

Dynamic Force Calibration

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1 Introduction

There is a widespread need to measure forces that are changing rapidly in time. Some examples are in wind-tunnel measurements of aerodynamic forces, automotive crash testing, machining, fatigue testing, force-controlled manufacturing (e.g. pressing, punching, automated assembly), and measurements of impact forces in sports, to name a few. The timescale over which forces change varies greatly across the range of applications, from seconds to sub-millisecond, as does the magnitude of the forces to be measured. On the other hand, the established and widely-practiced calibration procedures [1-3] are static.

It is usually the case that the sensitivity of a force transducer to an applied force depends on the loading rate, due to effects such as acceleration of internal masses, time-response of electronic parts of the transducer system, and others. Engineers carrying out dynamic force measurements therefore need to correct indicated forces based on static calibration data for these dynamic effects. However, the information to perform such dynamic correction (even to first order) is often lacking or can be only poorly estimated. This results in a larger-than-desired uncertainty, or even an inability to assign an uncertainty to the reported force measurements. In other words, while the measurement may be precise and repeatable, it is not traceable - its value cannot be represented in any established system of units.

Often, users of force transducers are unaware of the gap between static calibration and dynamic measurements, and the ensuing limitations. Force transducers are often advertised as being suitable for dynamic measurements, although in general no characteristic properties of the transducer are supplied other than the static sensitivity and a usable frequency range or sometimes the lowest resonance frequency of the (unloaded) transducer.

The consequences of not knowing the value of measured forces in terms of meaningful units are significant. In the first place it becomes impossible to standardize an operation based on the measured force value so that it is independent of the particular transducer used to perform the measurement. This also makes process modification difficult, as any such modification that affects the force measurement system will require a new determination of the best force values for the operation. It also means that measured force values cannot be compared to measurements made with other systems (including for example reference data), or to theoretical calculations. Finally, it means that the measured force values cannot be used to determine other quantities - for example force measurements cannot be combined with velocity measurements to determine power expenditure.

Dynamic force calibration aims to address the need for accurate measurements of rapidly-changing forces by directly calibrating force transducer systems under dynamic conditions. Measured time-varying forces are applied, and measurements are made of the time-varying transducer output. A system has been constructed at NIST (National Institute of Standards and Technology, Gaithersburg, Maryland) to perform such calibration with sinusoidal forces up to 2 kN in amplitude and up to 2 kHz in frequency.

2 Applications

Taking every single dynamic force measurement application into account is of course not possible. These applications cover a wide range of fields, spanning aerodynamics, civil structure load monitoring, manufacturing, engine thrust measurements, biomechanics, crash testing, sports, fatigue testing, high speed materials testing, and more. We consider a few examples here, to give a flavor of the varied calibration requirements.

2.1 Aerodynamics

Wind-tunnel aerodynamic testing is an area in which there is a strong need for low-uncertainty (i.e. accurate) dynamic force measurement. There are a number of important effects that lead to dynamic forces, such as aeroelastic flutter, vortex shedding, and buffet oscillations, in which designers of aircraft and civil structures are keenly interested. The frequency range of dynamic forces in wind-tunnel tests is typically below 500 Hz, with higher frequency measurements occasionally desired [4,5]; the range of force amplitude varies greatly - in many tests it is sub-newton, while the mean force can be several tens of kilonewtons in higher-speed tests of full-scale models [4]. The need for accurate force measurements in this field has sometimes led to the development of customized dynamic calibration systems.

2.2 Fatigue testing

Fatigue testing¹ of materials [5, 6] is a prototypical dynamic force measurement application. A material specimen is typically subjected to a continuous periodic force plus a steady bias force (which may be zero) until failure of the specimen occurs or the allotted test time is exceeded. Accurate knowledge of the force applied to the specimen is required for accurate stress versus lifetime results, and the need to take into account dynamic effects - most prominently the force required to accelerate connected masses - is understood in the industry. The testing frequency is most-commonly in the range below 100 Hz, although loading frequencies in the kilohertz range are often used to reduce the time duration of high-cycle tests. Force amplitudes vary greatly depending on the sample material and size as well as the desired test parameters, from the sub-newton range up into the meganewton range in some low-cycle tests.

2.3 Machining

Measurement of forces in machining operations has long been a driver for efforts to achieve accurate dynamic force measurement [8,9]. Having the ability to compare such measurements to theoretical calculations, and to derive from the measurements quantities such as expended power and material yield stresses, is desirable. This makes it necessary to know the the absolute value of the measured forces, that is the measurements must be traceable. The forces are typically periodic, and may range in frequency from tens of hertz to tens of kilohertz. The force amplitude varies widely amongst different machining operations, from the sub-Newton to tens of kilonewtons. A key consideration in the measurement of forces in machining is that the cutting system must remain sufficiently rigid to perform its function. Another is the presence of multiple force and moment components, and the desire that these not interfere with the measurement of the force component of interest.

2.4 Dynamic weighing

Dynamic weighing is a broad area, ranging from measurements of small mass additions in material production and processing, to weighing large vehicles such as buses and trains as they travel at high speed. The uncertainty-level desired (even if not achieved) in dynamic weighing can reach 0.1% or below in some applications [10]. However dynamic weighing is something of a counterexample: although it demands high accuracy measurements and the forces are dynamic, it does not require dynamic calibration. The reason for this is that the true measurand in weighing operations is mass, as opposed to force; therefore dynamic weighing instruments can be calibrated by comparing their outputs when dynamically weighing a test object to the known (statically-measured) mass of

¹Conventional fatigue testing is considered here, not including more specialized techniques such as ultrasonic fatigue testing or thermal fatigue testing.

the object.

3 NIST 2-kilonewton calibration system

3.1 System design

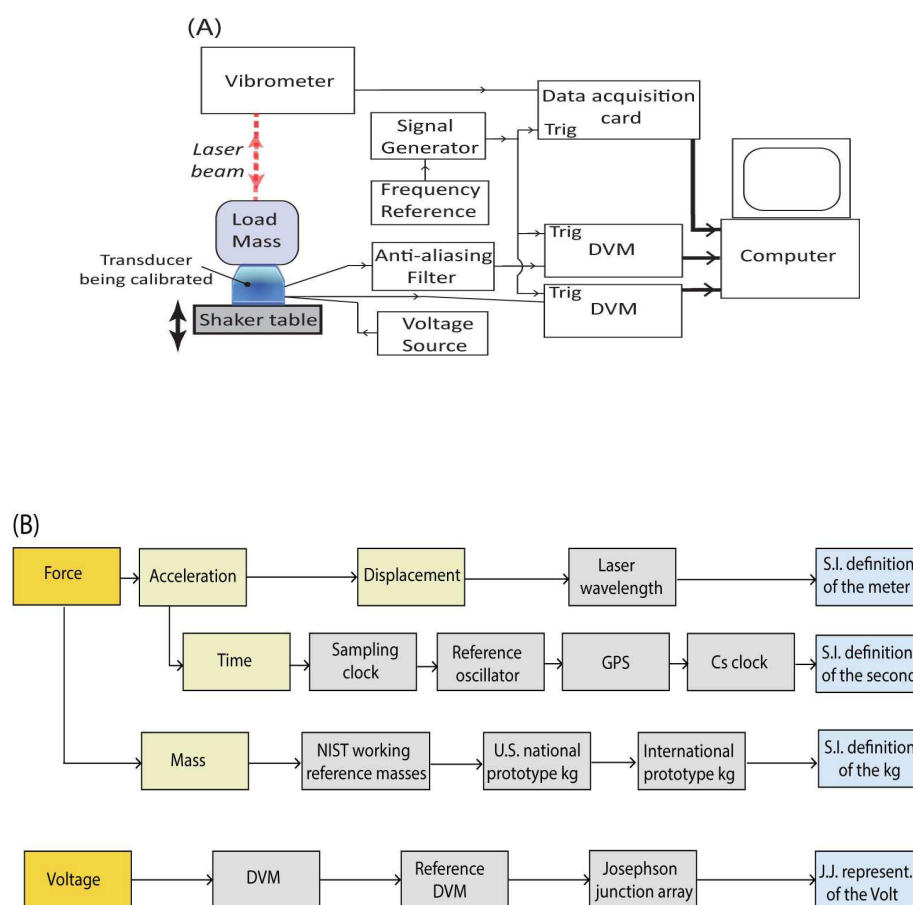


Figure 1: (a) Schematic diagram of NIST 2-kilonewton dynamic force calibration system. (b) Traceability chain for NIST 2-kilonewton dynamic force calibration system.

The design of the NIST dynamic calibration system is illustrated schematically in Figure 1(a). The force transducer to be calibrated is mounted on an

electrodynamic shaker, and an accurately-measured calibration mass is mounted on the transducer. The shaker is used to sinusoidally oscillate the transducer and mass at the selected frequency. The acceleration of the load mass is measured as a function of time by a laser vibrometer, and the applied force is thus determined from the mass and the acceleration. A fast-sampling DC voltmeter is used to measure the transducer response as a function of time. The acquisition of the transducer output voltage values and the mass acceleration values are synchronized. The data are transferred to a computer, where the sensitivity is determined as the ratio of the output voltage to the applied force. The operating region of the system covers frequencies ranging from 10 Hz to 2 kHz and forces from 1 N to 2 kN. The operating range is shown in Figure 2(a) as the maximum applicable force amplitude as a function of frequency, and in Figure 2(b) as the available range of acceleration amplitudes as a function of frequency and force value. The parameter range covered by this calibration system is relevant to a large fraction of dynamic force applications, including for example aerodynamic measurements, fatigue testing, crash testing, machining, biomechanical measurements, and robotics.

The force and voltage measurements made in the calibration system are traceable to the international system of units (SI), as shown in Figure 1(b). The force is determined by the product of mass and acceleration. The acceleration is determined from measurements of displacement at precisely-timed intervals. The displacement measurement is done by a laser interferometer, and is traceable via the laser frequency to the SI definition of the meter. The time intervals are set by a sampling clock, the period of which has been linked by a comparison to the GPS 1-pulse-per-second signal to the SI definition of the second, the duration of a fixed number of periods of oscillation of the cesium 133 atom between specified hyperfine levels of its ground state. The calibration mass is measured by comparison to mass standards at NIST, which have been calibrated by a chain of such comparisons to the SI definition of the kilogram, the international prototype kilogram in Paris. The voltmeter used is calibrated (via an intermediary precision voltmeter) to a programmable Josephson junction array, and thereby to the Josephson junction representation of the volt. The 2-sigma uncertainty of the force measurements is currently 1 % or less, and the uncertainty of voltage measurements is 1 % or less. Testing and validation of the system is currently ongoing.

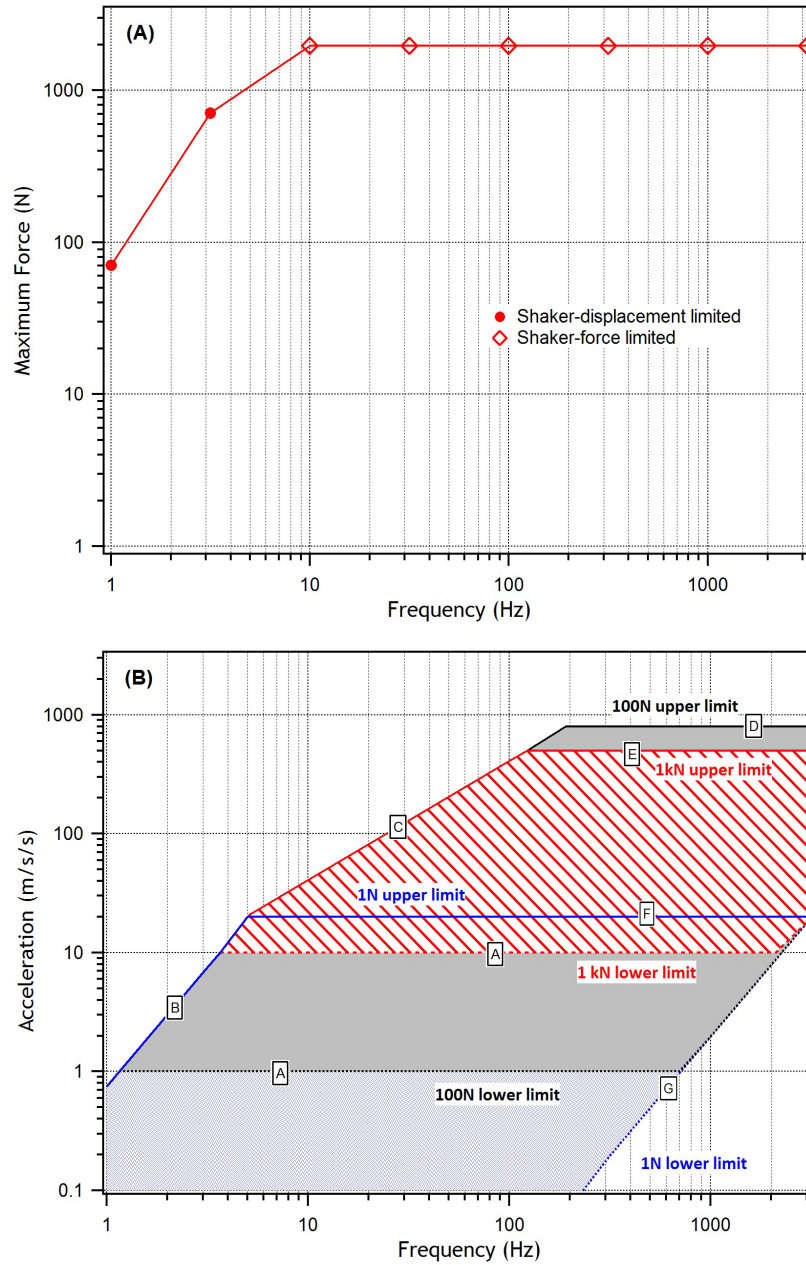


Figure 2: (a) Operating region of the NIST 2-kilonewton dynamic force calibration system, presented in terms of the maximum available force amplitude at a given frequency. (b) Operating region of the NIST 2-kilonewton dynamic force calibration system, presented as the available acceleration range for a given force amplitude. The acceleration range is limited by various factors labeled A to G: A - maximum mass that electrodynamic shaker can support, 100 kg; B - maximum allowed displacement of electrodynamic shaker, 19 mm; C - maximum velocity allowed by vibrometer, 0.65 m/s; D - maximum allowed acceleration of electrodynamic shaker, 800 m/s²; E - maximum force that electrodynamic shaker can generate, 2 kN; F - minimum calibration mass for low uncertainty calibration, 0.05 kg; G - minimum displacement for low-uncertainty calibration, 50 nm.

3.2 Sample calibration

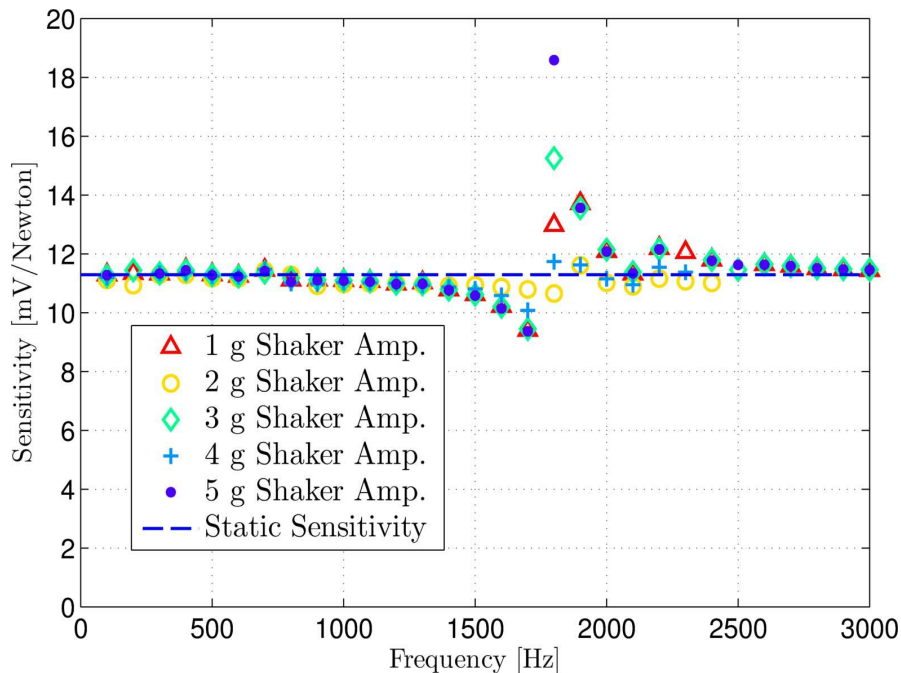


Figure 3: Dynamic calibration of a 500-newton-capacity piezoelectric force transducer from 100 Hz to 3 kHz, using a 1-kilogram calibration mass and several different nominal acceleration amplitudes. This transducer is specified to be accurate to 1 %, but its sensitivity was observed to deviate from the specified value by tens of percent in the vicinity of 1.8 kHz. The uncertainty ($k = 2$) of the dynamic sensitivity measurements was 0.009.

Figure 3 shows an example calibration measurement. In this case the sensitivity of a 500-newton-capacity piezoelectric force transducer was measured up to 3 kHz (somewhat exceeding the nominal 2 kHz range of the NIST calibration system). This transducer is specified as having a 1 % accuracy, based on a quasistatic calibration, and is indicated to be suitable for dynamic measurements up to a bandwidth of 30 kHz or more. It is evident from the figure that under the test conditions, variations of the sensitivity in the frequency range up to 2 kHz greatly exceed the 1 % specification. It was also observed that the frequency-dependence of the sensitivity was significantly affected by changes in the transducer mounting, despite remaining compliant at all times with the specified mounting requirements for the transducer. Although this measurement was done up to 3 kHz, the nominal frequency range of the NIST calibration system extends to 2 kHz.

4 Conclusion

Relying on static calibration data for force transducers when making dynamic measurements can lead to large errors. Even when users are aware of this problem, they generally lack the information to make corrections to their force measurements and assign reasonable uncertainties. Dynamic force calibration provides an answer to this situation. The new dynamic force calibration system under development at NIST performs harmonic calibration at frequencies up to 2 kHz, with force amplitudes up to 2 kN.

5 Acknowledgements

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6 References

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