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An Automated Fringe Counting Laser Interferometer for Low Frequency Vibration Measurements

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ABSTRACT

Low-frequency accelerometers and velocity transducers are widely used to investigate vibrations on structures such as buildings, bridges, aircraft, ships, power plant equipment, and in seismic applications. Previous work at NBS in this area has focused on the development of accurate calibration methods for transducers by optical methods in the frequency range of 2-100 Hz. This paper describes a computer-controlled fringe-counting interferometric system for transducer calibration. The calibration system uses digital signal analysis for accurate low-frequency voltage measurements. The measurement procedures are fully automated, with menu-driven programs using the computer soft keys for controlling the test frequencies and acceleration, setting test parameters, collecting and storing data and producing reports and graphs. An error analysis is given and experimental data are presented for a typical transducer calibrated on this system.

INTRODUCTION

The National Bureau of Standards provides a low-frequency vibration calibration service for calibration of accelerometers in the frequency range of 2 to 50 Hz. This calibration service has been offered for about fifteen years. Until recently, the calibration was performed manually by comparing the test or unknown sensor to a calibrated sensor located inside a low-frequency shaker of NBS design [1]. This will be referred to as the comparison method in this paper. The sensor inside the shaker was calibrated by a laser fringe-counting interferometer over the frequency range given above. The fringe-counting calibration method has been well documented [1],[2] and the estimated accuracy is +/- 1 percent from 5 to 50 Hz and +/- 2 percent from 2 Hz to 4 Hz. It was found to be impractical to calibrate accelerometers on a routine basis by the direct use of the laser interferometer because of the difficulty of the experiment and the time involved to perform the calibrations. For this reason the comparison calibration method described above has been used for routine accelerometer calibrations in this low-frequency range of 2 to 50 Hz.

This paper presents the implementation of a computer-controlled procedure that permits a direct laser interferometer calibration of accelerometers in this low-frequency range.

COMPARISON MEASUREMENT SYSTEM

Figure 1 shows a diagram of a comparison system for low-frequency calibration of accelerometers. The accuracy of this method depends upon the accuracy of the calibration of the internal accelerometer. The shaker used in this setup is a NBS design [1], which provides for low distortion and low cross-axis motion in the frequency range of 2 to 50 Hz. The shaker, shown in figure 2, has a maximum acceleration of 1.6 "g" or 1.8 inches displacement (peak-to-peak) The internal accelerometer is calibrated by

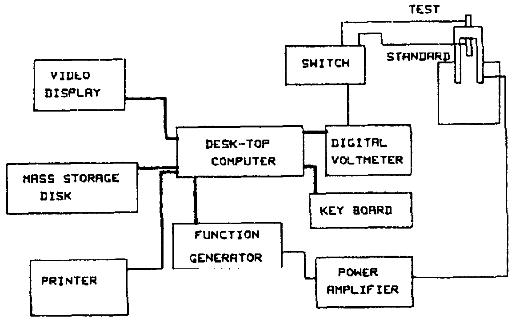

FIGURE 1 COMPARISON SYSTEM FOR LOW FREQUENCY MEASUREMENTS

the fringe-counting method which is described in the next section. The computer is programmed to set the signal generator at the desired frequencies (as selected by a soft-key on the computer keyboard) and voltage amplitudes for the desired test points. The power amplifier is set for constant gain, so that only the function generator output voltage determines the appropriate acceleration. The signal to be measured is selected by a computer-controlled switch. The digital voltmeter is read by the computer for each of the two switch positions (corresponding to the standard accelerometer and the test accelerometer). These readings are stored in the computer memory. As the data are collected the sensitivity of the test transducer is calculated, displayed, and stored on the disk storage. A single frequency or a range of frequencies can be selected from the soft-keys on the keyboard.

The main advantage of this system is its ease of operation; it does not require any optical alignments and it provides a sinusoidal calibration based upon simple voltage measurements. Its disadvantage is that it depends upon an internal calibrated standard accelerometer. This calibration must be verified by re-calibration periodically. The internal sensor is a servo-accelerometer with a low temperature sensitivity (0.02 percent/deg C) and high sensitivity (1 volt/g). Its long-term drift is low. Measurements made at NBS over a ten-year period have shown sensitivity changes of less than than 0.5% for any frequency between 2 and 50 Hz. This repeatability is possible however, only if care is taken to ensure the shaker's moving element is properly aligned with respect to the two air bearings (figure 2). This alignment consists of the following two steps.

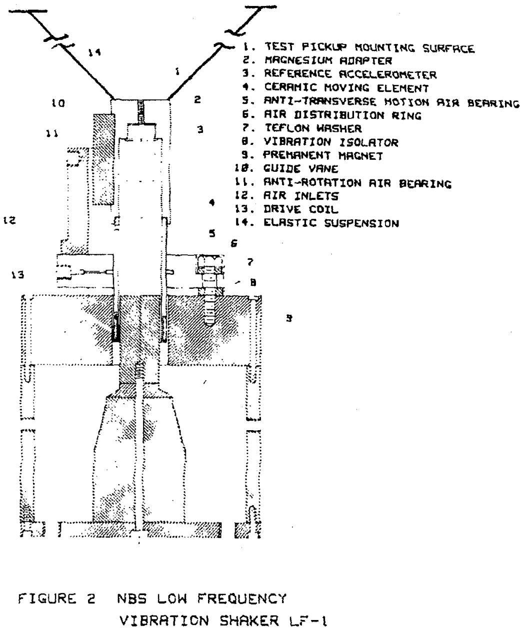

FIGURE 2 NBS LOW FREQUENCY VIBRATION SHAKER LF-1

1. The moving element must be vertically aligned with respect to the anti-transverse bearing (#5 in figure 2) to maintain the drive coil in the center of the magnetic field in order to provide low distortion. Any significant vertical misalignment will result in harmonic distortion and a consequent error in measurement (ref. 1).

2. The moving element must be aligned with respect to the anti-rotation bearing (# 11 in figure 2). This is done by rotating the elastic suspension with respect to the center axis of the shaker so that the proper force is applied by the air in the bearing to the guide vane (#10 in figure 2). A misalignment of this bearing will result in noise in the accelerometer signal. This rotation adjustment is performed while observing the accelerometer signal on an oscilloscope. This alignment is not difficult with some practice.

Once the alignments have been performed, only minor adjustments are required to fine tune the alignment unless the moving element has been removed for cleaning. The comparison method provides for accurate measurements in this low frequency range provided the internal standard has been accurately calibrated. In the following section, the procedure for the calibration of the internal standard is given. This fringe-counting method also applies to a test accelerometer which can be mounted on the shaker table.

FRINGE-COUNTING MEASUREMENT SYSTEM

It is desirable to have a measurement system that is based upon the wavelength of a light source (He-Ne laser) and does not depend upon a prior calibration of an internal standard. This section describes a new automated system for the fringe-counting interferometer. This is an automated implementation of the fringe-counting system given in ref. 1. The goal for this system was a completely automated system that would be easy to use. It would also be desirable to build the system as compact as possible so that it can be duplicated and set up in any laboratory where a high degree of accuracy is needed in low-frequency vibration calibration. The following sections give details of the system, data collection and analysis, and an error analysis of the measurement system.

The new automated system uses the same shaker as the manually controlled system (ref. 1), but includes computer control, a higher bandwidth photo-detector, a more accurate voltage measuring device, and a compact design which is suitable for movement to other test sites.

Description of the System

Figure 3 shows a diagram of the fringe-counting system. The shaker in the system is the one shown in figure 2. The NBS shaker is used in this system, since a commercial shaker of sufficient amplitude and low waveform distortion is not available. This shaker was designed by Robert Koyanagi [1]. The shaker is driven by a signal from a low distortion function generator whose harmonic distortion is at least 60 dB below the fundamental component. The signal is then amplified by a high quality audio amplifier whose contribution to harmonic distortion is no more than 0.05 percent. The shaker is placed on a granite block with air springs for isolation. The mounting table of the shaker (the top of the shaker's moving element) is large enough to mount a retro-reflector in the center and a small accelerometer along side. The laser is mounted above the shaker as shown in a drawing of the mechanical components of the system (figure 4).

Electrical and Optical Description

The accelerometers are connected to the digital voltmeters by means of a computer-controlled switch. The switch is programmed to select one of the accelerometers for the measurements. The digital voltmeter can measure voltages over the range of 2 to 100 Hz. However, below 5 Hz the commercial digital ac voltmeters fail to give sufficient accuracy for our requirements. The digital signal analyzer described in a later section is more accurate for the low-frequency measurements.

The interferometer consists of the laser light source, two beam-splitters mounted directly on the head of the laser, as shown in figure 3, and a retro-reflector mounted on the shaker table. The heavier lines in this figure represent computer control lines. The interferometer measures the displacement of the reflector on the shaker table with reference to the beam-splitters mounted

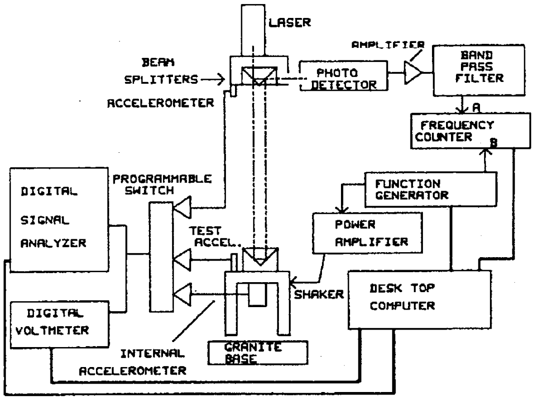

FIGURE 3 FRINGE-COUNTING MEASUREMENT SYSTEM

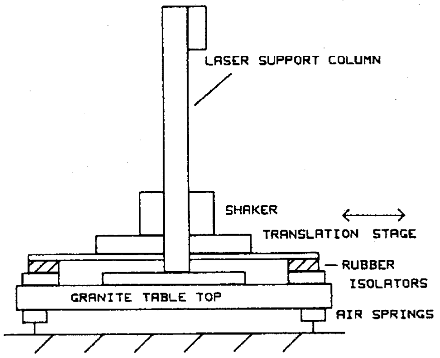

FIGURE 4A FRINGE-COUNTING SETUP, SIDE VIEW

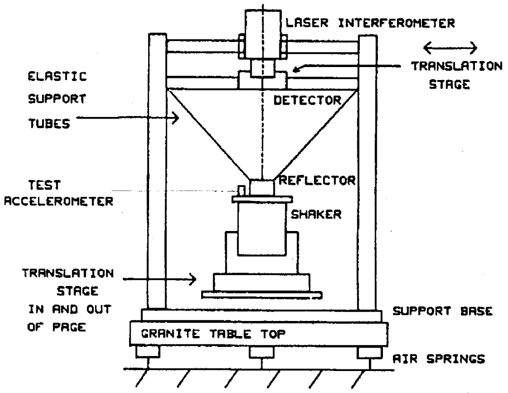

FIGURE 4B FRINGE-COUNTING SETUP, FRONT VIEW on the laser mount. The assumption is made that the test accelerometer mounted on the shaker moves with the same amplitude as the reflector. The light emerging from the interferometer forms interference fringes on the photo-detector. The laser has a wavelength λ of 632.8 nm. For every displacement of λ/2, the photo-detector generates an electrical pulse and the counter records one fringe count. The output voltage of the detector is amplified, filtered and then connected to a frequency counter. The filter is used to eliminate high-frequency and very low- frequency photo-detector noise. The counter measures the number of fringes corresponding to the shaker displacement amplitude. A sample photo-detector output signal has been digitized and is shown in figure 5. *This figure shows the pulses* for a typical vibration signal and corresponds to one half cycle of motion at 50 Hz.

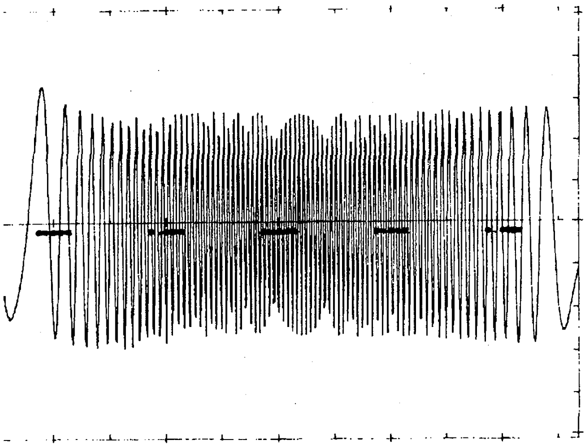

FIGURE 5 A PHOTO-DETECTOR SIGNAL AT 50 HZ, ONE HALF CYCLE

The number of fringe counts per vibration cycle read from the programmable counter (fig. 3) is proportional to the displacement amplitude. The acceleration (in "g" units) is given by

$$A = (2\pi f)^2 D/g \quad = \quad \lambda n \pi^2 f^2 / 2g \qquad (1)$$

where

A= acceleration in "g" units (single amplitude, peak),

D= displacement amplitude in metres (single amplitude, peak),

λ= wavelength of the laser light, 632.8×10^{-9} m

n= number of fringes per vibration cycle,

g= standard gravity of free fall: 9.80665 m/s^2 (ref. 1).

The photo-detector must have sufficient bandwidth to respond to the high frequencies due to the large amplitudes encountered at vibration frequencies below 50 Hz. The table below lists the range of the NBS low-frequency shaker in terms of minimum and maximum displacements, accelerations, and required frequency response of the photo-detector. The data in the table were calculated from eq. 1 with the requirement that n be a minimum of 500 and assuming an accelerometer of 1 V/g sensitivity with a minimum output of 10 mV rms.

Shaker Frequency (Hz)	Accel. "g"	Disp. inch	Disp. mm	Detector Freq. (kHz)	
2	0.01	0.05	1.3	16	(min)
	0.36	1.8	45.7	565	(max)
5	0.01	0.008	.2	6	(min)
	1.6	1.2	30.5	1004	(max)
10	0.02	0.004	.1	6	(min)
	1.6	0.31	7.9	335	(max)
50	0.4	0.003	.1	25	(min)
	1.6	0.01	.3	100	(max)
100	1.6	0.003	.1	50	(min)
	1.6	0.003	.1	50	(max)

The automated fringe-counting system uses a *commerical photo-detector with a* bandwidth in excess of 10 MHz in order to prevent the loss of signal counts at higher shaker amplitudes as shown in the table above.

Having obtained the acceleration, A, the sensitivity of the accelerometer, either the internal or the one mounted on the shaker table, is calculated by:

$$S = \sqrt{2}\, E/A \quad V/g, \qquad (2)$$

where E is the rms output voltage of the accelerometer charge amplifier at the measured displacement.

Mechanical Design Description

The interferometer measures the displacement of the shaker table with reference to the beam splitters mounted on the laser (figure 4). In setting up the interferometer care must be taken to insure that the supports for the laser and beam splitter module (figure 4) are rigid and are not directly coupled to the base of the shaker. The mechanical isolation of the shaker from the laser is necessary so that the cross-coupling of the shaker movement and resulting laser movement is minimized. The vertical columns are 4 inch I-beams fastened to a 1.5 inch thick aluminum base plate. The laser is attached to these vertical supports by *a* 2.5 *inch* by .75 *inch* aluminum strip on which is mounted a horizontal micrometer translation stage.

This translation stage and the one positioning the shaker are necessary for optical alignment and for positioning the interference pattern onto the small photo-detector.

The shaker is mounted on a translation stage that moves the shaker horizontally and at right angles to the stage on the laser mounting (x-y positioning). In figure 4b, this movement is perpendicular to the page. The shaker is mounted on a 1.5 inch aluminum plate and the plate rests on rubber pads sitting on the granite plate as shown in figure 4. An accelerometer is mounted on the beam splitter holder (figure 3) to monitor the movement of the laser and beam splitter module. The errors due to cross-coupling are discussed in the section on error analysis.

Data Acquisition

The system uses two instruments for voltage measurement (figure 3). One of these is a precision digital voltmeter which is useful for frequencies of 5 Hz and above. The second is a digital signal analyzer which is more accurate for frequencies below 5 Hz. The desk-top computer is programmed to select the digital signal analyzer for these low frequencies. The signal analyzer can be used over the entire range of 2-100 Hz but the digital voltmeter is prefered for frequencies of 5 Hz and higher because of its greater speed.

Digital Signal Analyzer

A digital signal analyzer is used to capture and store the accelerometer voltage. The analyzer digitizes and stores the analog signal and can also apply a large set of pre-programmed analysis functions to the stored data. This analyzer incorporates a 16-bit, 8 MHz CPU. An integral 9-inch CRT is used to monitor the input signal, display graphic and numerical outputs, and provide labels for the analyzer's display keys during local control of the instrument. Analog inputs are acquired at user programmed sampling speeds through a plug-in front end module. Several plug-in modules are available that provide 12-bit analog-to-digital conversion at rates up to 36 MHz, depending upon the input ranges and frequency response desired. The digitized signals from the plug-in module are then transferred to the main frame data storage for processing and display. Any of the keys on both the mainframe and plug-in module may be activated by the computer through an IEEE-488 interface.

The analyzer is not auto-ranging. The desk-top computer is programmed to select the input voltage range, and obtain a course voltage reading. Then the analyzer is programmed to down range until the best input range is obtained. Upon obtaining the best input range, the computer sets the graphic display parameters, and the optimum sampling rate of the analyzer. The analyzer then samples the voltage of the accelerometer (8000 samples), computes the rms voltage, E in eq. (2), and displays the the data graphically on the integral CRT graphics monitor. This rms voltage is output to the desk-top computer to calculate the accelerometer sensitivity as shown in eq. (2) above.

Sources of Error

This section lists the several sources of error in the fringe-counting measurements and estimates each component. Finally an overall estimate of error is given.

Error Due to Misalignment

The laser beam and the axis of the shaker can easily be manually aligned to within two degrees, corresponding to a misalignment error of less than 0.06 percent. As implemented at NBS, the alignment is better than 0.1 degrees. Therefore negligible error is assigned to misalignment.

Error in Voltage Reading

Harmonic distortion in the shaker motion results in distortion in the accelerometer voltage. The distortion in the shaker can be kept to 1 percent by proper alignment (see section above on comparison measurement). A 1 percent distortion results in an error in true rms voltage measurement of about 0.1 percent (as calculated in ref 1). In addition to errors due to distortions both the voltmeter and the digital signal analyzer error can be as much as 0.2 percent, depending upon frequency and signal level. This 0.2 percent error is for signals of at least 10 mV.The maximum estimated voltmeter error is then 0.3 percent for the 2-100 Hz frequency range.

Error Due to Cross Coupling

If shaker motion is transmitted through the laser support structure (fig. 3), and results in movement of the beam splitter module, an error proportional to the displacement of the beam splitter will be introduced in the measurement of the accelerometer displacement. A small accelerometer is mounted on the beam splitter module (as shown in fig 3) to monitor the cross coupling effect. By properly stiffening the laser support structure and isolating the shaker base from the laser support base, (fig 4) the cross coupling can be kept low. The cross coupling ranges from 0 to 0.1 percent of the shaker displacement. A maximum error of 0.1 percent is assigned to cross coupling effects in eq. 1.

Error in Wavelength of Light

Any error in λ will produce an error in the calculated acceleration (eq. 1). The wavelength of the HeNe laser is stable to about 1 part in 10^6. Therefore negligible error is assigned to λ .

Error in Frequency

Any error in frequency will result in an error in the calculated acceleration (eq. 1). The frequency of the function generator is accurate to about 5 parts in 10^6 (manufacturer's specifications). Negligible error is assigned to the frequency, f, in eq (1).

Error in Fringe Count

The estimated error in the fringe count varies from 0.002 to 0.2 percent depending upon the number of counts. This error occurs when the displacement amplitude is not an integral multiple of a half wavelength of the laser light. At 2 Hz the number of fringes/frequency cycle can be very large, typically at least 50,000. An error of one count will result in a .002 error in (eq 1). At 100 Hz for example, the shaker is limited in amplitude to about 500 fringes/frequency cycle. An error of one count will result in 0.2 percent error in (eq 1). An error of 0.2 (maximum) is therefore assigned to n.

The following table gives an estimate of each error in the fringe counting measurement system over the frequency range of 2 to 100 Hz.

Source of error	Maximum Estimated error %
Misalignment	0.0
Voltage measurement	0.3
Cross-coupling	0.1
Wavelength of light	0.0
Signal frequency	0.0
Fringe count	0.2
Total maximum	0.6

An estimate of expected error is often calculated using the square root of the sum of the squares of the individual error components. For the errors listed above, the root mean square error is 0.4 percent. Due to errors introduced by cable positioning of test accelerometers, the overall accuracy is estimated to be +/- 1 percent.

Experimental Data for a transducer

A servo accelerometer was calibrated on the fringe-counting system over the range of 2 to 50 Hz. The following table gives data for this accelerometer. The fringes were counted over a gate time of two seconds in order to obtain a better average than would have been obtained with only one cycle of vibration. This is especially beneficial at the frequencies of 50 Hz and above since the n is lower due to the drive limitations of the shaker. Each data point is the average of 50 measurements on the automated fringe-counting system.

Freq (Hz)	Number of Counts/ cycle (n)	Accel. (g)	Sensitivity (mV/g)
2	36,787	.05	993.9
5	14,322	.11	996.0
10	7,760	.25	995.7
15	5,169	.37	994.1
50	1,605	1.3	998.7

The data were taken using the digital signal analyzer described above. The 2-Hz measurement required a measurement of about 32 mV rms. Such low voltages at this low frequency cannot be readily measured by conventional voltmeters. The ability of the signal analyzer to measure low frequency signals with high precision is a significant advancement in the measurement process for low-frequency calibrations.

SUMMARY

Tests at NBS have demonstrated the feasibility of automating the fringe-counting measurement system for low-frequency (2-100 Hz) vibration measurements using a desk-top computer. The system was designed so that it can be disassembled and moved to another location and reassembled with minimum effort. The use of a programmable digital signal analyzer improves the accuracy of low-level voltage measurements for frequencies of 5 Hz and below.

Accurate low frequency measurements using this system depend on accurate alignment of the shaker's moving element with respect to the two air bearings. Accurate measurements also require care in isolating the shaker and its support structure from the optical components of the measurement system. The use of a desk-top computer automates the calibration procedures by setting the drive frequency and acceleration amplitude, programming the signal analyzer, collecting the data, and calculating the accelerometer sensitivity.

The automated fringe-counting system provides an efficient transducer measurement system for the low-frequency range. This system does not depend upon the stability of a transducer or signal condition for its accuracy as in a comparison system, but is based on a physical unit, the wavelength of a light source.

ACKNOWLEDGMENTS

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