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Improved System to Measure Vibrations

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ABSTRACT
In this article, improving the calibration accuracy of a vibration sensor is being discussed in a closed loop measurement system and its performance metrics using Back-to-back direct comparison; and Back-to-back alternative comparison methods. The experimental results were analysed for time domain system with incorrect sensitivity with referential vibration source of 20 m/s–2peak amplitude and time domain system with calibrated sensitivity with referential vibration source of 10 m/s–2 peak amplitude.

I. INTRODUCTION

A sensor is a transducer whose purpose is to sense(that is, to detect) some characteristic of its environments.It detects events or changes in quantities andprovides a corresponding output, generally as an electricalor optical signal. It has been widely used in mechanical engineering,aeronautics and astronautics engineering, industrialcontrol, etc. Sensors play important roles in industries suchas manufacturing, where all require the sensor to act as a reliableunit [1], [2]. In practical engineering applications, a sensoris often used for measuring vibrations, including acceleration,velocity, and displacement. It is the primary link in achievingconversion, processing, recording, and storage of information.Therefore, its performance directly influences the reliabilityand accuracy of the entire system. The calibration for vibrationsensors, which need to ascertain sensitivity, frequencyresponse characteristics, amplitude linearity, etc., are requiredbefore the measurement is made [3], [4]. Traditionally, an openloop device (in which the excitation signal is adjusted manuallyand the parameters are recorded manually) is used forsensor calibration. This type of manual calibration generates alarge amount of work and active jamming, which results in errors.If a closed loop calibration system can be designed (i.e.,the excitation signals are adjusted automatically by devices,and the real time data are sampled and analyzed), it will offerabundant measurement information and analysis methodswhich can help improve calibration accuracy and efficiency. Inthis article, we introduce such a closed loop calibration systemfor vibration sensors.

Basic Concepts of Sensor Calibration

For better understanding the calibration principle, these basicconcepts are introduced first:

Vibration Sensors

The function of a vibration sensor is to transfer the mechanicalmovements to optical or electrical signals by sampling thevibration signal through transducers. It can be classified as adisplacement (amplitude) sensor, velocity sensor, and accelerationsensor.

Sensitivity

Sensor sensitivity represents the output variation per inputvariation at stable working conditions. normally, sensitivityincludes amplitude and phase information, and it is the functionof frequency variation.

Uncertainty

The measurement error is the difference between the measuredquantity and the true value. It reflects the deviation ofthe measurement result. Normally, the true value cannot beobtained due to the boundedness of the measurement technique;it needs to give an estimation for the approximate value.Uncertainty is used for presenting the possible range of themeasurement error [5].

Frequency Response

Frequency response is used as a measure for the system outputcorresponding to the input. It usually contains informationabout output amplitude and phase, which can characterize thedynamic property of the system [6]. Generally, there are three methods for obtaining frequencyresponse.

The point-by-point method where the amplitude-frequencyresponse and phase-frequency response of the sensor aremeasured in the range of working frequency with themeasurement points being selected at 1/3 octave. Themerits of the method are that through measuring amplitude-frequency response of a few frequency points, theresponse characteristics of the calibrated sensor can bedescribed, which make it easy for operation, data recording,and calculation. The frequency distribution willbe averaged. However, the method has dead zones of measurement, which cannot reflect the response characteristicsvery well.

The continuous sine method (sine sweep-frequency method)adopts a continuous sweep frequency manner to implementsweep frequency tests at the working frequencyrange. The amplitude and phase shift of sensors aremeasured at each frequency. The offset curve is obtained through analyzing the bias relationship with a standardsensor. The method practically reflects the response characteristicsof sensor sensitivity. Furthermore, if the closedloop calibration approach is adopted, the constant outputof vibration magnitude can be effectively controlled.Through a transfer function, the response characteristicscan be automatically calculated.

The stochastic method (FFT method) uses white noise toimplement excitation on the entire frequency band.Through average calculation, the response curve can beobtained. During the test, the operation requirement ishigh, which requires that the operator have extensiveexperience.

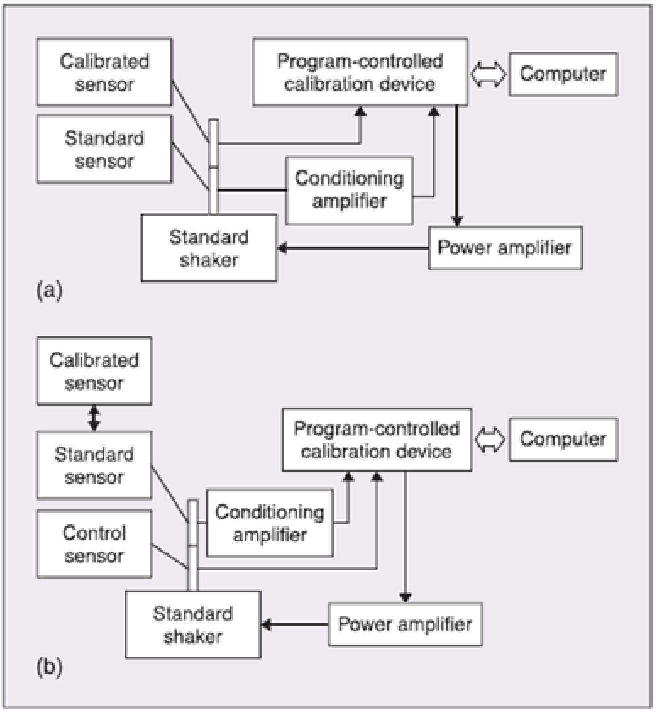

Fig. 1. Scheme of comparison methods. (a) Back-to-back direct comparison;(b) Back-to-back alternative comparison

Calibration

A comparison between two measurements, where one ofknown magnitude is set with one device (called the standarddevice), and another measurementis made in a similar waywith a second device beingcalibrated.

CalibrationMethods inExperiment

Aiming at realizing directcalibration of the sensor, thevibration exciter is neededto offer a controllable andmeasurable input, and thesampling method for the outputsignal is required to be reliable. The sensor should be fixed on a vibration exciter(when sensor output relies on the relative movement of thesensor and vibration exciter, the sensor should be mountedclose to the vibration surface). The configuration of the sensorshould consider having sufficient rigidity to help the vibrationexciter to transfer all the movement to the sensor at the workingfrequency range.

The principle of the calibration is based on comparison betweentwo measurements, which is described as: The standardsensor 1 is combined with the objective sensor 2 to receive thesame vibration input. The output U1 and U2, or the ratio betweenthem should be measured. If the two sensors measurethe same parameter, such as velocity or acceleration, and bothresponses of the sensors are linear, the relation between sensitivityS2 of the objective sensor 2 and the sensitivity S1 of thestandard sensor would be:

$$S_2 = \frac{U_2}{U_1} S_1 \quad (1)$$

According to this principle, two comparison methods are introducedin this article.

Back-to-Back Direct Comparison Method

The objective sensor being calibrated and the standard sensorare attached by rigid coupling, and they are installed atthe center position of the standard shaker's surface. The standardsensor is at the lower position and the objective sensor isat the upper position, as Fig. 1a shows. Through comparisoncalculation, the sensitivity, amplitude linearity, and frequencyresponse can be obtained.

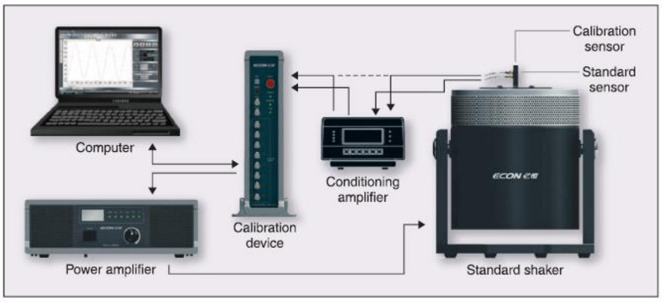

Fig. 2. Calibration system.

Back-to-Back Alternative Comparison Method

The control sensor is directly installed at the center positionof the shaker's surface, after which the standard sensor is installedwith the control sensor. The parameters of the standardsensor are obtained through comparison calculation. Thenthe standard sensor is demounted and the objective sensor isinstalled with the control sensor, as shown in Fig. 1b. The measuredparameters' performance is compared with the standardsensor for obtaining more accurate sensitivity, amplitude linearity,and frequency response. This technique can counteract most uncertainty componentscaused by shaker distortionand measurement error.

II. EXPERIMENTAL SIGNAL ANALYSIS

Experimental System

The closed loop method forsensor calibration selects astandard shaker as the vibrationsource, and the sensors areconfigured and fixed in a back-to-back manner (the objectivesensor is installed directly ontop of the standard sensor). Theentire measurement system iscomposed of:

a program-controlled calibrationdevice,

a standard reference device,

a standard shaker (Model:

ECON ECS VE 200, thrust:200 N (adjustable), havingfrequency range: 10 Hz-7000Hz, displacement: 4 mmpeak-to-peak value, velocity:1.2 m/s, acceleration:980 m/s2), a power amplifier, a charge amplifier (whichconverts charge to voltage),and a computer, as shown inFig. 2.

The control scheme forsensor calibration usedin the system is shown inFig. 3, which describes the entirecontrol process. When thesystem is operating the frequencycontrol or the signalinput, it will perform comparisoncalculations basedon the former received signalsand the preset target

spectrum. The calculated resultwill be used to influencethe next frequency, whichrealizes the control amplitudecorrection. The "changesignal frequency" in Fig. 3means when the amplitude

is corrected, the softwarewill move to handle the nextfrequency.

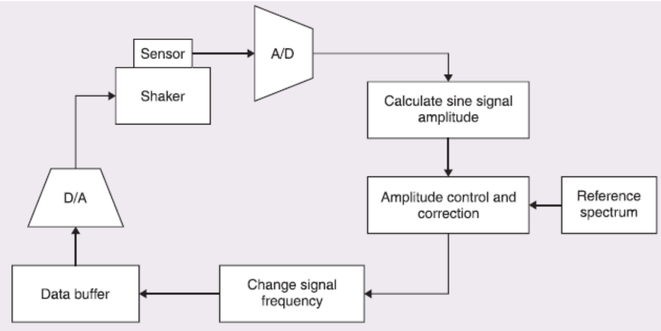

Fig. 3. The control scheme for sensor calibration

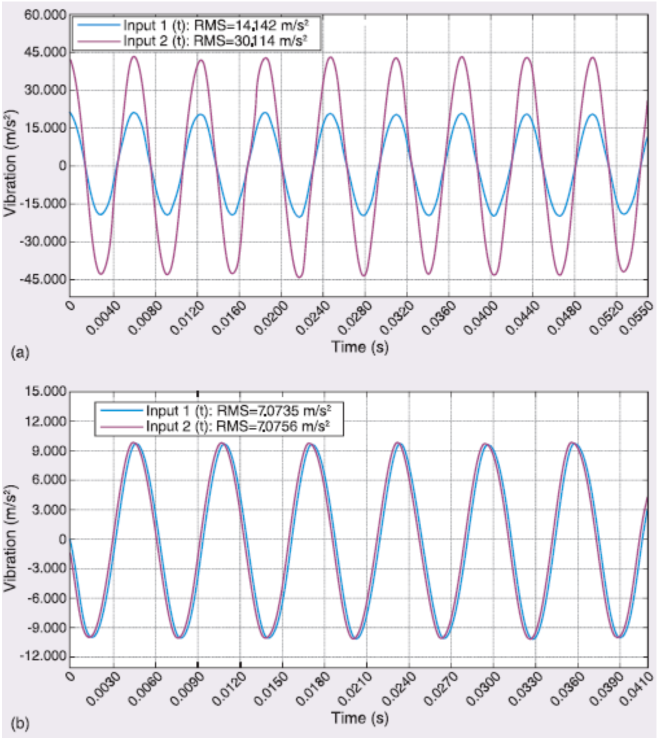

Fig. 4. Experimental Result. (a) Time domain waveform with incorrect sensitivity (referential vibration source has 20m/s^{-2} peak amplitude); (b) Time domain waveform with calibrated sensitivity (referential vibration source has 10 m/s^{-2}peak amplitude).

Fig. 5. The solution S2 = 10.647 mV/ms^{-2}s^{-2} was calculated from Equation (1) in software.

III. EXPERIMENTAL RESULT

The calibration procedure follows the standards and referencesfrom the literature [7]–[10]. The working frequencyrange is between 0.1 kHz to 10 kHz, which aims for vibrationmeasurement in experimental conditions.The objective sensor and standard sensor are installedon the standard shaker in a back-to-back manner. The sensitivityof the standard sensor is 0.113 pC/ms^{-2}. Supposingthat the sensitivity of the objective sensor is 5.000 mV/ms^{-2},the time domain waveform is shown in Fig. 4a. From thefigure, when the sensitivity of the sensor is incorrect, the measured values would have large bias with the same measurementcondition. If the traditional open loop calibrationis adopted, it can obtain U1 = 1.598 mV, U2 = 150.570 mV,and the time domain waveform is shown in Fig. 4b. From(1), S_2 = 10.647 mV/ms^{-2} is obtained, as shown in Fig. 5. Thelarge number of decimal point digits makes the calculationvery difficult and results in incorrect calculation caused byhuman factors.

The calculated result will be regarded as the sensitivity ofthe sensor, and then the calibrated time domain waveform isobtained after implementing the measurement. When adoptingthe closed loop manner, the U1, U2 , and S2 do not needto be measured again, and the software will complete thisunit and give the sensitivity of the sensor, which eliminatesthe human factor errors and greatly increase the calculationefficiency.

Furthermore, to quantify the uncertainty improvement, wehave calculated the standard deviation for both calibration approaches.For manual calibration, the standard deviation ofsensitivity of the objective sensor is 0.0303 mV/ms^{-2}. In comparison,for closed loop control based calibration, the standarddeviation of sensitivity of the objective sensor is 0.0003 mV/ms^{-2}. As a result, the closed loop control-based calibrationapproach is better than the manual calibration in terms of uncertaintyimprovement.

IV. CONCLUSION

A closed loop measurement system is presented to improvecalibration accuracy of a vibration sensor. As compared to theopen loop calibration where the operator needs to have richexperience, and some manual operations may influence thecalibration accuracy, the closed loop calibration is performedin an automatic manner. As a result, the human factor error canbe eliminated, and the operation is more convenient than thatof the open loop calibration. This improves the calibration accuracyas well as the working efficiency.

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