

IMPROVEMENT OF VERY LOW-FREQUENCY PRIMARY VIBRATION CALIBRATION SYSTEM AT NMIJ/AIST

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Abstract – The very low-frequency primary vibration calibration system at NMIJ/AIST was improved with a new signal processing framework. It contains commercial hard disk drive so that photoelectric signals from homodyne interferometer can be recorded. Sine-approximation method with a digital band-pass filter is applied to boost signal-to-noise ratio. By calibrating a reference accelerometer, compatibility with the existing primary vibration calibration system was confirmed.

Keywords: very low frequency, primary vibration calibration, band-pass filter, sine approximation method

1. INTRODUCTION

Accelerometer primary calibration in the very low-frequency (VLF) range below 1 Hz is increasingly important as vibration measurements of earthquake and infrastructure monitoring are growing markets in creating a sustainable society. Many national metrology institutes (NMIs) have spent dozens of years to develop primary calibration system for low-frequency accelerometers [1-8]. Some international comparisons by regional metrology organization have been conducted; APMP.AUV.V-K2 [9] and EURAMET.AUV.V-K3 attracted many participants from NMIs all over the world. In addition, key comparison CCAUV.V-K3 is under measurement in 2014-2015.

At National Metrology Institute of Japan (NMIJ), primary VLF vibration calibration system complying with ISO 16063-11 [10] method 1 (fringe counting) has been in operation since 2005 [11]. The measurement uncertainty of the system was relatively large; 1.5 % for 1 Hz and 6 % for 0.1 Hz. To reduce the uncertainty, technical problems particular to the low-frequency range should be solved: there are difficulties in displacement measurement, accelerometer signal measurement and vibration exciter [12, 13]. Among these, the most critical one is low signal-to-noise ratio (S/N) of accelerometer signals due to low acceleration amplitude. As shown in Figure 1(a), signal amplitude becomes very much lower as vibration frequency decreases.

A digital band-pass filtering (BPF) is valid and effective tool [14] to increase S/N, avoiding gain fluctuation and gain uncertainty of analog filters. However, it requires acquisition of large amount of data for in-phase and quadrature-phase

(I/Q) signals from two photodiodes in homodyne interferometer. Typically, sampling rate for I/Q signals need to be more than several MHz to satisfy the Nyquist condition because of high velocity over 1 m/s in VLF vibrations. In this case the data amount exceeds 1 GB (Figure 1(b)), making it impossible to process all the data in on-board memory. Some laboratories adopt real-time phase-unwrapping algorithm for self-made or commercial homodyne laser interferometer to reduce the data amount [2, 7]. On the contrary we have developed a new data handling framework based on large size buffer on a commercial hard disk drive (HDD). In this paper we explain the improvement of the system and validation of its calibration capability.

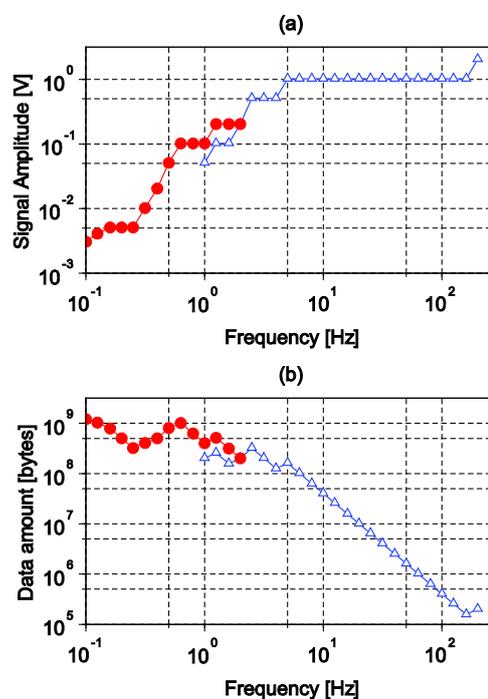


Fig. 1. (a) Signal amplitude of the reference accelerometer (b) expected data amount. The sampling rate is 10 times of the Nyquist frequency and 10 waveforms are acquired.

Thirty-two-bit of data length is assumed. Filled circles and triangles stand for VLF and LF system at NMIJ, respectively.



Fig. 2. The VLF calibration system at NMIJ.

2. IMPROVEMENT OF VERY LOW FREQUENCY VIBRATION CALIBRATION SYSTEM

The primary VLF vibration calibration system at NMIJ is shown in Figure 2 and the new signal processing framework is presented in Figure 3. Key changes between the two systems are summarized in Table 1. The former system was based on fringe-counting method (FCM). We replaced almost all of signal processing procedure to realize sine-approximation method (SAM).

The I/Q signals from the laser interferometer are acquired by a digitizer (NI PXI-5922) with sampling rate of 2 MHz or 5 MHz, depending on vibration frequency. Simultaneously, voltage signal from the accelerometer is measured with another digitizer (NI PXI-4462, National Instruments, Inc.), replacing digital voltmeter (Agilent 3458A) in the former system. The sampling frequency is 200 kHz. To compensate digitizer scale factor error, the digitizer is calibrated with standard voltage generator (Yokogawa GS210) with accuracy about 100 ppm. The voltage generator is calibrated by calibration laboratory so as to be traceable to the SI units. The two digitizers are phase-locked by using PXI bus features. In

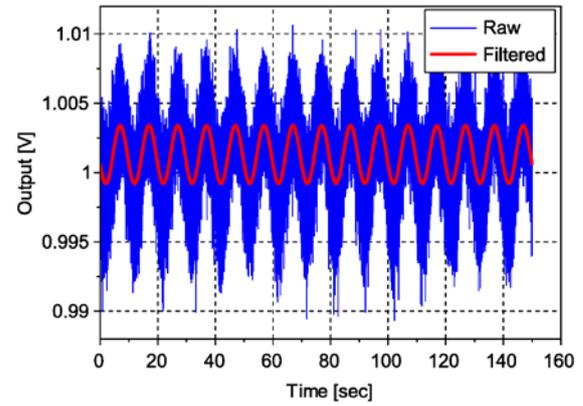


Fig. 4. An example waveform of digital BPF. Excitation frequency is 0.1 Hz.

addition, reference clock of 10 MHz from Rubidium timebase are input into the PXI bus, ensuring clock uncertainty to be less than 10^{-11} .

Collected data are sent to a personal computer (PC). In the PC 3-TB HDD is installed and the data is written on HDD in real-time so that we can storage data over several hundred GB. It should be noted that sinusoidal control signal to the vibration exciter is produced by a function generator. Although the clock of the function generator is not locked to the digitizers, the clock mismatch about 80 ppm is confirmed not to affect the measurement results.

After completing the data acquisition, offline data analysis software is activated. By the software I/Q signals are converted to displacement signal by taking arc-tangent and by multiplying with half-wavelength. Phase-unwrapping is also conducted. Next the time-domain data is decimated to the same sampling frequency as the accelerometer output. Then same BPFs have been applied to the two signals to cancel out the response of the BPF. An example of the effect of BPF is shown in Figure 4. The BPF consists of 4th-order Butterworth low-pass filter, 4th-order Butterworth high-pass filter and elliptic filter. Center frequency of the BPF is the excitation frequency. To avoid phase shift, we adopt zero phase-shift filtering: two same filters are applied to the normal and reverse order of data. Then three-parameter sine fitting is

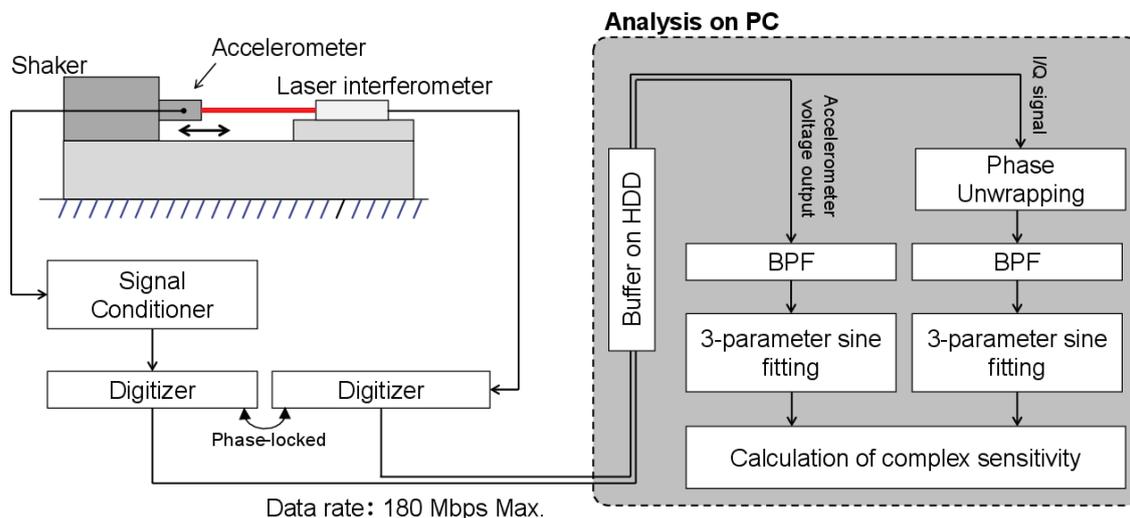


Fig. 3. Improved signal processing framework for the VLF calibration system.

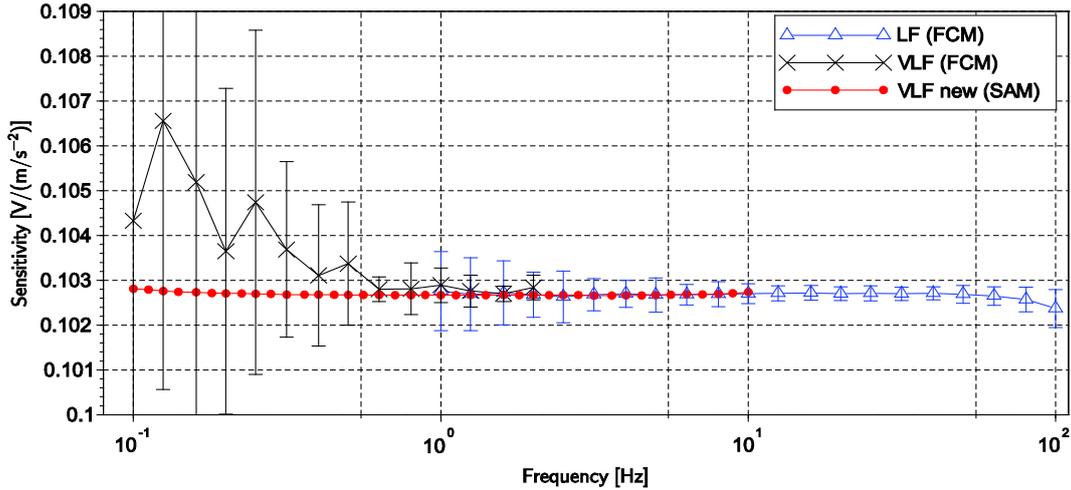


Fig. 5. Calibration result of the reference accelerometer. Uncertainty for the new VLF system is not calculated nor displayed.

applied, i.e. amplitude, phase and bias are estimated by regression analysis. Complex sensitivity of the accelerometer is then calculated.

Additionally, we decided to fix the vibration table on the floor to avoid resonance of air suspension around 2 Hz. In the former system the resonance deteriorated measurement stability to a great extent. Seismic motion or external vibration, blocked by the air suspension, does not affect the calibration results since vibration applied to accelerometer is by far stronger than the noise.

Table 1. Comparison between the former and new VLF calibration system

	Former system	New system
Displacement measurement	Fringe-counting	Sine-approximation
Voltage measurement	Digital voltmeter	Digitizer
Filtering	Not available	Digital BPF
Vibration table	On air suspension	Fixed to the floor

3. VALIDATION OF THE SYSTEM

To validate the new system, we conducted calibration of a reference accelerometer (JA-5V E1, Japan Aviation Electronics, Inc.). The accelerometer has been tested annually for more than 10 years and it has sufficient stability to evaluate consistency of primary vibration calibration system. Its nominal sensitivity is $0.102 \text{ V}/(\text{m}/\text{s}^2)$. As shown in Figure 4, the calibration result of the new VLF system shows excellent flatness, agreeing with that of the former VLF system within its uncertainty.

In addition, compatibility with the low-frequency (LF) calibration system at NMIJ [15] is also tested. The LF system covers frequency range from 1 Hz to 200 Hz and the laser interferometer is based on FCM. Note that the accelerometer under calibration is mounted vertically in the LF system. On the contrary horizontal vibration is added in the VLF

calibration. A good agreement is also observed as shown in Figure 4.

Total uncertainty for the new system is not estimated yet. However, it is expected to be smaller than 0.5 % since measurement repeatability, which is normally main contribution to the total uncertainty, is below 0.05 %.

4. DISCUSSION

In this experiment it is clearly shown that digital BPF is useful to avoid undesirable dispersion caused by random noise. As BPF narrows signal bandwidth into excitation frequency, other problems derived from higher order harmonics may also be solved with BPFs. One example is distortion effect caused by vibration exciter as reported in recent studies [1, 4].

It should be noted that the sensitivity to horizontal vibration from 1 Hz to 10 Hz is consistent to that to vertical vibration within the uncertainty in the frequency range of 1 Hz to 10 Hz. For a long time, calibrations with both vertical and horizontal vibrations are thought to be necessary since reference accelerometers have been considered to have large nonlinearities. However, if the two ways of calibrations are considered to be equivalent, we do not need to operate both calibration systems, achieving significant cost reduction.

There is a slight increase in the sensitivity curve below 0.5 Hz: The sensitivity at 0.1 Hz has excess of 0.15 % compared to that at 1 Hz. A study explains that this kind of low-frequency sensitivity rise may derive from noise contribution to narrow-band signals [1]. However, we suspect that the reason in our system is the coupling to the Earth's gravity caused by non-flatness of the vibration exciter. We will study on it further and the result will be reported in the near future.

We also consider further improvements of the system. Assignment of digitizers is not optimized at the present. For example, digitizer for accelerometer voltage signal should be replaced to NI PXI-5922 or similar, which has high reliability to measure voltage [16]. I/Q signals will be measured with high-speed digitizer. In addition, we will also try to calibrate accelerometers at lower frequency below 0.1 Hz.

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REFERENCES

- [1] D. A. Scott and L. P. Dickinson "Distortion effects in primary calibration of low-frequency accelerometers," *Metrologia*, Vol. 51, No. 3, pp.212-, (2014).
- [2] N. Garg, et al., "A novel approach for realization of primary vibration calibration standard by homodyne laser interferometer in frequency range of 0.1 Hz to 20kHz," *Measurement*, Vol. 45, no. 8, pp. 1941-1950, (2012).
- [3] T. R. Licht and S. E. Salboel, "0 Hz and low frequency calibration of low frequency reference accelerometers," *3rd IMEKO TC22 Symposium, Cape town, South Africa*, (2014).
- [4] W. He, et al., "A long-stroke horizontal electromagnetic vibrator for ultralow-frequency vibration calibration," *Measurement Science and Technology*, Vol. 25, No. 8, pp. 085901, (2014).
- [5] C. D. Ferreira, G. P. Ripper, R. S. Dias and D. B. Teixeira, "Primary calibration system for vibration transducers from 0.4 Hz to 160 Hz," *Journal of Physics: Conference Series*, Vol. 575, pp. 012003-, (2015).
- [6] T. Bruns, et al., "Primary acceleration measurement using fringe counting with heterodyne interferometry," *3rd IMEKO TC22 Symposium, Cape town, South Africa*, (2014).
- [7] Y-B. Lee, "Low frequency vibration calibration system," presented at *APMP TCAUV meeting, Daejong, Korea*, (2014).
- [8] D-Z. Zhang, et al., "The application of orthogonal homodyne interferometer in the vibration calibration of ultra-low frequency and large amplitude," *AIP Conference Proceedings*, Vol. 1457, No. 206, (2012).
- [9] Q. Sun, and C. I. Veldman, "Final report on supplementary comparison APMP. AUV. V-S1," *Metrologia*, Vol. 50, No. 1A, pp. 09001-, (2013).
- [10] ISO 16063-11:1999 Methods for the calibration of vibration and shock transducers -- Part 11: Primary vibration calibration by laser interferometry
- [11] T. Usuda, et al., "The current progress of measurement standards for vibration in NMIJ/AIST," *Proc. SPIE, Sixth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications*, 30-38, (2004).
- [12] M. Schiefer and N. Garg, "Low frequency accelerometer calibration challenges, analysis and new developments," *XX IMEKO World congress, Busan, Korea* (2012).
- [13] M. Mende and N. Holger, "Calibration of Very Low Frequency Accelerometers-A Challenging Task," *Sound & vibration*, Vol. 45, No. 5, pp. 14-17, (2011).
- [14] G. P. Ripper, G. A. Garcia, G. R. S. Dias, "An interferometric accelerometer calibration system with flexible acquisition rate and recursive moving average filtering," *Proc. SPIE, Seventh International Conference on Vibration Measurements by Laser Techniques: Advances and Applications*, 634505 (2006).
- [15] T. Usuda, et al., "Current status on vibration metrology in Japan," *XVIII IMEKO World congress, Rio de Janeiro, Brazil*, (2006).
- [16] F. Overney, et al., "Characterization of metrological grade analog-to-digital converters using a programmable Josephson voltage standard," *IEEE Transactions on Instrumentation and Measurement*, Vol. 60, No. 7 pp. 2172-2177, (2011).