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INTERNATIONAL COLLABORATION

COMPARING HYDROPHONE CALIBRATION RESULTS FOR RUSSIAN AND CHINESE STANDARDS

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Russian and Chinese national standards have been compared by exchanging hydrophones for calibration in the frequency range from 1 Hz to 630 kHz. The results agree very closely, which confirms that the estimates made of the errors in the two standards are reliable.

A comparison of hydroacoustic measurements was made in 1997–8 by comparing the calibrations of piezoceramic hydrophones on the standards held by the All-Russia Technical Physics and Electronics Research Institute (VNIIFTRI) in Russia and Hanchou Applied Acoustics Institute (HAAI) in China. HAAI sent hydrophones of types 8100 and 8103 made by Bruel and Koer in Denmark together with a hydrophone of RHS_2 type developed by that institute, which has a spherical sensing element of diameter 20 mm. VNIIFTRI sent HAAI hydrophones designed by the Institute types GI-20 and GI-22, which have spherical sensing elements correspondingly of diameters 20 and 7 mm, together with a GI-30 high-frequency hydrophone whose active element is a radially polarized thin-walled (0.2 mm) cylinder of diameter and length 2 mm.

The calibrations were performed with the equipments in the primary and secondary national standards over the frequency range 1 Hz to 630 kHz. The measurements were made at standard frequencies in a three-octave series. Table 1 gives the calibration methods and any distinctive features of the equipment used to calibrate the hydrophones.

We now consider briefly the features of the methods. Piezoelectric compensation methods were developed at the Russian Institute [1] and are recommended by the International Electrotechnical Commission IEC, and they have been used to calibrate hydrophones on the Chinese standards (at 1 Hz to 2 kHz) and the Russian ones (0.8 Hz to 4 kHz). The equipments that employ this method have much in common: closed chambers of approximately equal dimensions, balancing converters in the form of two coaxial piezoceramic cylinders with elastic coupling between them, and similar forms of supporting hardware, with the measurements managed under the control of a personal computer.

The Chinese standard equipment employs a two-channel oscillator to excite the radiator and the null detector in the balancing converter, which has independent amplitude and phase regulation for each channel, and where particular attention is given to errors of measurement for the voltage (±0.1 dB) and phase (±0.1°) for the null detector.

The distinctive features of this method in the Russian standards are related to corrections for the nonuniformity of the sound pressure distribution in the chamber [3]. The corrections incorporated the height of the null detector, the dimensions of the hydrophone's active component, the shifts in the acoustic centers of the hydrophone and null detector from the geometrical center of the chamber, and also the measurement frequency. This enabled us to reduce the errors of measurement and to extend the frequency range to 4 kHz.

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TABLE 1. Methods Used and Distinctive Standard Equipment Features

Hydrophone type	Frequency range	Method		Equipment features	
		VNIIFTRI	HAAI	VNIIFTRI	HAAI
GI-20	1–4000 Hz	Piezoelectric balancing	–	Closed chamber	–
	1–2000 Hz	–	Piezoelectric balancing	–	Closed chamber ∅ 72 × 60 mm
	20–1400 Hz	–	Oscillating liquid column	–	Open cylindrical vessel $H = 200$ mm
	3.15–50 kHz	Free-space reciprocity	–	Basin 10 × 6 × 6 m	–
	2–50 kHz	–	Free-space reciprocity	–	Anechoic basin 8 × 5 × 5 m
B&K 8100	1–4000 Hz	Piezoelectric balancing	–	Closed chamber	–
	1–2000 Hz	–	Piezoelectric balancing	–	Closed chamber ∅ 72 × 60 mm
	20–1400 Hz	–	Oscillating liquid column	–	Open cylindrical vessel $H = 200$ mm
	3.15–100 kHz	Free-space reciprocity	–	Basin 10 × 6 × 6 m	–
	2–100 kHz	–	Free-space reciprocity	–	Anechoic basin 8 × 5 × 5 m
GI-22	5–200 kHz	Free-space reciprocity	Free-space reciprocity	Basin 10 × 6 × 6 m	Anechoic basin 8 × 5 × 5 m
RHS_2	3.45–100 kHz	Free-space reciprocity	Free-space reciprocity	Basin 10 × 6 × 6 m	Anechoic basin 8 × 5 × 5 m
B&K 8103	100–200 kHz	Free-space reciprocity	Free-space reciprocity	Basin 10 × 6 × 6 m	Anechoic basin 8 × 5 × 5 m
	200–630 kHz	Free-space reciprocity	Free-space reciprocity	Basin 1 × 1.5 × 1 m	Anechoic basin 1.8 × 1.2 × 1.4 m
GI-30	200–630 kHz	Free-space reciprocity	Free-space reciprocity	Basin 1 × 1.5 × 1 m	Anechoic basin 1.8 × 1.2 × 1.4 m

The bounds to the fiducial error in these equipments at the 0.95 level are not more than 0.45 dB (China) or 0.25 dB (Russia).

The oscillating liquid column method recommended by the IEC [4] is used at HAAI to calibrate relatively large hydrophones in the range 20–1400 Hz. The equipment contains a calibrated accelerometer, bandpass filter, and digital voltmeter (±0.1 dB), and corrections are applied for the high-frequency distortions in the acoustic field, which provide for calibration with an error of not more 0.45 dB at the 0.95 fiducial level. HAAI used that method to calibrate the GI-20 and B&K 8100 hydrophones as an alternative to the piezoelectric balancing method.

The participants used the reciprocity method widely employed and recommended by IEC [2] at frequencies above 2 kHz, in which a free field is used with three converters. One of them is used only as a radiator, while the second is a reversible converter and operates either as a radiator or as a receiver, and the third is the hydrophone to be calibrated, which operates only in reception.

During the calibration, one measures the signals from the hydrophone and the reversible converter with a fixed and accurately measured current through the radiator, and also the hydrophone signal on excitation of the reversible converter by the same current as with the radiator. At frequencies up to 200 kHz, the free-field conditions were realized in large hydroacoustic basins. In China, that basin was 8 × 5 × 5 m, with the walls and bottom covered with wedge-shaped sound-absorbing material. The dimensions of the Russian basin were 10 × 6 × 6 m. To eliminate effects from signals reflected from the surface, the bottom, and the walls, as well as those from the auxiliary structures in the water, i.e., to provide free-field conditions, both of the participants used radio-pulse working.

The differences in the implementation of the method are related to the disposition of the converters in the three measurement stages. In the Russian standards, the three converters are arranged in a line. When one measures the signal passing from the radiator to the hydrophone, the middle converter is moved to one side. In the Chinese standard, only a two-position scheme is used, in which the radiator and the converter to be calibrated are successively replaced by the reversible converter. The displacements and rotations of the converters are automated at all stages in the calibration in the two equipments.

To check the free-field conditions and evaluate the decay law away from the radiator, the Russian standard provides for accurately controlled displacement of the converters over ranges of 25–85 cm, in which the signal received by the hydrophone

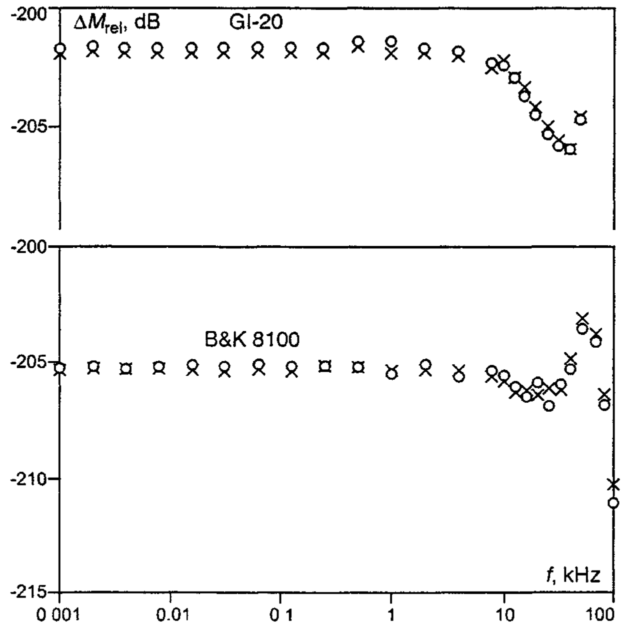

Fig. 1. Calibration results in decibels relative to 1 V/μPa for hydrophones GI-20 and B&K 8100 at HAAI (o) and VNIIFTRI (×).

is recorded as a function of the radiator distance. That check is recommended by the IEC [2], and it provides for the best choice of measurement distance for the various types of hydrophone. The relative error Δ for 0.95 fiducial probability is not more than 0.35 dB for the Russian equipments in the range 3.15–200 kHz. The analogous figures for the Chinese equipment are 0.36 dB up to 50 kHz and 0.46 dB up to 200 kHz.

The free-field conditions at 200 kHz–1 MHz were produced in substantially smaller basins. The Chinese used a tank 1.8 m long, 1.2 m wide, and 1.4 m deep, with the plastic walls and bottom coated with sound-absorbing material in the form of sets of rubber wedges. The Russians used a somewhat smaller tank: length 1.5 m, width and height 1 m. As in the equipments described above, the three converters were arranged on a single line with transverse displacement of the hydrophone to be calibrated (VNIIFTRI). The HAAI apparatus used a two-position system. The measurements were made with radio pulses and the calibration was completely automated. The calibration errors in this frequency range on the Russian and Chinese standards did not exceed 0.5 dB for 0.95 fiducial probability.

Each participant measured the hydrophone sensitivity at the output from the cable under open-circuit conditions by a method developed and agreed by the two sides. The method included a statement of the frequency ranges in which each hydrophone should be calibrated, the orientation of it in the measurements, and the processing algorithms.

The hydrophones were sent for calibration without any statement on their characteristics. The calibrations were exchanged and discussed at a conference on hydroacoustic measurements (which included other interested Chinese organizations) in May 1998 in Fuyan (China).

The measurements were repeated not less than eight times in order to provide the necessary accuracy and to estimate the random error; each hydrophone was used with the determination of its sensitivity at a preset frequency in the working range corresponding to a frequency of the standard equipment. After each measurement cycle, the hydrophone was removed from the water and released from its holder. The measurements were averaged over all the cycles, which reduced the random-error component associated with inaccuracy in setting the hydrophone in the holder and locating it in the measurement field. This recommended number of repeated cycles provided a reasonably low random error relative to the residual systematic error in each standard.

The two sets of calibration results for each hydrophone are given in Figs. 1–3, where they are paired in accordance with the working frequency ranges. Only the octave points are given for the GI-20 and B&K 8100 in the range 1 Hz–10 kHz for convenience in illustrating the frequency response.

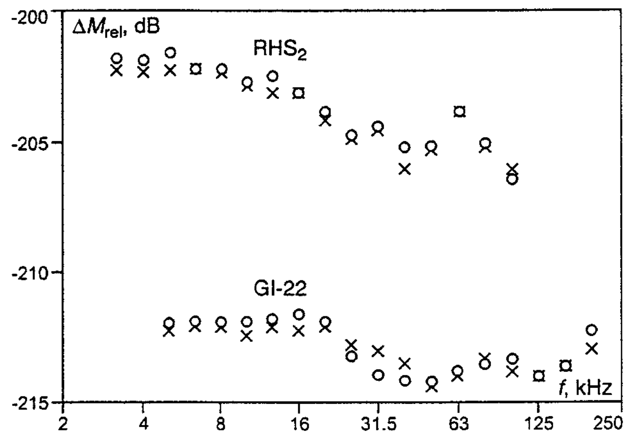

Fig. 2. Calibration results in decibels relative to 1 V/μPa for hydrophones GI-22 and RHS_2 at HAAI (O) and VNIIFTRI (×).

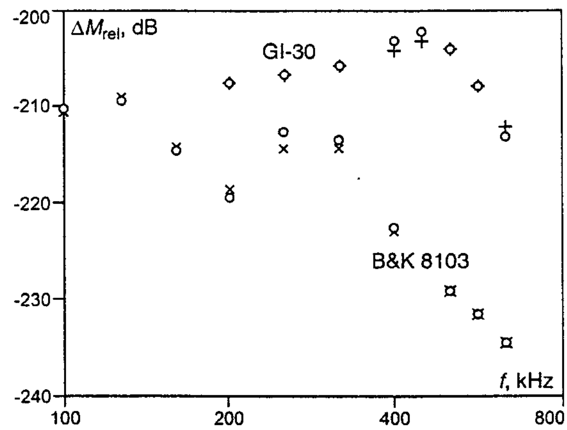

Fig. 3. Calibration results in decibels relative to 1 V/μPa for hydrophones GI-30 and B&K 8103 used at HAAI (O) and VNIIFTRI (+ GI-30 and × B&K 8103).

We used the sensitivity differences $\Delta M = M_{ch} - M_{ru}$ to evaluate the agreement. The maximum value of it ΔM_{max} over the entire frequency range for each hydrophone characterizes the best result. The standard deviation ΔM_{sd} of that difference gives a more reliable evaluation of the discrepancies, for which random excursions do not have a major effect. Arithmetic averaging of the ΔM gives the average difference ΔM_{av}, which serves to estimate the systematic deviation of one set of measurements relative to the other. That approach is used in analyzing interlaboratory comparisons in Britain [5].

Table 2 gives ΔM_{max}, ΔM_{sd}, and ΔM_{av} for each hydrophone, which shows that the least ΔM_{sd} = 0.24 dB occur for GI-20 and B&K 8100. They give the best agreement and do not have any appreciable systematic difference (ΔM_{av} = 0.05–0.08 dB). The frequency curves in Fig. 2 for the sensitivities of GI-22 and RHS_2 have somewhat larger differences: their ΔM_{sd} are respectively 0.43 and 0.36 dB (Table 2), while there are elevated ΔM_{av} of 0.1 and 0.24 dB, which show that there is a certain systematic difference between the results with them at the two institutions. Figure 3 shows the frequency dependence of the sensitivity for GI-30 and B&K 8103, which differ substantially in the degree of agreement. In the latter, ΔM_{sd} = 0.68 dB, i.e., about twice as great; ΔM_{av} = –0.18 dB; and ΔM_{max} = 1.6 dB make them very different from the other hydrophones. Nevertheless, the varying signs for the maximal and average differences for GI-30 and B&K 8103 do not necessarily indicate a systematic discrepan-

TABLE 2. Comparison of the HAAI and VNIIFTRI Standards

Hydrophone type	Frequency range, kHz	ΔM_{max}, dB	ΔM_{av}, dB	ΔM_{sd}, dB
GI-20	0.001–50	0.6	0.08	0.24
B&K 8100	0.001–100	–0.9	0.05	0.24
GI-22	5–200	–0.9	0.1	0.43
RHS_2	3.15–100	0.8	0.24	0.36
GI-30	200–630	0.8	0.09	0.43
B&K 8103	100–630	–1.6	–0.18	0.68

TABLE 3. Comparison of GI-20 and B&K 8100 Hydrophones

f, kHz	ΔM, dB for		ΔM_{sd}, dB	Δ^*_{ch}, dB (%)	k_1	k_2
	GI-20	B&K 8100				
0.001	0.2	0.1	0.11		0.25	0.19
0.002	0.3	0.1	0.16		0.38	0.27
0.004	0.1	–0.1	0.07		0.13	0.12
0.008	0.1	0	0.05		0.13	0.08
0.016	0.1	0.2	0.11		0.25	0.19
0.032	0.1	0.2	0.11		0.25	0.19
0.063	0.2	0.3	0.18	0.52	0.38	0.3
0.125	0.1	0.2	0.11	(6.2)	0.25	0.19
0.25	0.1	0.1	0.07		0.13	0.12
0.5	0.3	0	0.15		0.38	0.25
1.0	0.5	–0.1	0.25		0.63	0.42
2.0	0.2	0.2	0.14		0.29	0.28
4.0	0.3	–0.2	0.18		0.43	0.36
8.0	0.1	0.3	0.10	0.42	0.43	0.2
16.0	–0.4	–0.1	0.18	(4.9)	0.87	0.36
20	–0.3	0.5	0.17		0.73	0.34
25	–0.3	–0.8	0.24		1.16	0.48
31.5	0.2	0.1	0.24		1.31	0.48
40	0	–0.5	0.28		1.16	0.56
50	–0.1	–0.5	0.15	0.54	0.62	0.25
63	–	–0.3	0.11	(6.4)	0.37	0.18
80	–	–0.4	0.17		0.49	0.28
100	–	–0.9	0.28		1.11	0.46

* Δ_{ru} = 0.27 dB (3.2 %).

cy between the two sets of results in this frequency range. Table 2 also implies that all the hydrophones apart from B&K 8103 have essentially identical ΔM_{max}, while they differ in sign for the pairs of hydrophones in similar frequency ranges (GI-20 with B&K 8100, GI-22 and RHS_2, and GI-30 and B&K 8103), which shows that these deviations are random.

There is good agreement between the two institutes over the frequency characteristics given in Figs. 1–3 at least for the range up to 20 kHz. The entire set of ΔM (for all frequencies in the three-octave series and all hydrophones) for that range may be processed by least squares fitting to estimate the average discrepancies for the standard calibrations, which is 0.13 dB and increases slightly with frequency from 0.08 dB at 1 Hz to 0.18 dB at 20 kHz.

TABLE 4. Comparison of GI-22 and RHS_2 Hydrophones

f, kHz	ΔM, dB for		ΔM_{sd}, dB	Δ_{ch}, dB (%)	k_1	k_2
	GI-22	RHS_2				
8.0	0.2	0.1	0.10		0.43	0.2
16.0	0.6	0	0.18		0.87	0.36
20	0.2	0.3	0.17	0.42 (4.9)	0.73	0.34
25	−0.4	0.2	0.24		1.16	0.48
31.5	−0.9	0.3	0.24		1.31	0.48
40	−0.6	0.8	0.28		1.16	0.56
50	0.3	0.1	0.15		0.62	0.25
63	0.1	0.1	0.11		0.37	0.18
80	−0.3	0.1	0.17		0.49	0.28
100	0.5	−0.4	0.28	0.54 (6.4)	1.11	0.46
125	0	–	0.05		0.12	0.08
160	0	–	0.25		0.62	0.41
200	0.7	–	0.36		0.99	0.6

* Δ_{ru} = 0.27 dB (3.2 %).

TABLE 5. Comparison of B&K 8103 and GI-30 Hydrophones

f, kHz	ΔM, dB for		ΔM_{sd}, dB	Δ_{ru}, dB (%)	Δ_{ch}, dB (%)	k_1	k_2
	B&K 8103	GI-30					
100	−0.2	–	0.28			1.11	0.46
125	0.1	–	0.05	0.27 (3.2)	0.54 (6.4)	0.12	0.08
160	0.5	–	0.25			0.62	0.41
200	0.8	−0.1	0.36			0.99	0.6
250	−1.6	0	0.85			1.04	0.98
315	−0.8	−0.1	0.40			0.52	0.46
400	−0.3	0.7	0.38			0.46	0.44
450	–	0.8	0.8	0.56 (6.7)	0.66 (7.9)	0.52	0.92
500	−0.1	0	0.05			0.07	0.06
550	−0.1	0	0.05			0.07	0.06
630	0	−0.6	0.3			0.39	0.34

All the above ΔM are quite small; they can be compared with analogous comparisons made in Britain [5], where a somewhat larger standard deviation (up to 2 dB) was found on a basis of all the participants; the maximum deviation from the mean sometimes exceeded 3 dB. The agreement is not considered as accidental on the basis that the comparison was made for six different types of hydrophone and gave over 140 results.

A major purpose has been to compare the differences in the measurements with the errors in the comparison with the standard equipments. This is particularly important because the two participants have a fairly high opinion of the metrological characteristics of their standards: estimates of the relative fiducial errors do not exceed 0.25–0.5 dB. To confirm the reality of these estimates, one can use the ΔM with two convergence parameters, which are as follows: the soft parameter $k_1 = |\Delta M_{max}|(\Delta_{ru} + \Delta_{ch})^{-1}$ and the harder parameter $k_2 = \Delta M_{sd}(\Delta^2_{ru} + \Delta^2_{ch})^{-1/2}$.

Averaging the ΔM for all the hydrophones calibrated at a given frequency gives a deviation related not to the hydrophone construction but instead to features of the standard equipment. It is clear that if the errors have been estimated correctly, one should have $k < 1$ and $k_2 < 1$. Tables 3–5 give ΔM, ΔM_{sd}, Δ_{ru}, Δ_{ch}, k_1, and k_2 for the range 1 Hz–16 kHz only for the octave frequencies. They imply as follows:

1) the differences ΔM_{max} for most frequencies are less than the errors in the standards, i.e., $k_1 < 1$, and only for five out of the 61 frequencies does the maximal difference exceed that sum by 10–30%;

2) values of $k_1 > 1$ at 25–40 kHz are due to the large ΔM for three different hydrophones (B&K 8100, GI-22, and RHS_2);

3) the large ΔM for the B&K 8103 at 200–300 kHz are evidently due to resonance in the sensor, which causes an anomalous increase in the collimation, and that is a source of large measurement errors. The same effect occurs at 400–450 kHz for GI-30, where the main resonance in the sensor lies; and

4) the ΔM_{sd} at all frequencies do not exceed the standard deviation in the errors of the standards. This shows that the estimates of the errors for the standard equipments are reliable.

REFERENCES

1. A. N. Golenkov and L. E. Pavlov, *Izmer. Tekh.*, No. 5, 44 (1967).
2. IEC Standard: *Hydrophone Calibration*, Publ. 565, Geneva (1977).
3. A. N. Golenkov and S. M. Likhachev, *Izmer. Tekh.*, No. 11, 57 (1994).
4. IEC Standard: *Hydrophone Calibration: First Supplement to IEC 565*, Publ. 565A, Geneva (1980).
5. S. P. Robinson, R. C. Preston, and D. R. Bacon, *A National Intercomparison of Hydrophone Calibration Methods*, NPL Acoustics Report Ac 116, June (1988).
6. IEC Standard: *A Primary Standard Hydrophone*, Publ. 500, Geneva (1974).