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NIST 1-KILONEWTON SINE FORCE CALIBRATION SYSTEM

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Abstract: Many force-measurement applications are of a dynamic nature, and in recent decades there has been much progress in demonstrating and developing dynamic calibration systems for force transducers. The National Institute of Standards and Technology (NIST), U.S.A., is developing a system for sinusoidal calibration of force transducers with forces up to 1 kilonewton at frequencies up to 2 kilohertz, in a manner that is traceable to the International System of Units (SI). The system is based on harmonic excitation of a calibrated mass (m) using an electrodynamic shaker, laser interferometric measurement of acceleration (a), and voltage measurement using a calibrated fast digital voltmeter. The output voltage from a force transducer system under calibration is indexed against the input force given by $F = m\,a$. The design and operation of the system are described.

Keywords: dynamic force, harmonic force, calibration, traceability

1. INTRODUCTION

In many force-measurement applications, such as machining, crash testing of automobiles and fatigue testing, the measured forces vary rapidly in time, with the timescale of variation ranging down to the sub-millisecond. However force transducers are usually calibrated only statically. The deviation under dynamic loading conditions of a transducer's response from its static calibration has long been recognised as a practical problem [1, 2]. This has led in the past 2 to 3 decades to the investigation and development of a number of dynamic calibration systems, e.g. [3 – 11].

The force and frequency range up to 1 kilonewton and 2 kilohertz is important to a number of dynamic force measurement applications, as illustrated in Figure 1. To support calibration needs in this range, NIST is constructing a harmonic-force calibration system. The system is similar to those developed at the Physikalisch-Technische Bundesanstalt, Germany [5,6,9,12], the Centro Español de Metrología, Spain [13] and the Laboratoire Nationale de Métrologie et d'Essais, France [13]. A calibrated load mass is placed in contact with the transducer to be calibrated and accelerated by a force transmitted through the transducer, the drive being provided by an electrodynamic shaker. The force applied to the transducer is determined from Newton's 2nd law, $F = m\,a$, or $F = \int \rho(\mathbf{r})a(\mathbf{r})dr^3$, when the spatial variation of acceleration a and density ρ are taken into account.

2. SYSTEM DESCRIPTION

The calibration system configuration is shown schematically in Figure 2. The load mass is attached to the top of the transducer to be calibrated, which in turn is attached to the table of an electrodynamic shaker. Specifications of the shaker are given in Table 1. The acceleration of the load mass is measured interferometrically by a laser vibrometer. Two vibrometers are implemented, a commercial differential heterodyne interferometer and a custom heterodyne interferometer. The use of two largely-independent systems allows a consistency check on the measured acceleration at a single point, and alternatively allows accelerations at two different vertical positions on the assembly to be measured. The vibrometers are further described below. The transducer output voltage is measured by a fast-sampling DC digital voltmeter (DVM), and for

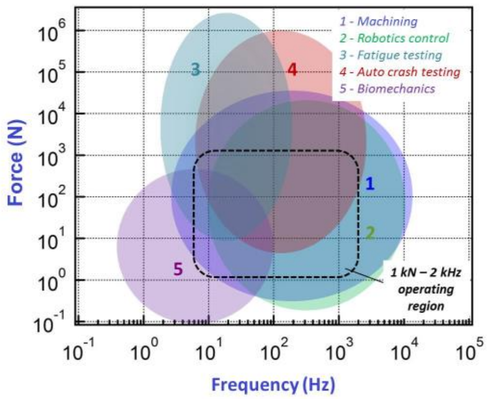

Figure 1. 1 kN, 2 kHz operating range compared to typical amplitude-timescale range of some force measurement applications.

strain-gauge-based force transducers the excitation voltage is measured by a second fast-sampling DVM. The DVM specifications are given in Table 1. Displacement and voltage data are sampled synchronously, as timed by a common signal generator output. The sampled data are transferred to a personal computer for processing.

Traceability: The traceability of the applied calibration force is provided via the traceability of the measured mass and acceleration values. The load mass value is traceable via a series of comparisons to the international prototype kilogram. The acceleration is determined by measurement of displacement over timed intervals. The displacement is measured by a laser interferometer, operating at an accurately determined laser frequency, and traceable thereby to the SI definition of the meter. The time intervals are provided by a signal generator with a frequency reference that has been calibrated to the Global Positioning System 1 pulse-per-second signal and is thereby traceable to the SI definition of the second. A number of additional parameters are measured in determining small correction terms to the force; these measurements are also SI-traceable. The transducer output voltage is measured by a fast-sampling digital voltmeter, with well-characterized measurement uncertainty against its internal DC reference. This is calibrated via an intermediary DMM to a Josephson Voltage Standard and thereby to the SI Volt. At present, measurement of transducer output signals other than voltages or digital numbers has not been implemented.

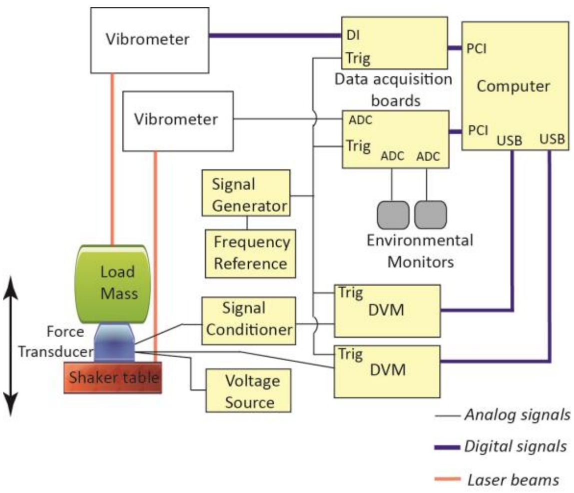

Figure 2. Calibration system configuration. Trig: trigger input, ADC: analog-to-digital converter, DI: digital input, PCI: PCI bus interface, USB: USB bus interface.

Acceleration measurement: The acceleration measurement is performed by laser vibrometry. In the first place a commercial heterodyne system with a differential configuration is used, which provides an overall displacement accuracy of a few nanometers. This system is shown schematically in Figure 3. The optical path of this within the interferometer optical unit of the vibrometer is arranged so that measurement and reference beams trace almost the same path within glass elements, and the two beams travel in parallel, close-proximity paths through air. It is a double-pass system (not shown on figure), which is to say

Shaker (*Spectral Dynamics model SD-440-6/DA-2*)[1]		**Vibrometer** (*Agilent Technologies models 5517DL + 10715A + N1231B*)		**DVM** (*Agilent Technologies model 3458A*)		**DVM** (*Agilent Technologies model 34411A*)	
Maximum force	2 kN	Maximum velocity	0.65 m/s	Nominal digits	8.5	Nominal digits	6.5
Maximum displacement	± 19 mm	Resolution	0.15 nm	DC rel. uncertainty (2 V signal, 1 yr)	8.3×10^{-6}	DC rel. uncertainty (10V signal, 1 yr)	3.7×10^{-5}
Maximum velocity	2 m/s	Max. sample readout rate	2×10^{7} /s	DC rel. uncertainty (50 mV signal, 1 yr)	1.5×10^{-5}		
Maximum acceleration	800 m/s^2			Single-point rel. uncertainty at 5 000 samples/s (2V signal, 1 yr)	5.6×10^{-5}	Single-point rel. uncert. at 5000 samples/s (10V signal, 1 yr)	7.9×10^{-5}
Max. total supported mass	100 kg			Maximum sample reading rate	100 000 /s	Maximum sample reading rate	50 000 /s
Frequency limit	4 kHz						

Table 1. Manufacturer's specifications for some components of the calibration system.

[1] Certain commercial equipment, instruments, or materials are identified in this article in order to describe the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

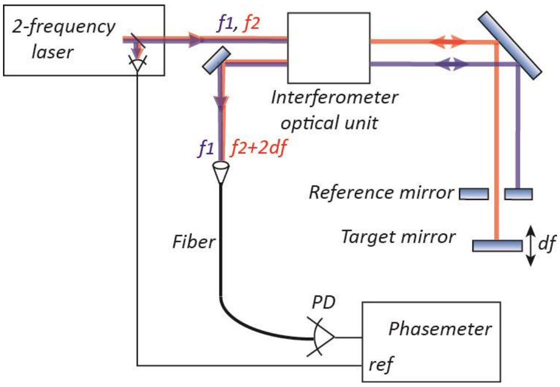

Figure 3: Agilent vibrometer system configuration. f_1, f_2 indicate the frequencies of the probe and reference beams, and *df* indicates the frequency shift due to the target mirror motion. PD: photodetector

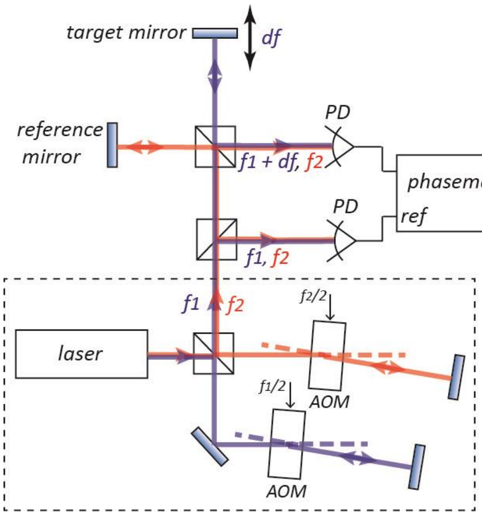

Figure 4: Custom auxiliary vibrometer configuration (simplified). f_1, f_2 indicate the frequencies of the probe and reference beams, and *df* indicates the frequency shift due to the target mirror motion. Dashed line encloses heterodyne-generation section. PD: photodetector; AOM: acousto-optic modulator.

that the measurement and reference beams each probe their respective mirrors twice, doubling the measurement resolution at the expense of a proportional reduction in the allowed target velocity.

The second vibrometer implemented is a custom heterodyne configuration, shown schematically in Figure 4. The heterodyne frequency shifts are generated using acousto-optic modulators (Bragg cells), and a lock-in amplifier is the phasemeter used to beat the probe and reference signals and provide sine and cosine quadrature phase outputs. A mirror in the reference arm can be used to make the reference and probe beampaths of this vibrometer parallel and close to each other as well.

3. SYSTEM OPERATING LIMITS

The sensitivity of a force transduction system, defined as the ratio of the output signal to the force that is to be measured, is in general a function not only of the excitation frequency but also of a number of other variables which have values that vary from one measurement application to another, and which are of varying significance in their effect on the transducer response. Variables of relatively small impact can in principle be accommodated by evaluating and including their contribution to the calibration uncertainty. Variables with larger impact, or in cases where a smaller uncertainty is desired than the accomodation of such variables in the uncertainty budget would give, require a different approach. Possible methodologies include using the dynamic calibration to extract sufficient dynamical

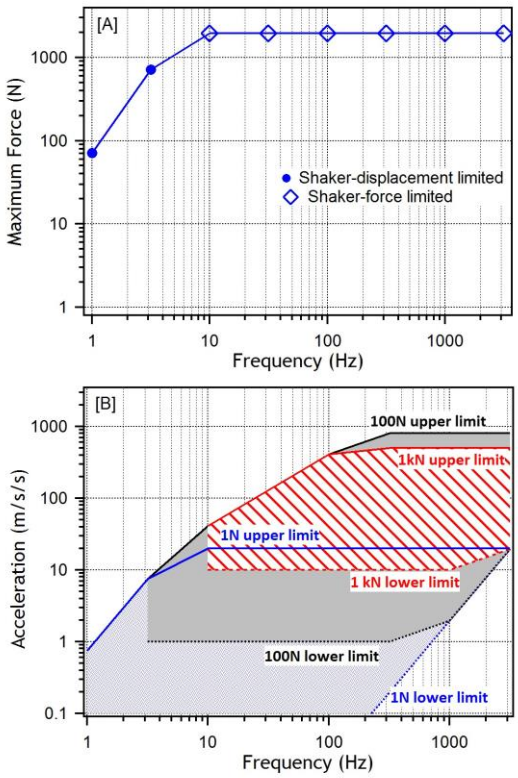

Figure 5: System operating limits. [A] shows the maximum force that can be applied to a transducer as a function of frequency. [B] shows the available range of acceleration values at each frequency, with limits achievable at different force levels indicated. In addition to the component specifications listed in Table 1, a minimum displacement criterion of 50 nm has been imposed, and a mass of 2 kg has been assumed for the transducer (with couplings).

parameters to represent the transducer's behaviour by an adequate model, thereby enabling the transducer user to calculate the expected sensitivity for the conditions of the particular application (within the applicability range of the model, including the parameter values); performing calibrations in an application-targeted manner that subjects the transducer to the loading conditions of a particular application under consideration; and performing dynamic calibration of the transducer over a wide variety of loading conditions that attempt to cover a broad range of application conditions.

Figure 5 shows the operating limits of the designed calibration system, in the form of the maximum force that can be applied at each frequency and the nominal transducer acceleration values that are available at each force value. It should be noted that these plots do not provide information on the relative uncertainties achievable at the different accessible operating points.

4. CURRENT STATUS OF THE SYSTEM

The described system has been partially constructed and is presently able to make transducer sensitivity measurements using the custom vibrometer for acceleration measurement and a 6.5-digit fast-sampling DVM for voltage measurement. Integration of the commercial differential vibrometer and the 8.5-digit DVM into the system are being carried out. The next steps are integration of environmental monitoring into the system and the detailed evaluation of the achieved uncertainty of calibration measurements.

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