The current status of Acoustics, Ultrasound and Vibration measurement standards at NMIJ/ AIST

National Metrology Institute of Japan (NMIJ)
National Institute of Advanced Industrial Science and Technology (AIST)
AIST-Central 3, Umezono 1-1-1, Tsukuba, Ibaraki 305-8563
e-mail:ryuzo.horiuchi@aist.go.jp

1. Introduction

In April 2015, the NMIJ was re-organized and has four research institutes. Acoustics and Ultrasonics Standards Group is involved in the Research Institute for Measurement and Analytical Instrumentation. Vibration and Hardness Standards Group is involved in the Research Institute for Engineering Measurement.

Acoustics and Ultrasonics Standards Group is responsible for the development, supply and maintenance of acoustic and ultrasonic standards. Acoustic standards are essential for precise measurement of audible sound, airborne ultrasound and infrasound. Acoustic measurements are closely related to human hearing, noise pollution and safety evaluation. Ultrasonic standards are essential for the precise measurement of ultrasonic power, ultrasonic pressure and ultrasonic field parameters. Ultrasonic measurement are related to the medical diagnostics, treatments, and industrial applications.

Vibration and Hardness Standards Group is responsible for the development, supply and maintenance of vibration and acceleration standards, hardness standards and material impact strength standards necessary in order to ensure the safety and quality control of transport equipment and structures. Vibration and acceleration standards cover vibration acceleration, shock acceleration and angular velocity.

2. Acoustics

<u>**Activities after last CCAUV meeting**</u>

(1) Sound power level standards

Japanese manufacturers of electrical products, such as copy machines, printers, and air conditioners, are required to precisely measure sound power level emitted from their own products to sell them worldwide. The main purpose of the measurement is that laws and regulations etc. in foreign countries require reliable measurement, and/or the manufactures need to get “eco-label” approvals to differentiate competitor manufacturers.

Practically, sound power measurement of the products is often made in comparison with reference sound sources (RSSs). Thus the calibration of the RSSs is essential and has an important

Fig. A1: Hemisphere frame for fixing microphones and RSS located in anechoic chamber

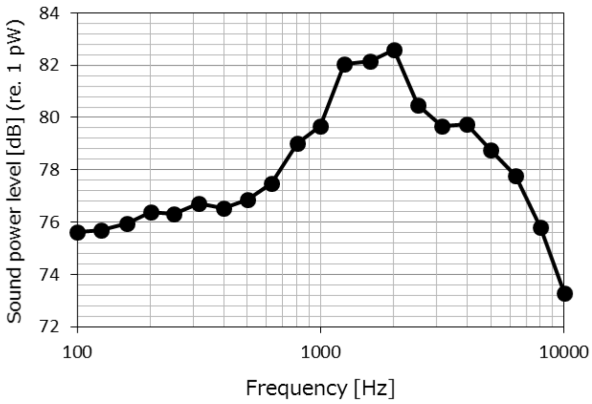

Fig. A2: Sound power level of RSS determined by our calibration system (Brüel and Kjær Type 4204)

role in the sound power measurement. The calibration procedure for RSS is standardized in ISO 6926, but there was no calibration laboratories in Japan except for NMIJ having hemi-anechoic environment that satisfies the requirements of ISO standard. The RSS users in Japan were keen for NMIJ to calibrate them.

Under these background, we had developed the RSS calibration system, and in 2015 we started the RSS calibration service from 100 Hz to 10 kHz with 1/3 octave sequence. The expanded uncertainties of the calibration (k=2) are from 0.4 dB to 0.9 dB.

Fig. A1 shows a photo of our calibration system, composed of hemisphere frame for fixing microphones and the RSS. The NMIJ does not have hemi-anechoic room and the hemi-anechoic environment is realized by underlying wooden plates in the anechoic room. The influence of the wooden board floor was investigated in detail by experiments and we found that it can be precisely corrected in the calibration [1]. **Fig. A2** shows an example of sound power level of RSS determined by our system.

To meet with customer requirements, we keep improving the calibration system to expand the frequency range, covering from 50 Hz to 20 kHz. Furthermore, we are developing a practical method to qualify the hemi-anechoic environment by using the RSS. ISO 3745 requires a special loudspeaker which satisfies the directivity requirement but we proposed a simulation method to see if the RSS is available for the room qualification [2].

(2) Calibration of free-field sensitivity levels for type WS3 microphones

Airborne ultrasound has been used in many occasions such as object detection and pest extermination. Recent application also includes haptic technology for virtual reality. As airborne ultrasound has been used, our concern increased for the safety of human exposure to airborne ultrasound. Although we cannot perceive airborne ultrasound by auditory organs, some research has found that exposure to very high sound pressure levels can be harmful. Thus, in 2009, NMIJ has established the acoustic standards in order to measure airborne ultrasound quantitatively and contribute to its safe use. Primary standards for airborne ultrasound is realized by the free-field sensitivity levels of WS3 microphones, ranging from 20 kHz to 100 kHz. We use the reciprocity technique to absolutely calibrate WS3 microphones at airborne ultrasound range, following to IEC 61094-3. Now, we summarized the results of uncertainty analysis on free-field reciprocity calibration of WS3 microphones, based on the document “Guide to the Expression of Uncertainty in Measurement" (GUM). Significant uncertainty component includes the deviation from the plane sound field. NMIJ realized the expanded uncertainty of 0.4 dB to 0.7 dB in a frequency range from 20 kHz to 100 kHz [3].

(3) Research works

Our research activity includes improving measurement repeatability on the pressure reciprocity calibration of LS1 microphones, examining the consistency of pressure sensitivities of LS microphones determined by using a large volume coupler and plane wave coupler, measuring and evaluating an airborne ultrasound emitted from rat-proof sound sources, and developing optical microphones.

Calibration services

NMIJ has developed calibration systems to provide the national standards of sound pressure in air [4-6].

1) Primary calibration of pressure sensitivity level of laboratory standard microphones (LS1P & LS2P) by using the pressure reciprocity technique (20 Hz to 20 kHz).
2) Primary calibration of free-field sensitivity level of laboratory standard microphones (LS1P & LS2P) by using the free-field reciprocity technique (1 kHz to 20 kHz).
3) Comparative calibration of free-field sensitivity level of working standard microphones (WS1, WS2 & WS3, 20 Hz to 20 kHz).
4) Comparative calibration of free-field response level of sound level meters (20 Hz to 12.5 kHz).
5) Determination of sound pressure level of sound calibrators (31.5 Hz to 16 kHz).
6) For airborne ultrasound, the microphone calibration system by the free-field reciprocity technique in the compact anechoic chamber (**Fig. A3**) was established. The calibration frequency range of WS3 microphones is from 20 kHz to 100 kHz. This standard is essential for human safety evaluation and for testing equipment which radiates air-borne ultrasound.
7) For infrasound, the pressure sensitivity calibration system by “laser pistonphone method” was established (**Fig. A4**), Calibration frequency range of LS1P microphones is from 1 Hz to 20 Hz.

This standard is essential for low frequency noise analysis and evaluation.

8) Calibration of sound power level of RSS (100 Hz to 10 kHz with 1/3 octave sequence)

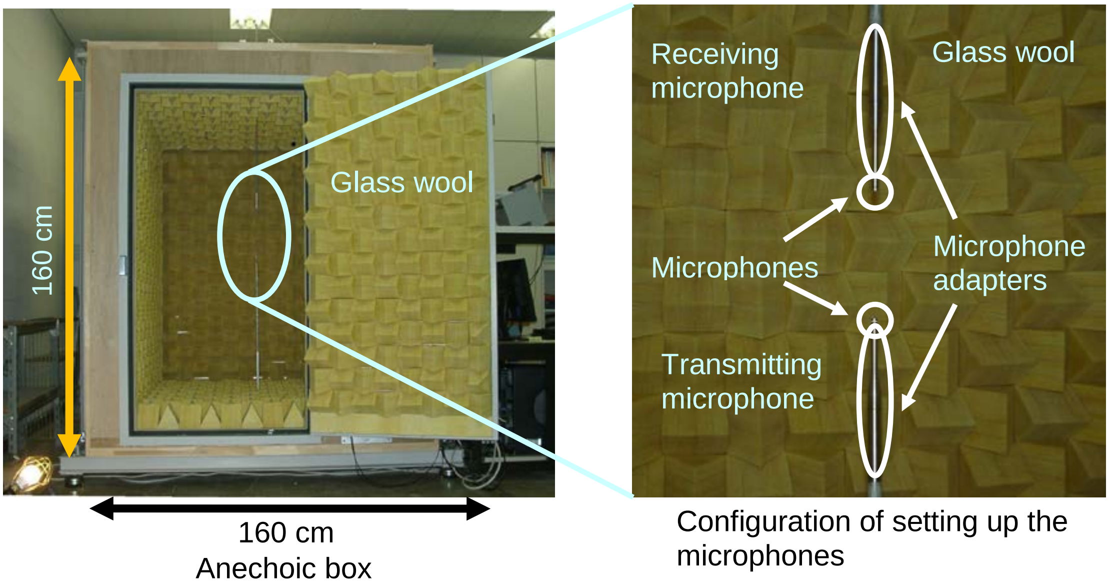

Fig A3: Compact anechoic chamber used for the calibration of airborne ultrasound by the reciprocity technique.

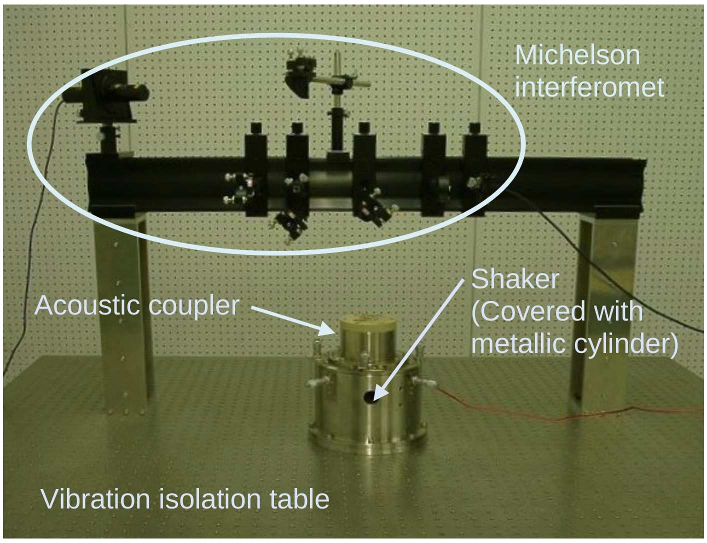

Fig. A4: “Laser pistonphone” which composes the microphone calibration system for infrasound.

Key comparisons and peer review

There are no international key comparisons since last CCAUV meeting. Technical competence in our calibration system was confirmed by the peer review in Dec. 2012, and our calibration services for acoustics were re-accredited in May 2013. NMIJ will have the next peer review early next year.

CMCs

There are no changes in CMCs since last meeting.

References:

[1] K. Yamada, H. Takahashi and R. Horiuchi, "Sound power transmitting through reflecting plane on the calibration of reference sound sources", Acoustical Science and Technology, Vol. 36, No. 4, pp 374-376, 2015.

[2] K. Yamada, H. Takahashi and R. Horiuchi, "Availability of reference sound sources for qualification of hemi-anechoic rooms based on deviation of sound pressure level from inverse square law", IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, under review, 2017.

[3] H. Takahashi and R. Horiuchi, "Uncertainty analysis on free-field reciprocity calibration of WS3 microphones", Journal of Acoust. Soc. of Am., submitted, 2017.

[4] H. Takahashi, W. Yoneshima and R. Horiuchi, "Validation of free-field sensitivity calibration by comparison for WS3 microphones in audible frequencies", 2015 Spring meeting of Acoust. Soc. of Jpn., 1-Q-13, 2015.

[5] H. Takahashi and R. Horiuchi, "Primary calibration systems for acoustic standards", Journal of Acoust. Soc. of Jpn., Vol. 72, No. 7, pp 404-405, 2016.

[6] H. Takahashi and R. Horiuchi, "Realization of reliable calibration on microphone sensitivities - Metrological traceability system introduced by Measurement Law –", Architectural Acoustics and Noise Control, Vol. 45, No. 1, pp 14-18, 2016.

3. Ultrasound

We have established three kinds of ultrasonic standard.

1) Ultrasonic power

The radiation force balance (RFB) system of NMIJ is shown as **Fig. U1**. The primary standard of ultrasonic power using RFB has been started up to 500 mW in 2005. In 2009, the power range has been expanded up to 15 W. The frequency range and the power range are as follows;

1 mW ~ 15 W (0.5 MHz ~ 15 MHz)

1 mW ~ 500 mW (15 MHz ~ 20 MHz)

The measurement uncertainties are 5 % ~ 12 % (95 % level of confidence).

Ultrasonic high power standard was developed by using "calorimetric method" with water as heating material for applying HITU (High Intensity Therapeutic Ultrasound). In this measurement, water bath is one of the important key elements. We have developed "free field" water bath. **Fig. U2** shows the photograph of the water bath. The radiated ultrasound repeats reflections at the water bath wall, and finally, circulates one-way in the water bath. An ultrasonic power calibration service from 15 W to 100 W in frequency range from 1 MHz and 3 MHz using "calorimetric method" was started in 2014. The corresponding expanded uncertainty is 9 % for 95 % level of confidence. We are due to expand the calibration range of ultrasonic power up to 200 W. So we are developing a reference transducer that is capable of radiating an ultrasonic wave beyond 200 W of ultrasonic power.

Fig. U1: A photograph of ultrasonic power calibration system.

Fig. U2: A "free field" water bath.

2) <u>Hydrophone sensitivity</u>

The primary calibration system, as shown in **Fig. U3**, for sensitivity of the standard membrane hydrophone (CPM04, Precision Acoustic Ltd.) using the laser interferometry has been established in 2005. The frequency range of the calibration is 0.5 MHz to 20 MHz. We have also established comparative calibration system for calibrating end-user hydrophones. Typical values of the expanded uncertainties are 6.1 % ~ 8.8 % (95 % level of confidence). In addition we have expanded the frequency range up to 40 MHz in 2014. The expanded uncertainty is 13 % above 20 MHz to 30 MHz and 17 % up to 40 MHz for 95 % level of confidence.

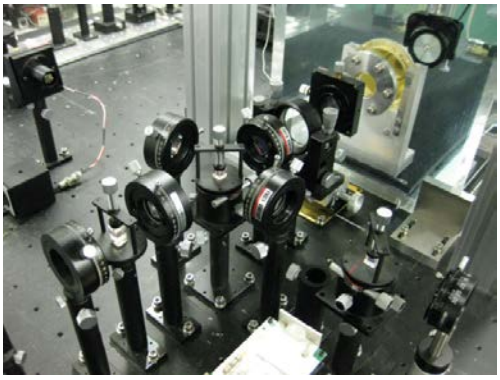

Fig. U3: A photograph of primary hydrophone sensitivity calibration system using laser interferometry.

Fig. U4: A photograph of fabricated 40 MHz ultrasonic transducer with 2 mm diameter active element.

One of the most serious problems of high frequency calibration is the ultrasonic attenuation in water. So, we have to achieve "ultrasonic far-field" at near distance from the transducer as possible. One of the solutions of this problem is to develop an ultrasonic transducer whose active element size is as small as possible as shown in **Fig. U4.** In order to expand the higher frequency range of the calibration, we are developing a small diameter transducers that is applied to the calibration over 60 MHz.

We have also developed the hydrophone sensitivity calibration system whose frequency range is 100 kHz to 1 MHz by reciprocity technique according to IEC 60565. The photograph of measurement system is shown in **Fig. U5**. The expanded uncertainties for the calibration are 10 % to 13 % (95 % level of confidence). We have started the calibration service of hydrophone sensitivity

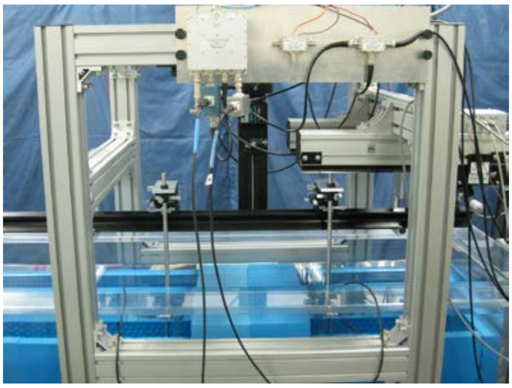

Fig. U5: A photograph of hydrophone sensitivity calibration system for reciprocity technique.

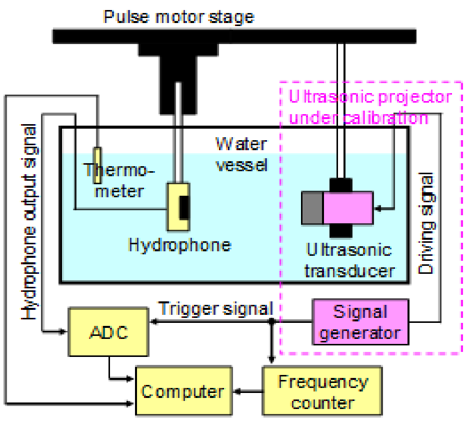

Fig. U6: A block diagram of measurement system for ultrasonic field parameters.

for frequency range between 100 kHz and 1 MHz in 2014.

Now we are conducting a technical transfer of the comparative calibration of hydrophone sensitivity from 0.5 MHz to 40 MHz to a Japanese calibration laboratory for a promotion of measurement standard that is traceable to the ultrasonic standard of NMIJ.

3) Ultrasonic field parameters

For the evaluation of performance and safety of ultrasonic medical equipment, measurement of ultrasonic fields is required in related IEC standards. Manufacturers of the equipment will be able to achieve validation of their measurement by comparing given references of ultrasonic field with their measurement results. We have already started the calibration service of three kinds of ultrasonic field parameters characterizing an ultrasonic field radiated from a reference transducer in 2007. The schematic diagram of the measurement system is shown in **Fig. U6**. Uncertainties of these ultrasonic field parameters, such as the peak-rarefactional acoustic pressure p_{R}, the spatial-peak temporal average intensity I_{SPTA}, and the spatial-average temporal average intensity I_{SATA}, from 500 kHz to 20 MHz in our calibration are as follows (95 % level of confidence);

p_{R}: 7 % ~ 10 %

I_{SPTA}: 14 % ~ 20 %

I_{SATA}:14 % ~ 21 %

Furthermore, we intend to append the effective radiating area A_{ER} and the beam non-uniformity ratio R_{BN} required for the evaluation of ultrasonic physiotherapy systems in IEC 61689 to our ultrasonic field parameter calibration in a few years.

4) Key comparisons

We participated in key comparisons of CCAUV.U-K3.1 (March 2014 to April 2015) and CCAUV.U-K4 (March 2014 to September 2015) that are for calibrations of ultrasonic power and hydrophone sensitivity, respectively. The final reports of the comparisons have been published on February and September 2016, respectively. Continuously, we are preparing a calibration of ultrasonic power for APMP key comparison planed in 2018.

References:

[1] T. Uchida, T. Kikuchi, M. Yoshioka, Y. Matsuda, and R. Horiuchi, Development of high ultrasonic power measurement technique by calorimetric method using water as heating elements for high ultrasonic power standard, Acoust. Sci. & Tech, 36, 5 (2015).

[2] M. Yoshioka, NMIJ measurement service on ultrasonic field parameters available to demonstrate performance and safety of medical ultrasonic equipment, APMP TCAUV TCI

Workshop (2015).
[3] M. Yoshioka, NMIJ ultrasonic standards necessary to demonstrate performance and safety of medical ultrasonic equipment, Workshop for APMP focus area working group of Medical Diagnostic Equipment (2015).
[4] T. Uchida, M. Yoshioka, Y. Matsuda, S. Takeuchi, and R. Horiuchi, Study on measurement technique for amount of generated cavitation -Relationship between concentration of microbubbles and output signal of sensor-, Proceedings of Symposium on Ultrasonic Electronics, Vol. 36, p. 1P4-8 (2015).
[5] T. Uchida, M. Yoshioka, Y. Matsuda, and R. Horiuchi, Study on measurement technique for acoustic cavitation using cavitation bubble signals, J. Acoust. Soc. Am. 140, p. 3372 (2016).

4. Vibration and acceleration standards

NMIJ has developed five calibration systems for the national standard of vibration, shock and angular velocity [1]-[12]. The three systems for vibration calibration are in compliance with ISO 16063-11 (Methods for the calibration of vibration and shock pick-ups. Part 11: Primary vibration calibration by laser interferometry) [13]. The system for shock calibration is in compliance with ISO 16063-13 (Methods for the calibration of vibration and shock transducers. Part 13: Primary shock calibration using laser interferometry) [14]. They are classified for their calibration range as follows.

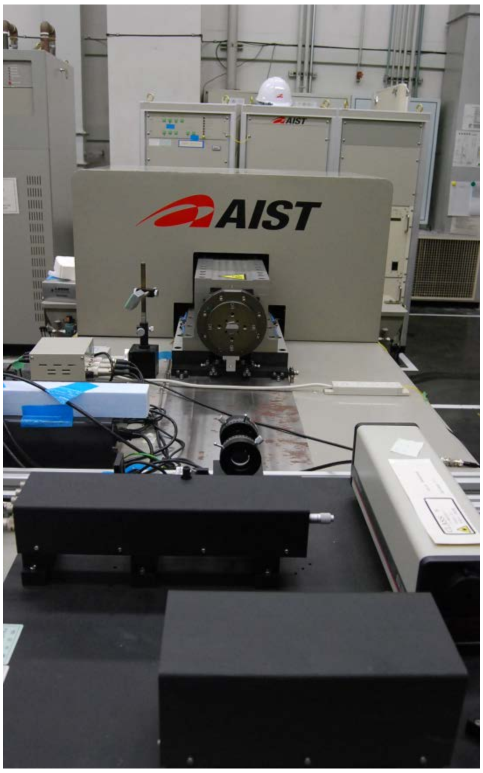

Fig. V1 System 1: Very low-frequency vibration calibration system

Fig. V2 System 2: Low-frequency vibration calibration system

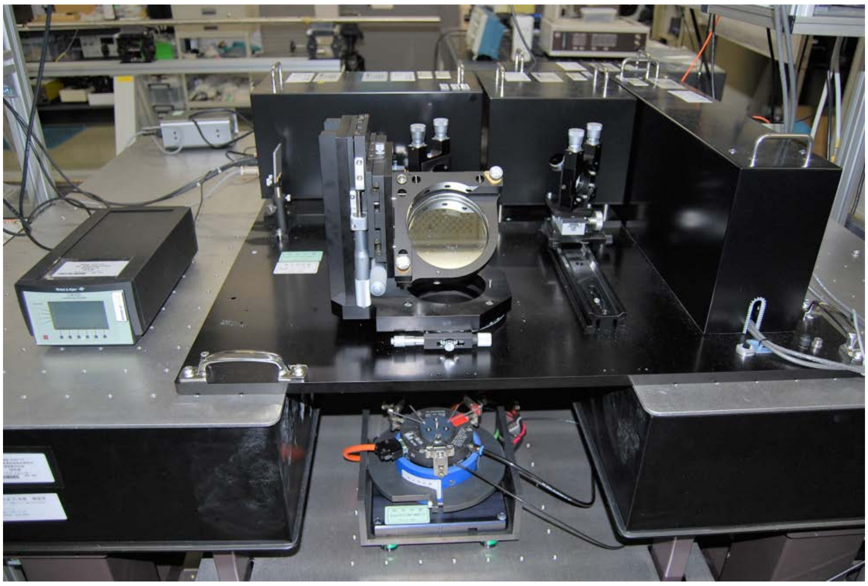

Fig. V3 System 3 High-frequency vibration calibration system

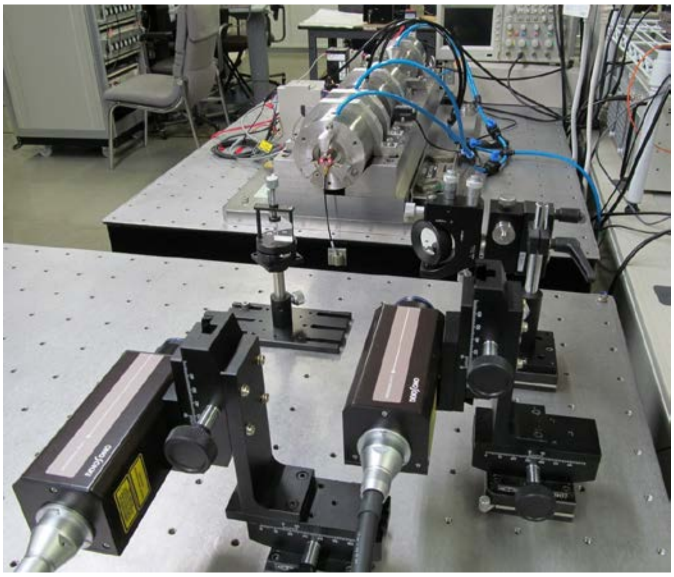

Fig. V4 System 4: Low-shock calibration system

Fig. V5 System 5: Angular velocity calibration system

System 1 is realized by a combination of modified homodyne Michelson laser interferometer for fringe-counting method in compliance with ISO 16063-11 and an electro dynamic vibrator with air-born slider which maximum stroke is 36 cm in horizontal direction. Some improvements with signal processing for sine approximation method and good-performance digitizers have been carried out to reduce the expanded uncertainty down to 0.2 %, to apply phase shift calibration, and to expand the applicable frequency range up to 200 Hz since 2012. The quality system for the improved System 1 will be established in 2017 and the low frequency range of 0.1 Hz to 200 Hz can be covered by this single system.

System 2 is realized by a combination of Michelson laser interferometer for fringe-counting method in compliance with ISO 16063-11. The vibrator can generate rectilinear motion with horizontal or vertical direction by changing its posture.

System 3 is realized by a combination of modified homodyne Michelson laser interferometer with double optical path and an electro dynamic vibrator with air-borne slider. The sine approximation method in compliance with ISO 16063-11 is applied to this system. The motion of vibrator is vertical direction. In 2017, applicable frequency range of this system was expanded down to 20 Hz. By using this system, the sensitivity calibration is provided in the frequency range from 20 Hz to 10 kHz, and the phase shift calibration is also provided in the frequency range from 20 Hz to 5 kHz.

System 4 is the shock calibration system for high acceleration amplitude. The shock exciter generates pulse-like acceleration which is monitored by two heterodyne laser interferometers. In order to calibrate shock sensitivity more precisely, the investigation has been done together with PTB [15, 16].

System 5, an angular velocity calibration system, for gyroscopes from 5 deg/s to 300 deg/s was developed with the use of a self-calibratable rotary encoder (selfA) as shown in **Fig. V5** [11]. Its expanded uncertainty is around 1.2×10^{-2} deg/s.

Technical competence in five systems from system 1 to 5 before above improvements has been confirmed by peer-reviews in 2002, 2007 and 2013. But, the system 6 was not peer-reviewed yet, because it was just established in 2014. Technical competence in our new systems will be confirmed by peer-review in 2018.

.

Figure	System	Calibration Range	Exp. Unc. (*k*=2)
Fig. V1	Very low frequency	0.1 Hz – 200 Hz	0.2 %
Fig. V2	Low frequency	1 Hz – 200 Hz	0.3 % - 2.0 %
Fig. V3	High frequency	20 Hz – 10 kHz	0.3 % - 0.8 %
Fig. V4	Low shock	50 m/s^2 – 10000 m/s^2	0.6 %
Fig. V5	Angular velocity	5 deg/s – 300 deg/s	1.2×10^{-2} deg/s

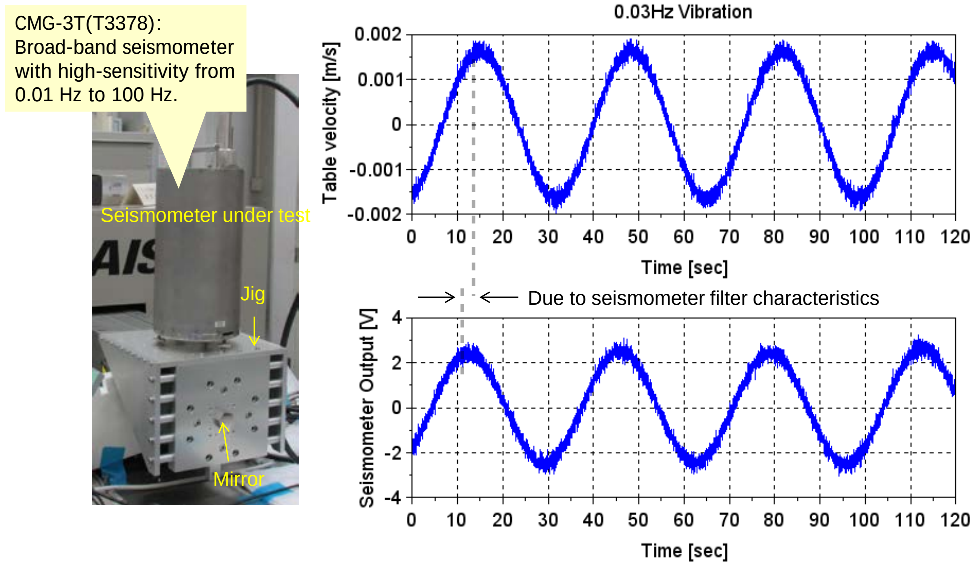

Fig.V6 Evaluation of broad-band seismometer with high-sensitivity from 0.01 Hz to 100 Hz

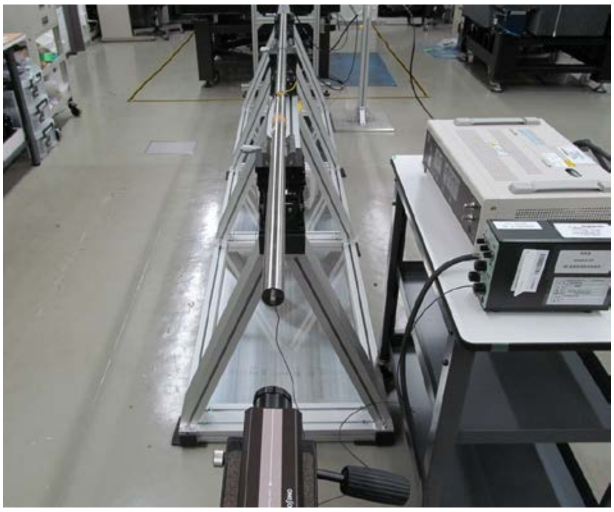

Fig. V7 High-shock calibration system

Now, NMIJ has tried to extend the calibration range. For lower frequency range, we try to extend the frequency range down to 0.01 Hz to contribute Geoscience. [17] **Fig. V6** shows evaluation of broad-band seismometer with high-sensitivity from 0.01 Hz to 100 Hz. On the other hand, for higher frequency range, we try to extend up to 20 kHz. Additionally, for shock acceleration, we try to develop the high-shock calibration system with heterodyne-type laser measurement for fast velocity up to 20 m/s as shown in **Fig. V7**. [18]

References:

[1] T. Usuda and T. Kurosawa, "Calibration methods for vibration transducers and their

uncertainties”, Metrologia, 36, 375-383 (1999).

[2] M. Dobosz, T. Usuda, T. Kurosawa, “Methods for the calibration of vibration pick-ups by laser interferometry: I. Theoretical analysis”, Measurement Science and Technology, Vol. 9, No. 2, 232-239 (1998).

[3] M. Dobosz, T. Usuda, T. Kurosawa, “Methods for the calibration of vibration pick-ups by laser interferometry: II. Experimental verification”, Measurement Science and Technology, Vol. 9, No. 10, 240-249 (1998).

[4] T. Usuda, M. Dobosz, T. Kurosawa, “Methods for the calibration of vibration pick-ups by laser interferometry: III. Phase-lag evaluation”, Measurement Science and Technology, Vol. 9, No. 10, 1672-1677 (1998).

[5] A. Oota, T. Usuda, H. Aoyama, S. Sato, Development of primary calibration system for vibration and acceleration standard in high frequency range with laser interferometer with multifold optical path, IEEJ Trans. SM, Vol.126, No.11, pp612-620 (2006).

[6] A. Oota, T. Usuda, H. Nozato, Correction and evaluation of the effect due to parasitic motion on primary accelerometer calibration, Measurement, Vol.43, No.5, 714-725 (2010).

[7] H. Nozato, T. Usuda, A. Oota, T. Ishigami, Calibration of vibration pick-ups with laser interferometry Part IV : Development of shock acceleration exciter and calibration system, *Measurement Science and Technology*, Vol.21, No.6, 065107 (2010).

[8] H. Nozato, T. Usuda, A. Oota, T. Ishigami, S. Okamoto, K. Yamamoto, H. Unejima, K. Kawaguchi, T. Sawada, I. Kanno, A round robin test of accelerometer in shock acceleration calibration -Development of shock acceleration calibration system traceable to national standard-(in Japanese), *Journal of the Japan Society for Precision Engineering*, Vol.77, No.8, 800-806 (2011).

[9] H. Nozato, A. Oota, T. Ishigami, T. Usuda, The methods for the calibration of vibration pick-ups by laser interferometer: Part V. Uncertainty evaluation on the ratio of transducer’s peak output value to peak input acceleration in shock calibration, *Measurement Science and Technology*, Vol.22, No.12, 125109 (2011).

[10] H. Nozato, W. Kokuyama and A. Ota, Improvement and validity of shock measurements using heterodyne laser interferometer, Measurement, (accepted).

[11] W. Kokuyama, T. Watanabe, H. Nozato, A. Ota, Development of angular velocity calibration facility using self-calibratable rotary encoder, Proceedings of Joint IMEKO International TC3, TC5 and TC22 Conference 2014 (2014).

[12] W. Kokuyama, T. Ishigami, H. Nozato, A. Ota, “Improvement of very low-frequency primary vibration calibration system at NMIJ/AIST”, Proceedings of XXI IMEKO World Congress,

Prague, Czech Republic (2015).

[13] ISO 16063-11: Methods for the calibration of vibration and shock pick-ups. Part 11: Primary vibration calibration by laser interferometry, International Organization for Standardization, 1999

[14] ISO 16063-13: Methods for the Calibration of Vibration and Shock Transducers. Part 13: Primary Vibration Calibration by Laser Interferometry, International Organization for Standardization, 2001.

[15] H. Nozato, T. Bruns, H. Volkers, A. Oota, Digital filter design with zero shift on charge amplifiers for low shock calibration, Measurement Science and Technology, Vol. 25, No. 3, 035005 (2014).

[16] H. Nozato, T. Bruns, H. Volkers, A. Oota, A study of Savitzky-Golay filters for derivatives in primary shock calibration, ACTA IMEKO, 2 (2) 41-47, (2013).

[17] H. Nozato, W. Kokuyama, A. Araya, Frequency response evaluation of broadband seismometer in primary calibration using laser interferometer, Proc. JpGU-AGU Joint Meeting, S-TT59 (2017) (in Japanese)

[18] H. Nozato, W. Kokuyama, T. Mashiko, Investigation of triaxial shock measurement by using three laser Doppler vibrometers, Proc. IMEKO TC3, TC5, TC22 Joint Conference (2017)