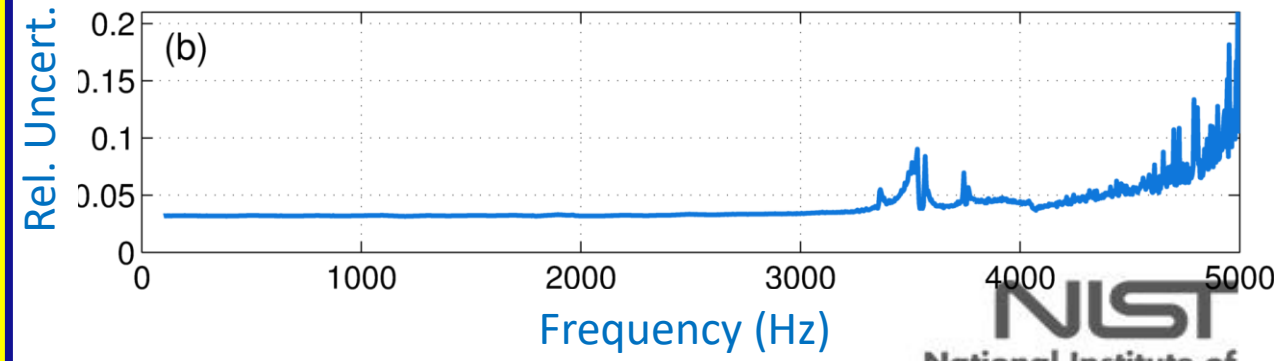
NIST Instrumented Hammer Calibration Test





- **Force does not need to be explicitly determined.**
- **Voltage measurement in transfer does not need to be traceable**





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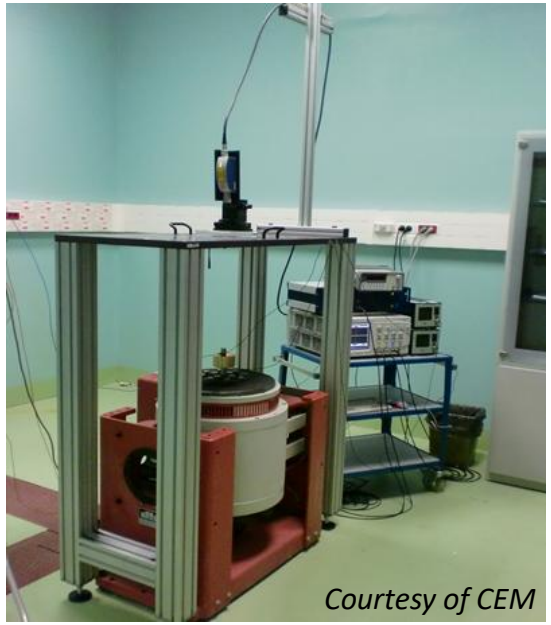
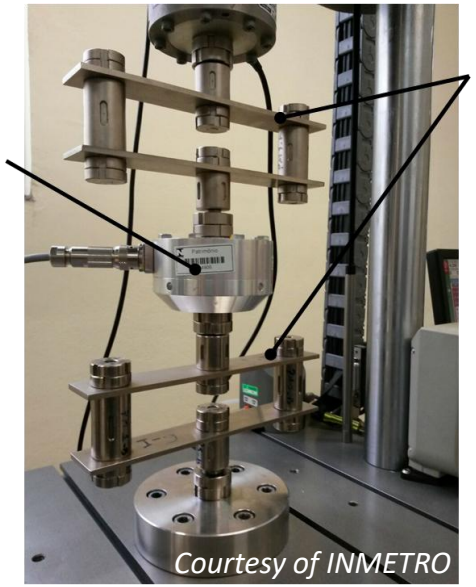
NMI Dynamic Force Facilities

PTB Shaker-driven standard

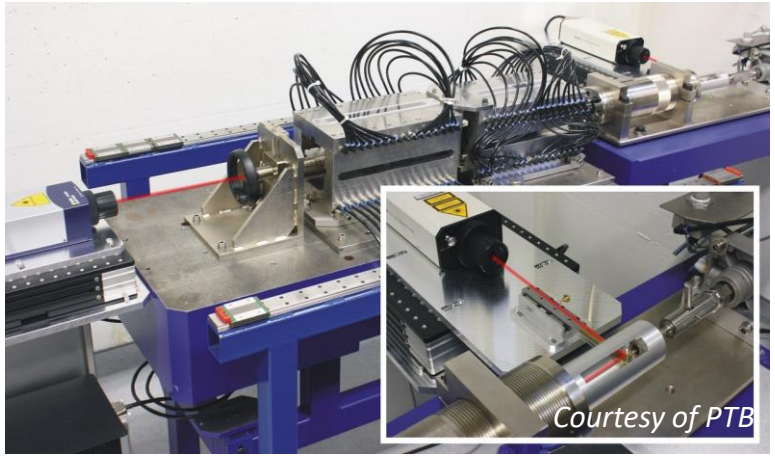


CEM Shaker-driven standard

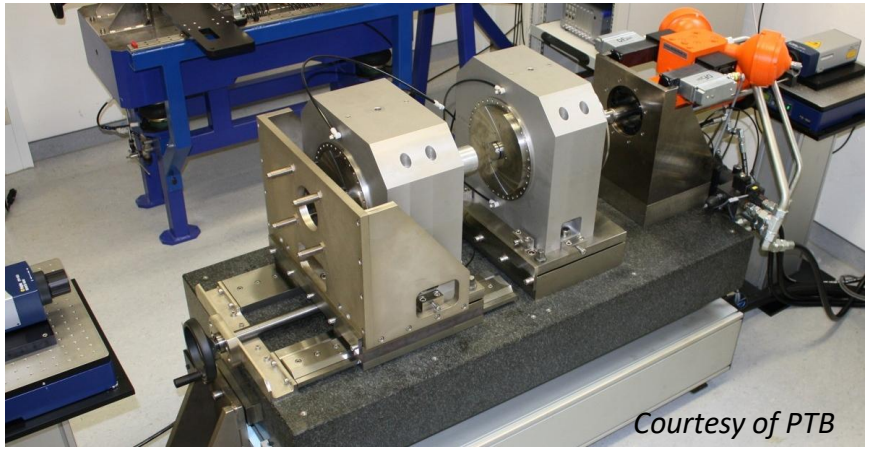
NIST Shaker-driven standard



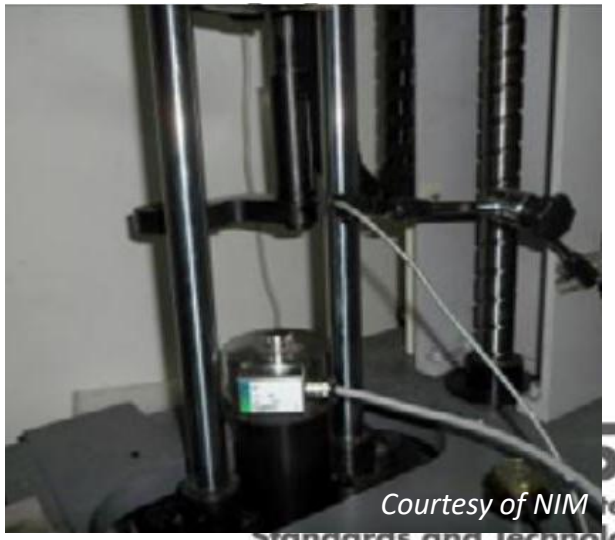
INMETRO Fatigue system



PTB 20 kN impact standard

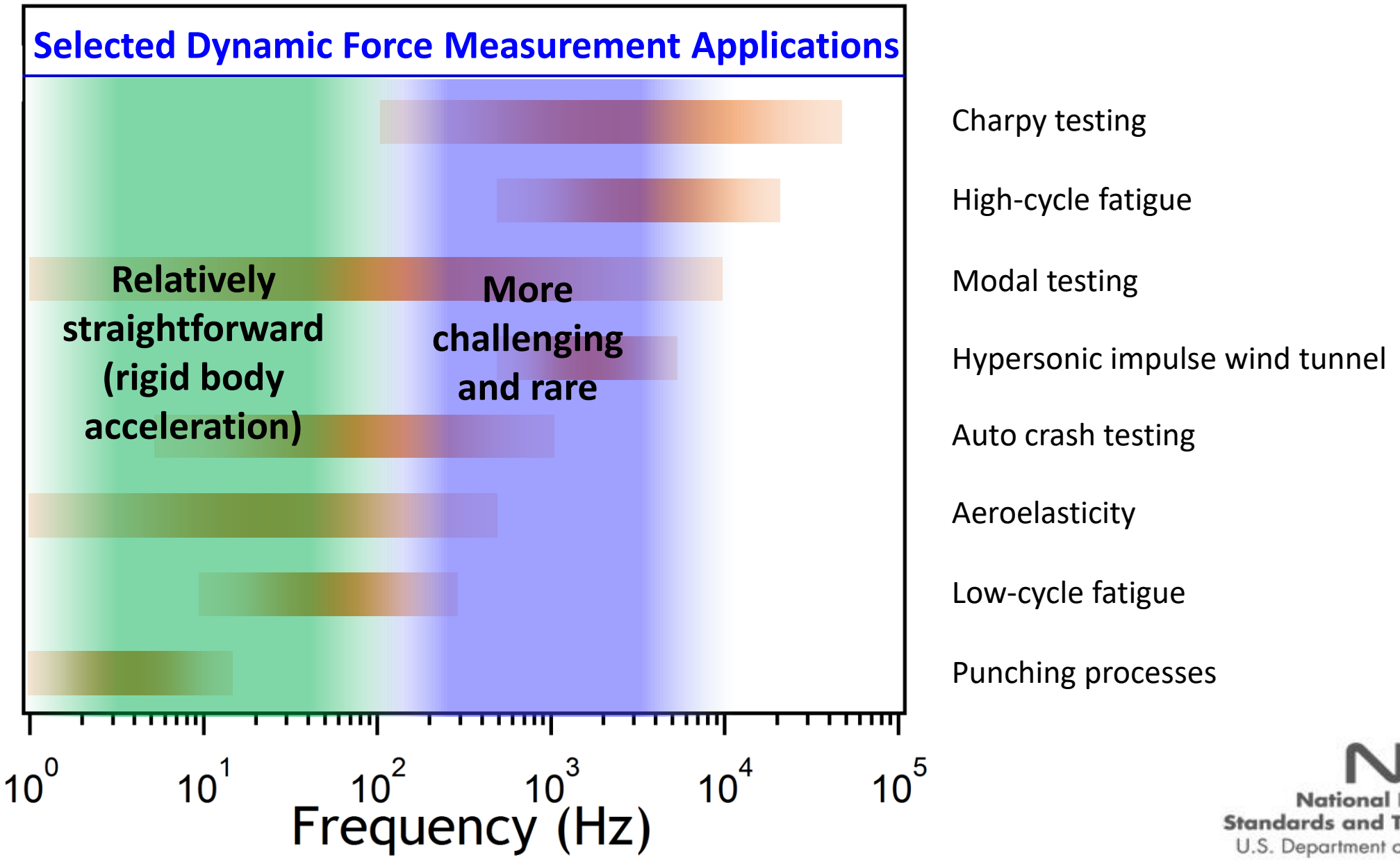


PTB 250 kN impact standard



NIM 1 MN impact standard

Availability of low-uncertainty dynamic force standards



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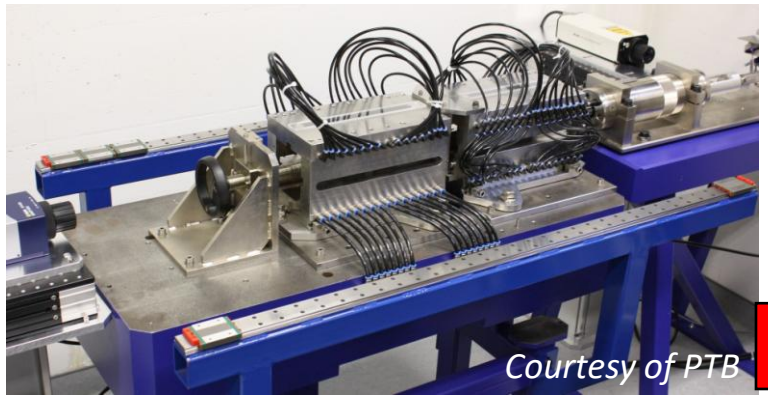
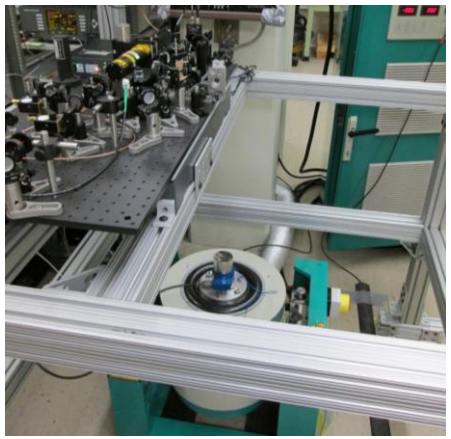
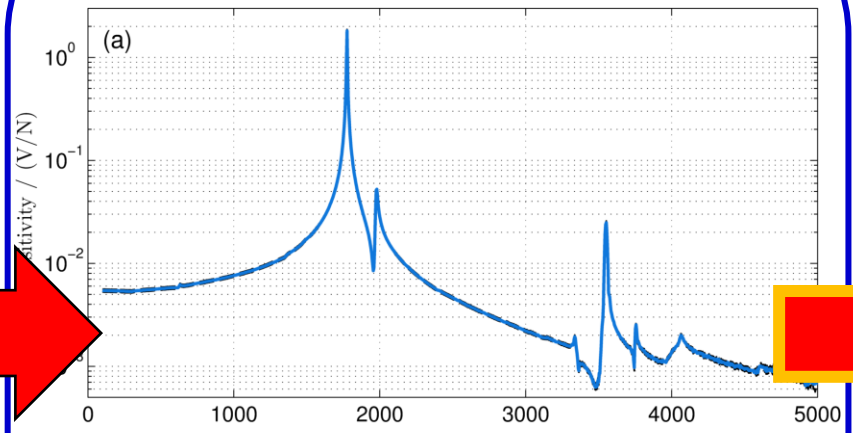
Going from dynamic calibration to dynamic measurement

Standards



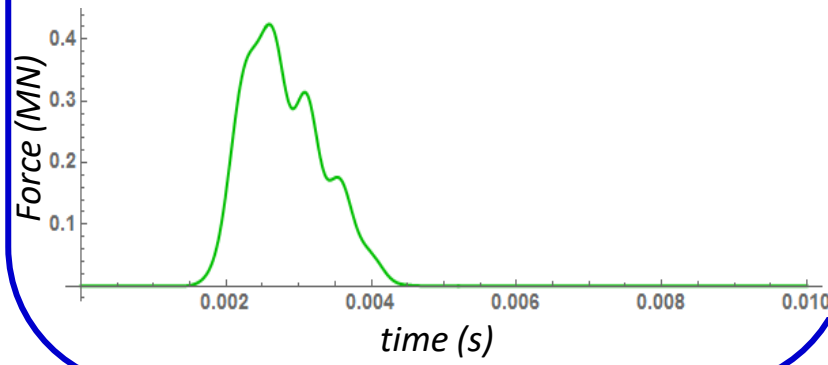


Calibration



- Transfer function / impulse response (linear system)
- Model parameters describing dynamic response of the system
- Response to particular force-time profile of interest

Measurement



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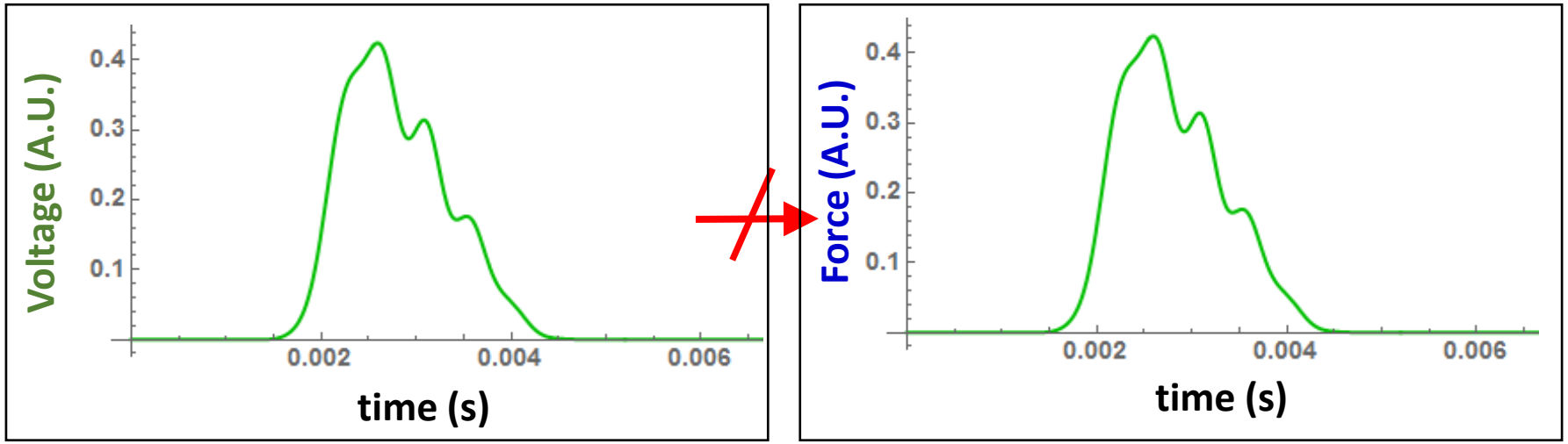
Going from dynamic calibration to dynamic measurement

There is **not** proportionality between output signal (e.g. voltage) and the input force, as a function of time:

$$V(t) = \int_{-\infty}^{\infty} F(\tau)S(t-\tau)d\tau$$



In the frequency domain, for a linear time-invariant system, there is proportionality

$$V(s) = F(s)S(s)$$

Various methods to deconvolve (invert) are available in time, frequency domains. However the problem is *ill-posed*: insufficient signal-to-noise will lead to large errors in the deconvolved force.

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Going from dynamic calibration to dynamic measurement

Challenge 1: "Regularization" to make the inversion stable ✓

Many techniques are available to regularize, in time, frequency domains

Challenge 2: Quantifying the uncertainty of the deconvolved input (force)

- Propagation of measurement and calibration uncertainty handled through digital inverse filters

  S. Eichstädt, V. Wilkens, A. Dienstfrey, P. Hale, B. Hughes and C. Jarvis. *Metrologia* **53(4)**, 2016

  S. Eichstädt, C. Elster, T. J. Esward and J. P. Hessling (2010) *Metrologia* **47**, 522-533
- Efficient implementation of Monte Carlo methods for real-time point-by-point coverage interval determination

  S. Eichstädt, A. Link, P. Harris and C. Elster. *Metrologia* **49**, 401-410, 2012.
- Application of Kalman filter to inversion and uncertainty determination for linear and nonlinear systems

  S. Eichstädt, N. Makarava and C. Elster. *Meas. Sci. Technol.* **27(12),** 125009, 2016.
- Open-source software packages for inversion and uncertainty evaluation of dynamic measurements

  S. Eichstädt, C. Elster, I.M. Smith, T.J. Esward. *J. Sens. Sens. Syst.*, **6,** 97-105, 2017

  S. Eichstädt and V. Wilkens. *Meas. Sci. and Technol.*, ***27****(5),* 2016.

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Cross-NMI activities

MATHMET Dynamic: Mathematical and statistical tools for dynamic measurements

BIPM workshop on Challenges in Metrology for Dynamic Measurement (2012)

EMRP IND09 (2011-2014): Traceable Dynamic Measurement of Mechanical Quantities

EMPIR 14SIP08 (2015-2018): Standards and software to maximise end user uptake of NMI calibrations of dynamic force, torque and pressure sensors

SIM-IADB Project on Dynamic Force Measurement (2017-2018)

Conclusion: Status of Dynamic Force Metrology

Are SI-traceable dynamic force measurements with quantified, low uncertainties *ubiquitously available*?

No. Not yet.

Are SI-traceable dynamic force measurements with quantified, low uncertainties *possible*?

Yes. At least sometimes.

Are SI-traceable dynamic force measurements with quantified, low uncertainties ~~widely~~ *available*?

Yes, sometimes.

Are SI-traceable dynamic force measurements with quantified, low uncertainties sometimes *impossible*?

Currently, **yes**.

Progress is being made!

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“It is thought that no apology is necessary for any proposition that promises to advance, be it ever so slightly, our capacity to measure forces.”

B. W. Dunn, *J. Franklin Institute*, 144 (1897)

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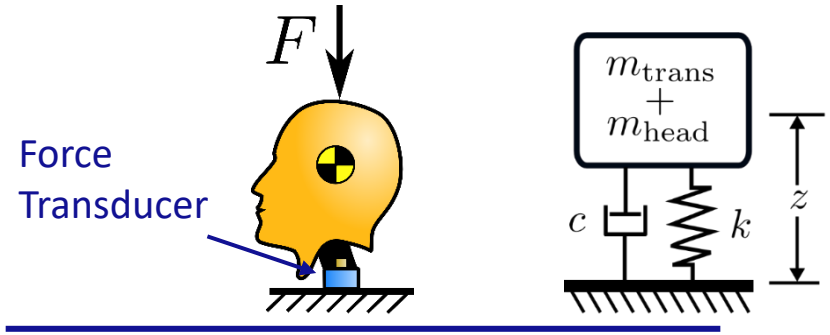
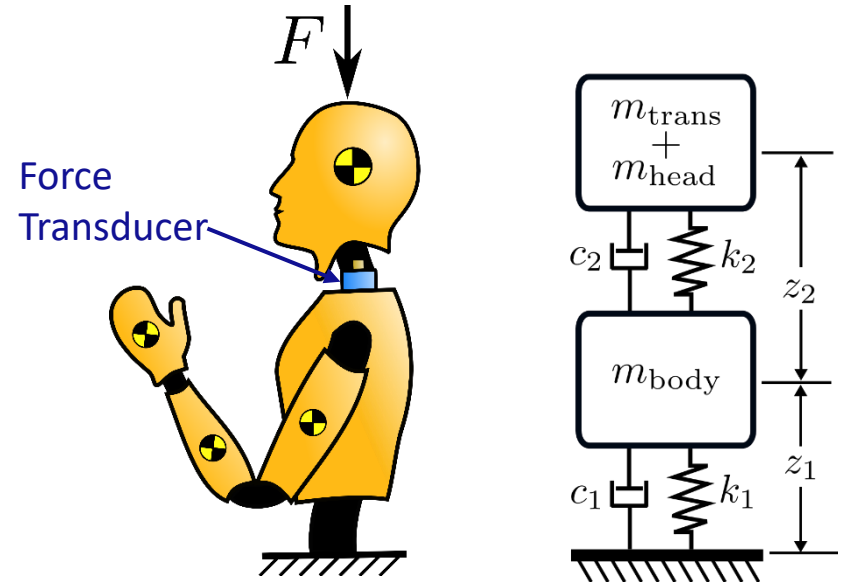
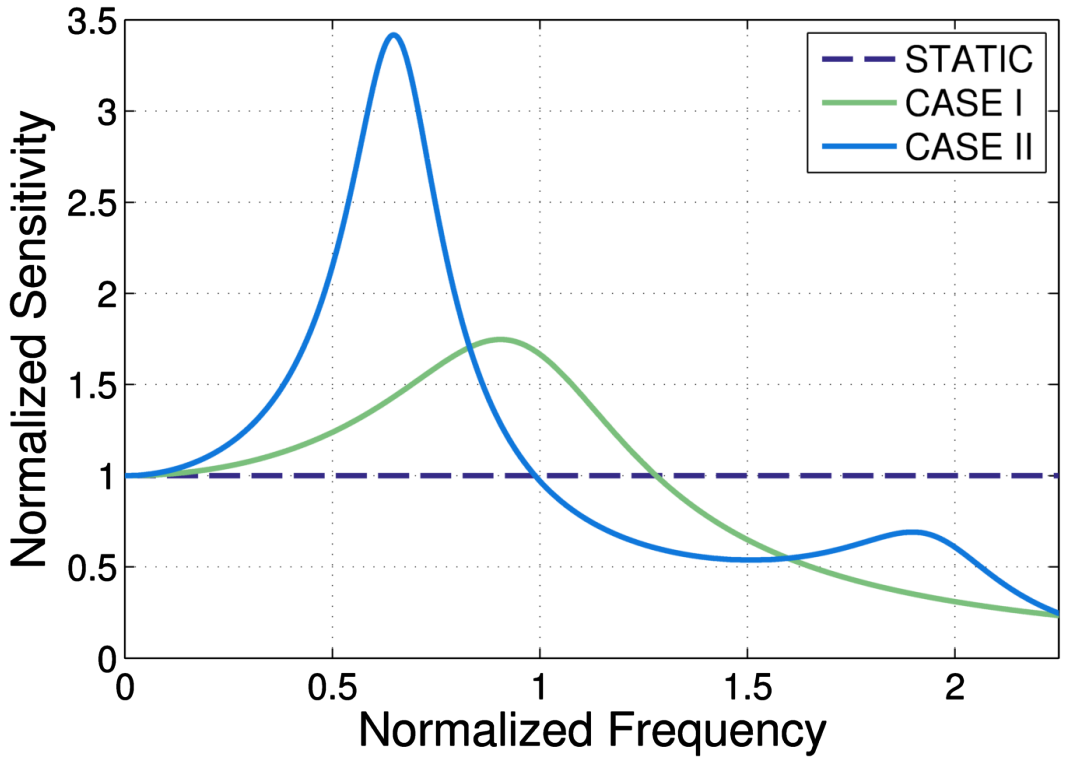
x

SUPPORTING STRUCTURE I:



SUPPORTING STRUCTURE II:





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Sinusoidal Calibration System – Force Amplitude Uncertainty

Source of Uncertainty	Standard Uncertainty [N/N]	Type
Misalignment & rocking	3.0×10^{-2} - 1.3×10^{-3}	B
Interferometer nonlinearity	3.0×10^{-3} - 7.6×10^{-6}	B
Optical platform vibrations	2.4×10^{-3} - 3.0×10^{-5}	A
Phasemeter error	2.0×10^{-3} - 5.1×10^{-6}	B
Interferometer resolution	1.2×10^{-3} - 3.0×10^{-7}	A
Calibration mass elasticity	1.2×10^{-3} - 1.7×10^{-5}	B
Mass measurement	1.5×10^{-5}	B
Air drag	2.9×10^{-5} - 2.9×10^{-8}	B
Combined Standard Uncertainty	**3.1×10^{-2} - 1.3×10^{-3}**	
Expanded Uncertainty ($k = 2$)	**6.2×10^{-2} - 2.6×10^{-3}**	

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Transfer to Working Transducer

Strike the working transducer in the application setting

Working Transducer:

$$V_{\mathrm{wt}}(s) = A_{\mathrm{wt}}(s)F(s)$$

Transfer Standard:

$$V_{\mathrm{ts}}(s) = A_{\mathrm{ts}}(s)F(s)$$

$$A_{\mathrm{wt}}(s) = A_{\mathrm{ts}}(s)\left(\frac{V_{\mathrm{t}}(s)}{V_{\mathrm{ts}}(s)}\right)$$

unknown — known — measured

Transfer calibration performed using a ratio of voltages

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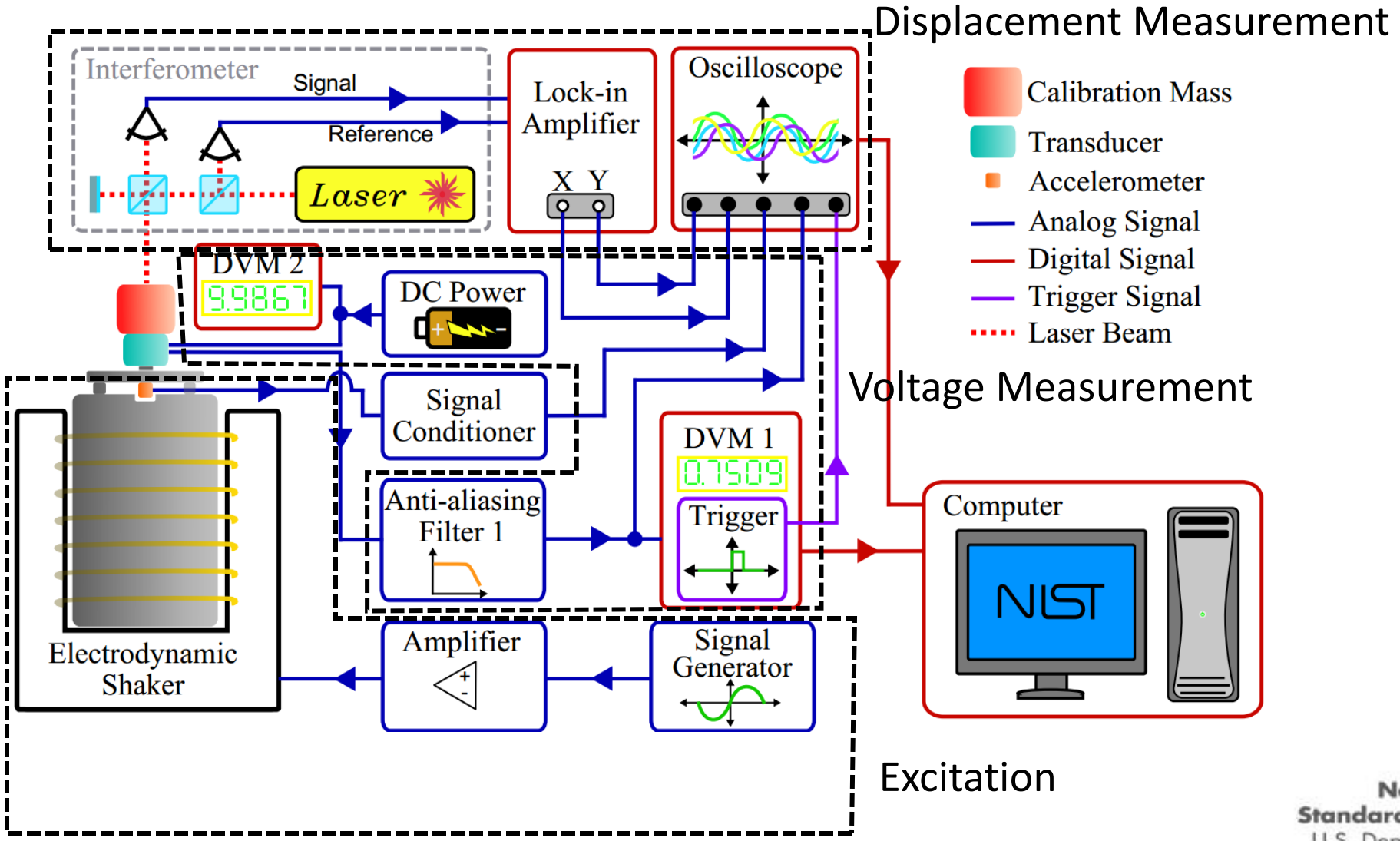
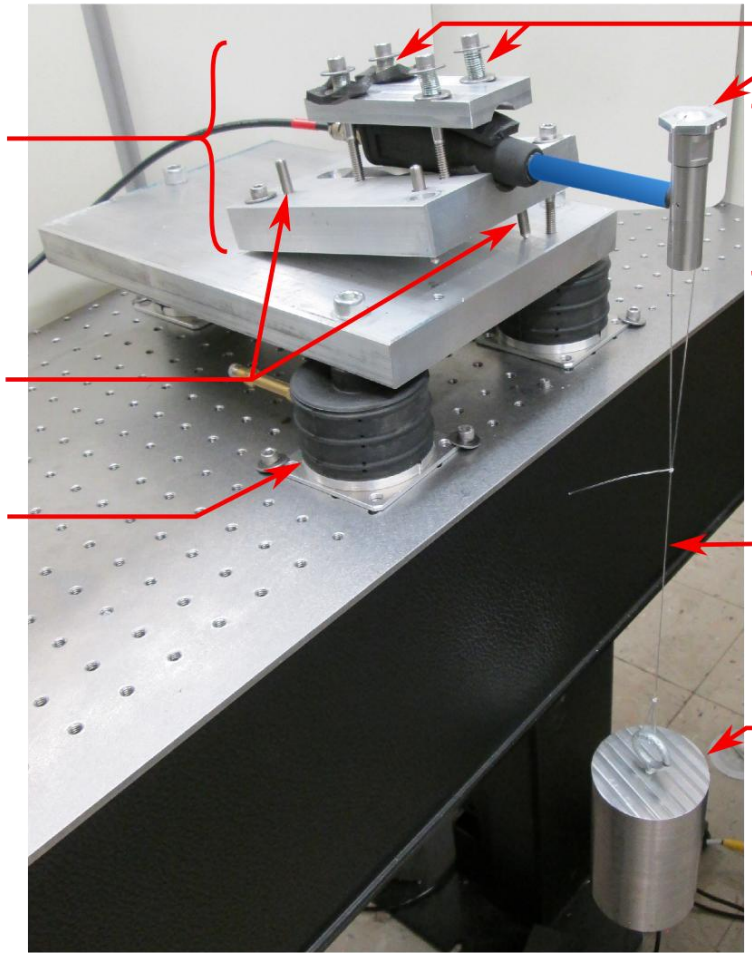
Calibration System



(a)



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Origin of Uncertainty	Rel. Unc.	Unc. Type	Distr. Type	D.O.F.
Uncertainties in Voltage				
misalignments, $\tilde{u}_{V_{\mathrm{ts}},\mathrm{align}}$	3.1×10^{-3}	B	Uniform	∞
instrumentation, $\tilde{u}_{V_{\mathrm{ts}},\mathrm{inst}}$	1.8×10^{-4}	A	Gaussian	6-8
Combined Uncertainty	3.1×10^{-3}			
Expanded Uncertainty ($k = 2$)	6.2×10^{-3}			
Uncertainties in Force				
force profile*, $\tilde{u}_{f_o,\mathrm{profile}}$	0 - 4.7×10^{-3}	B	Uniform	∞
misalignments, $\tilde{u}_{f_o,\mathrm{align}}$	4.8×10^{-4}	B	Uniform	∞
mass, $\tilde{u}_{f_o,\mathrm{mass}}$	1.2×10^{-4}	A	Gaussian	90
gravity, $\tilde{u}_{f_o,g}$ (See Ref. [18])	1.0×10^{-6}	A	Gaussian	35
Combined Uncertainty*	5.0×10^{-4} - 4.7×10^{-3}			
Expanded Uncertainty* ($k = 2$)	1.0×10^{-3} - 9.5×10^{-3}			
Uncertainties due to Nonrepeatability				
amplitude nonrepeatability*, $\tilde{u}_{A_{\mathrm{ts}},\mathrm{rep}}$ (5 kHz bandwidth)	2.4×10^{-3} - 7.2×10^{-3}	A	Gaussian	47 (at 100 freqs.)
Expanded Uncertainty* ($k = 2$)	4.9×10^{-3} - 1.4×10^{-2}			
Uncertainties due to User-to-User Variability				
amplitude variability*, $\tilde{u}_{\mathrm{user}}$	4.7×10^{-4} - 3.5×10^{-3}	A	Gaussian	2 (3 means at 4 freqs.)
Expanded Uncertainty* ($k = 2$)	9.4×10^{-4} - 7.0×10^{-3}			
Total Amplitude Uncertainty†				
Combined Uncertainty* ($k = 1$)	5.5×10^{-3} - 1.1×10^{-2}			
Expanded Uncertainty* ($k = 2$)	1.1×10^{-2} - 2.1×10^{-2}			

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Table 3: Uncertainties in amplitude of the transfer calibration of the application transducer, over a 3 kHz bandwidth. The abbreviation D.O.F. is the assumed or known number of degrees of freedom. Quantities denoted with a star (*) are frequency dependent. †The total uncertainty is calculated from inserting the sub components into equation (9) and evaluating at each frequency.

Origin of Uncertainty	Rel. Unc.	Unc. Type	Distr. Type	D.O.F.
Uncertainties in Voltage				
angle of common force, $\tilde{u}_{V_r,\mathrm{ang}}$ (10°)	1.5×10^{-2}	B	Uniform	∞
repeatability*, $\tilde{u}_{V_r,\mathrm{rep}}$	7.2×10^{-4} - 5.1×10^{-3}	A	Gaussian	368 (at 1250 freqs.)
channel-to-channel, $\tilde{u}_{V_r,\mathrm{ch2ch}}$	6.4×10^{-6}	B	Uniform	∞
Combined Uncertainty	1.5^{-2} - 1.6^{-2}			
Expanded Uncertainty ($k = 2$)	3.0^{-2} - 3.2^{-2}			
Uncertainty in Impact Hammer Calibration				
impact hammer*, $\tilde{u}_{A_{ts}}$	5.5×10^{-3} - 8.1×10^{-3}	A,B	Gaussian, Uniform	47 (at 100 freqs.), ∞
Expanded Uncertainty* ($k = 2$)	1.1×10^{-2} - 1.6×10^{-2}			
Total Amplitude Uncertainty†				
Combined Uncertainty* ($k = 1$)	1.6×10^{-2} - 1.7×10^{-2}			
Expanded Uncertainty* ($k = 2$)	3.1×10^{-2} - 3.4×10^{-2}			

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