CALIBRATION METHODS OF VECTOR RECEIVERS IN THE FREQUENCY RANGE 5 HZ TO 10 KHZ AND THEIR COMPARISON VERIFICATIONS

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Abstract: *A description of calibration methods of vector receivers in the frequency range 5 Hz to 10 kHz and comparison verifications are given here. At the low frequencies, the vertical and horizontal standing wave tube methods can be used for calibration of vector receivers. At the high frequencies, free-field reciprocity method and comparison method can be used for calibration. To verify the calibration methods, a pilot comparison calibration of vector receivers was performed between Hangzhou Applied Acoustics Research Institute (HAARI), China and Russian National Research Institute for Physicotechnical and Radio Engineering Measurements (VNIIFTRI). The vertical standing wave tube comparison method working in the frequency range 5 Hz to 400 Hz and free-field three-transducer spherical-wave reciprocity method working in the frequency range 500 Hz to 10 kHz were used for calibrating of three vector receivers VHS56, VHS90 and KGP-10. From the calibration results, the veracity of two calibration methods was proved effectively, no significant discrepancies were detected within these comparisons.*

Keywords: *Calibration method, vector receiver, comparison verification*

1. INTRODUCTION

Vector receivers are widely used in underwater acoustics area for their special capabilities on sensitivities and directivities. They are not only proportional sensitive to the sound pressure, but also to the sound pressure gradient and the particle velocity which are existed at the centres of these vector receivers in water. And there are three sensitivities for a vector receiver, and can be transformed between them [1].

Another special capability of vector receivers is that they have very strong directivities with their patterns of dipole type, and the directivities are independent of frequency within their working frequency bands. They can be measured in free-field and standing wave tube according to the different working frequencies and calibration methods.

The methods for calibrating vector receivers are always developing since the birth of vector receivers [2]-[6]. The free-field methods are usually used for calibrating vector receivers at the frequencies higher than 1 kHz, and standing wave tube method can be used for calibrating of vector receivers at low frequencies, generally low to 5 Hz.

In order to calibrate the sensitivity of vector receivers at low frequencies in laboratory water tank, special signal processing techniques such as CMWA shall be used to eliminate or decrease the sound waves which reflecting from the walls and water surface of the water tank [6]. The low calibration frequency when using this technique can usually be 250 Hz.

To verify the veracity of these calibration methods and prepare for drafting IEC International Standard on calibration methods of vector receivers, a pilot comparison calibration COOMET 646/RU/14 was performed in the frequency range 5 Hz to 10 kHz between Hangzhou Applied Acoustics Research Institute (HAARI, DI for Underwater Acoustics, China) and Russian National Research Institute for Physicotechnical and Radio Engineering Measurements (VNIIFTRI, DI CIPM MRA, Russia) from 2015 to 2018 [7].

Two vector receivers VHS56 and VHS90 which manufactured by HAARI and a vector receiver KGP-10 which manufactured by VNIIFTRI were used in the comparison as reference vector receivers, they were calibrated by HAARI and VNIIFTRI using their facilities independently. The consistency was proved by the calibration results, and no significant discrepancies were appeared within these comparisons.

2. CALIBRATION METHODS OF VECTOR RECEIVERS

2.1 Free-field calibration methods

There are two calibration methods which can be used in free-field for calibrating vector receivers [8]. One is free-field reciprocity method, which is an absolute calibration method, the other is free-field comparison method, which is a relative calibration method.

2.1.1 Free-field reciprocity method

The free-field reciprocity method used here is the free-field three-transducer spherical-wave reciprocity method which is often used for calibrating reference hydrophones. In this method, three transducers are applied, and at least one shall be reciprocal. The transducers shall be paired off in three measurement configurations, as shown in Fig.1. For each measurement configuration, the transducer pair shall be deployed in water separated by a known distance, d , with their axes aligned towards each other.

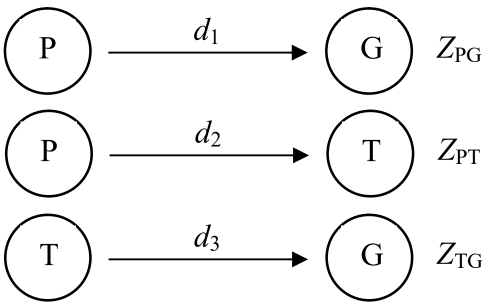


Fig. 1: Measurement configurations of free-field reciprocity method

The requirements for acoustic free-field conditions, far-field conditions and steady-state conditions shall be met for all configurations. In each case, using one transducer as a projector and the other as a hydrophone, the electrical transfer impedance can be determined at the calibration frequencies, and the free-field receiving sensitivity of vector receiver can be calculated from Equation (1)

$$M_{\mathrm{G}} = \sqrt{\frac{2}{\rho f}\frac{Z_{\mathrm{TG}}Z_{\mathrm{PG}}}{Z_{\mathrm{PT}}}\frac{d_{\mathrm{PG}}d_{\mathrm{TG}}}{d_{\mathrm{PT}}}}\sqrt{\frac{d_{\mathrm{PG}}d_{\mathrm{TG}}}{\sqrt{k^2d_{\mathrm{TG}}^2+1}\sqrt{k^2d_{\mathrm{PG}}^2+1}}} \tag{1}$$

Where, M_{G} is the pressure gradient sensitivity of vector receiver, f is the frequency, ρ is the density of water, Z_{PG}, Z_{TG} and Z_{PT} are electrical transfer impedances of projector and vector receiver, transducer and vector receiver, projector and transducer, d_{PG}, d_{TG} and d_{PT} are distances between projector and vector receiver, transducer and vector receiver, projector and transducer, k is the wavenumber.

2.1.2 Free-field comparison method

The comparison calibration of vector receiver in free-field can be accomplished by use of a reference hydrophone which had been previously calibrated by absolute calibration method. Since the uncertainty in calibration of the reference hydrophone will be inevitably introduced, free-field comparison method will have a higher uncertainty than the free-field reciprocity method.

When measuring, the sound field generated by an auxiliary projector in water is measured at a point in the acoustic far-field with the reference hydrophone. The vector receiver can measure the sound pressure at the same time or replace the reference hydrophone. The ratio of the open circuit voltages of such two transducers is equal to the ratio of their free-field sensitivities, and the free-field sound pressure receiving sensitivity of the vector receiver can be determined. Also, the directivity of vector receiver in free-field can also be determined by this method.

2.2 Standing wave tube calibration methods

There are also two kinds of calibration methods which can be used in standing wave tube for calibrating vector receivers. One is vertical standing wave tube method, the other is horizontal standing wave tube method, and the former is more widely used than the latter for its convenient installation and operation.

2.2.1 Vertical standing wave tube method

The calibration principle used in vertical standing wave tube is like vibrating column method. In this method, a vertical open-topped circular cavity which made of stainless steel is used as the standing wave tube. The tube is filled with water, and an auxiliary transducer is installed at the bottom of the tube as a projector to continuously transmitting the sound waves vertically upwards. A schematic diagram of vertical standing wave tube calibration is shown in Fig.2.

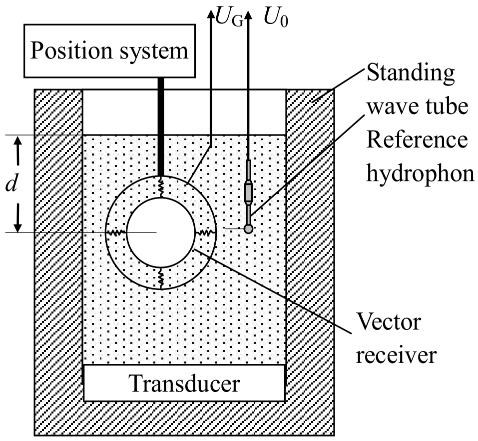


Fig. 2: Schematic diagram of vertical standing wave calibration

When measuring, the vector receiver and reference hydrophone were placed in the depth d and d_0 of the vertical standing wave tube, the open-circuit voltages U_G and U_0 of vector receiver and reference hydrophone were measured, and the sound pressure gradient sensitivity can be calculated from Equation (2).

$$M_G = \frac{U_G M_0}{k U_0} \frac{\sin kd_0}{\cos kd} \tag{2}$$

Where, M_G is sound pressure sensitivity of the reference hydrophone, k is the wavenumber.

Using this method, the directivity of vector receiver in standing wave tube can also be determined. If an accelerometer is used for determination of the sound pressure, it shall be an absolute calibration method, and the measurement uncertainty of this method can be lower than vertical standing wave tube comparison method.

2.2.2 Horizontal standing wave tube method

The measurement principle of the horizontal standing wave tube method is shown in Fig.3. The vector receiver is fixed in a rigid water-filled pipe closed at both ends, and the rigid pipe vibrates as a whole in horizontal direction, and the medium in the pipe moves like a small section of the standing wave.

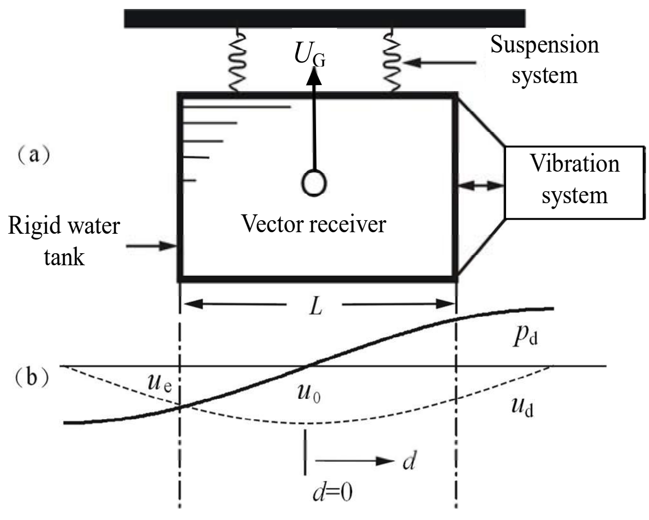


Fig. 3: Schematic diagram of horizontal standing wave tube calibration

The velocity sensitivity of vector receiver can be calculated from Equation (3).

$$M_{\mathrm{u}} = \frac{U_{\mathrm{G}} \cos(\frac{kL}{2})}{u} \tag{3}$$

Where, U_{G} is the open-circuit voltage of the vector receiver, L is the length of the tube, k is the wavenumber, and u is the vibration velocity of the pipe.

From the Fig.3, it can be seen that at the centre of the length of the standing wave tube, the sound pressure will be zero, and the vibration velocity and sound pressure gradient will be maximum. If the sound pressure gradient at the centre is measured, the pressure gradient sensitivity of vector receiver can also be calibrated.

3. COMPARISON CALIBRATION AND THEIR RESULT VERIFICATION

To verify the veracity of calibration methods of vector receiver, a pilot comparison calibration with its identifier number of COOMET/646/RU/14 beginning from 2015 was performed between HAARI, China and VNIIFTRI, Russia. Free-field three-transducer spherical-wave reciprocity method and vertical standing wave tube comparison method were used for this comparison, and the calibrations of vector receivers were carried from June to September, 2017 in Hangzhou, China and from April to July, 2018 in Moscow, Russia.

3.1 Vector receivers to be calibrated

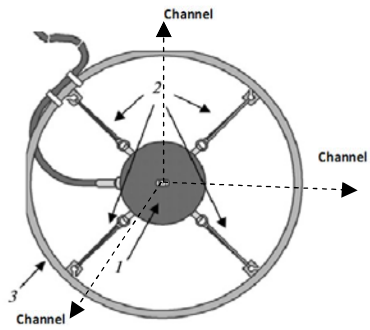
Three vector receivers were calibrated in this pilot comparison, each vector receiver is a three component sound particles velocity transducer, the detailed information of these vector receivers was listed in Table 1. They were calibrated at frequencies of 1/3 octave interval by different persons using different facilities and water tanks at different time and places.

Table 1: Detailed information of three vector receivers used in comparison

Type	Channels	Manufacturer	Frequency range [Hz]	Length of integral cable [m]	Diameter of transducer [mm]	Power supply [V]
KGP-10	X,Y,Z	VNIIFTRI	500–10000	6	53	±12 DC
VHS90	X,Y,Z	HAARI	5–4000	6	90	±12 DC
VHS56	X,Y,Z	HAARI	500–10000	6	56	±12 DC

3.2 Suspension of vector receiver when calibrating

The vector receiver to be calibrated was suspended into a ring which made of stainless steel through four rubber shock absorbers, and the vector receiver will be at the centre of the ring and in a zero buoyancy situation in water. The diagram of suspension of vector receiver when calibrating was shown in Fig. 4.



1 – three-component transducer in a spherical case, 2 – rubber shock absorbers, 3 – mounting ring

Fig. 4: Diagram of Suspension of vector receiver when calibrating

3.3 Calibration results and their comparisons

Three channels of three vector receivers were calibrated in the comparison, and the X channel calibration results of vector receivers VHS90 and VHS56 were given in Table 2 and Table 3. The comparison calibrations were carried in the frequency range 5 Hz to 10 kHz. At the frequencies from 5 Hz to 400 Hz, the vector receivers were calibrated by vertical standing wave tube comparison method. From 500 Hz to 10 kHz, free-field three-transducer spherical-wave reciprocity method was used for calibration.

Table 2: Calibration results of X channel of vector receiver VHS90

f [Hz]	M_{CN} [dB]	U_{CN} [dB]	M_{RU} [dB]	U_{RU} [dB]	f [Hz]	M_{CN} [dB]	U_{CN} [dB]	M_{RU} [dB]	U_{RU} [dB]
5	-224.2	1.0	-224.5	0.8	160	-195.4	1.0	-194.8	0.8
6.3	-222.5	1.0	-222.8	0.8	200	-193.3	1.0	-192.2	0.8
8	-220.5	1.0	-220.0	0.8	250	-191.4	1.0	-190.9	0.8
10	-218.9	1.0	-218.3	0.8	315	-189.4	1.0	-188.5	0.8
12.5	-217.2	1.0	-216.9	0.8	400	-186.5	1.0	-186.3	0.8
16	-215.1	1.0	-214.3	0.8	500	-184.8	0.7	-184.5	0.8
20	-213.2	1.0	-212.9	0.8	630	-182.7	0.7	-182.7	0.8
25	-211.0	1.0	-210.1	0.8	800	-181.0	0.7	-180.8	0.8
31.5	-209.8	1.0	-208.6	0.8	1000	-179.1	0.7	-178.9	0.8
40	-207.6	1.0	-207.0	0.8	1250	-177.2	0.7	-177.5	0.8
50	-205.4	1.0	-204.4	0.8	1600	-175.0	0.7	-175.3	0.8
63	-203.6	1.0	-202.7	0.8	2000	-173.1	0.7	-173.3	0.8
80	-201.2	1.0	-200.3	0.8	2500	-171.1	0.7	-171.2	0.8
100	-199.3	1.0	-198.4	0.8	3150	-168.8	0.7	-169.0	0.8
125	-197.2	1.0	-196.4	0.8	4000	-166.3	0.7	-166.6	0.8

Table 3: Calibration results of X channel of vector receiver VHS56

f [Hz]	M_{CN} [dB]	U_{CN} [dB]	M_{RU} [dB]	U_{RU} [dB]	f [Hz]	M_{CN} [dB]	U_{CN} [dB]	M_{RU} [dB]	U_{RU} [dB]
0.5	-196.6	0.7	-196.5	0.8	2.5	-183.2	0.7	-183.3	0.8
0.63	-194.8	0.7	-194.5	0.8	3.15	-181.2	0.7	-181.2	0.8
0.8	-192.9	0.7	-192.6	0.8	4	-179.1	0.7	-179.0	0.8
1	-191.2	0.7	-190.5	0.8	5	-176.9	0.7	-177.0	0.8
1.25	-189.2	0.7	-189.3	0.8	6.3	-174.8	0.7	-174.9	0.8
1.6	-187.0	0.7	-187.3	0.8	8	-171.2	0.7	-171.7	0.8

2	-185.3	0.7	-185.3	0.8	10	-168.5	0.7	-168.0	0.8

Where, M_{CN} and M_{RU} are sensitivity levels measured by HAARI and VNIIFTRI, U_{CN} and U_{RU} are expanded uncertainties declared by HAARI and VNIIFTRI [9].

The degrees of equivalence of X channel of vector receiver VHS90 and VHS56 are respectively presented graphically in Fig.5 and Fig.6 [10]. It can be seen that the calibration results of HAARI and VNIIFTRI are in good agreement, the equivalence of the results to the expanded uncertainties declared by HAARI and VNIIFTRI is not violated at any frequency points.

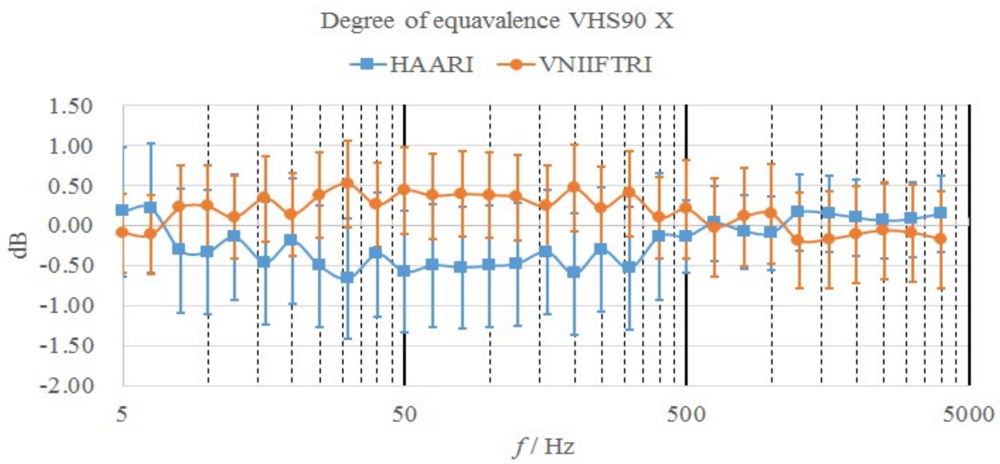


Fig. 5: Degrees of equivalence of X channel of vector receiver VHS90

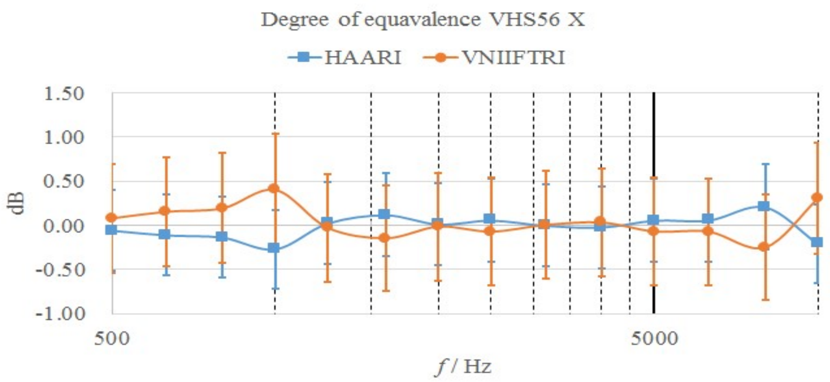


Fig. 6: Degrees of equivalence of X channel of vector receiver VHS56

4. CONCLUSION

The calibration methods of vector receivers and their comparison verifications are introduced here, and a pilot comparison COOMET/646/RU/14 was successfully performed between HAARI, China and VNIIFTRI, Russia.

From the calibration results, it can be seen that there is a good agreement between HAARI and VNIIFTRI, no significant discrepancies were detected within these comparisons. It effectively proves the veracity of free-field three-transducer spherical-wave reciprocity method and vertical standing wave tube comparison method, and the reliability of the calibration results. These works lay a good beginning for drafting an IEC International Standard on calibration methods of vector receivers.

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