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# Absolute calibration of hydrophones

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## Summary

Because no absolute standard exists as a reference unit for acoustic measurements, absolute calibration of hydrophones would require complicated measurements of related physical quantities. However, with the reciprocity technique the calibration can be performed in a simple way, using an additional reciprocal transducer beside the sound source. A special method is described which reduces the number of observations and which improves the reliability. The error in the calibration result is less than 1 dB.

## 1. Problem

The measurement of a physical magnitude generally consists of a comparison of the unknown magnitude with an appropriate standard which is derived from a unit standard of length, mass, time, electric current, temperature or light. Unfortunately, no standard exists for sound pressure, so that a direct measurement of this quantity is not possible. Delicate instruments exist with which the radiation force of an acoustic wave can be measured at high frequencies in the megahertz range, but the use of these instruments at low frequencies is impractical.

## 2. Solution

There is a fundamental rule in acoustics which can be applied at any linear passive system (a system without additional energy sources or sinks) which is called the rule of reciprocity. According to this rule the voltage at the terminals of an electroacoustic receiver in the sound field of an electroacoustic transmitter, divided by the current through that transmitter, remains constant if the functions of transmitter and receiver are interchanged, provided that in each transducer the conversion of electric to acoustic energy is the same as from acoustic to electric energy. Both transducers may have different conversion systems, but these systems should be reciprocal, like electrodynamic, electrostatic or piezoelectric systems.

This principle is generally used to realise absolute calibration of microphones and hydrophones without using a primary standard. If such a hydrophone has been calibrated, it can be used as a secondary standard to calibrate other hydrophones in a much more simple way.

## 3. Definitions

3.1 Free-field sensitivity of a hydrophone, or "hydrophone sensitivity": The ratio of the open circuit voltage of the hydrophone to the sound pressure in the undisturbed free field which should exist in the position of the hydrophone if that hydrophone were removed. Symbol: M volt per pascal.

3.2 Transmitting response to current of a projector, or "projector sensitivity": At a given frequency and in a specified direction, the ratio of the sound pressure at a distance of one metre from the acoustic centre of the projector to the current flowing through the electrical terminals.
Symbol: S pascal metre per ampere.

Note: If the near field of the projector extends to a distance of the order of magnitude of 1 metre or more, the sound pressure should be defined at a larger distance, amply into the far field, and then multiplied by that distance. See figure 1.

3.3 Transfer impedance: The ratio of the open circuit voltage $E_h$ across the hydrophone terminals to the current $I_p$ through the projector, if projector and hydrophone are mounted in a free field with their acoustic axes in line and towards each other:

$$Z_{hp} = \frac{E_h}{I_p} \text{ ohm} \tag{1}$$

Note: As a result of the reciprocity principle $Z_{hp} = Z_{ph}$

## 4. Principle

The reciprocity principle states that under the conditions as described in the definitions above:

$$\frac{M}{S} = \frac{2}{\rho f} \tag{2}$$

where $\rho$ is the density of the medium, i.c. water,
and $f$ is the frequency of the sinusoidal signal.

Now we need three transducers: One projector P;
one hydrophone H, generally the unknown hydrophone;
one reciprocal transducer T.

The projector and the hydrophone need not be reciprocal.
With these three transducers three measurements are performed at the same signal frequency. See figure 2.
First measurement: The projector P and the hydrophone H are under water at a distance $d_1$. The acoustical axes of both transducers should coincide.
Through the projector flows a current $I_p$. Then the sound pressure at the hydrophone is $S_p \; I_p/d_1$ and the hydrophone develops an open circuit voltage:

$$E_{hp} = \frac{M_h \; S_p \; I_p}{d_1} \tag{3}$$

Now the transfer impedance is:

$$Z_{hp} = \frac{E_{hp}}{I_p} = \frac{M_h \; S_p}{d_1} \tag{4}$$

Second measurement: The projector is replaced by the reciprocal transducer T which is fed by a current $I_t$, causing at the hydrophone an open circuit voltage $E_{ht}$. The distance between the transducers may be $d_2$.
Then the transfer impedance of this pair will be:

$$Z_{ht} = \frac{M_h\ S_t}{d_2} \tag{5}$$

Third measurement: The hydrophone H is replaced by the projector P. The distance may be $d_3$. Now the reciprocal transducer acts as hydrophone and gives a voltage $E_{tp}$ in response to the projector current, the ratio of which is the transfer impedance

$$Z_{tp} = \frac{M_t\ S_p}{d_3} \tag{6}$$

Now it can easily be shown that

$$\frac{Z_{ht}\ Z_{tp}}{Z_{hp}} = M_t\ S_t\ \frac{d_1}{d_2\ d_3} \tag{7}$$

so that

$$M_t\ S_t = \frac{Z_{ht}\ Z_{tp}}{Z_{hp}} \cdot \frac{d_2\ d_3}{d_1} \tag{8}$$

The reciprocity principle gives that

$$\frac{M_t}{S_t} = \frac{2}{\rho\ f} \tag{2a}$$

Now of transducer T the product and the quotient of its two sensitivities are known, so that each value can be calculated:

$$M_t^{\ 2} = \frac{2\ d_2\ d_3}{\rho\ f\ d_1}\ \frac{Z_{th}\ Z_{tp}}{Z_{hp}} \tag{9}$$

In the same way the sensitivity of the hydrophone is found as:

$$M_h^{\ 2} = \frac{2\ d_1\ d_2}{\rho\ f\ d_3}\ \frac{Z_{hp}\ Z_{ht}}{Z_{pt}} \tag{10}$$

Note: For the sake of simplicity in the last equations the transfer impedances are rewritten in the sense that $Z_{hp} = Z_{ph}$, etc., which makes the equations easier to reconstruct.

Using eq. 2 the transmitting responses to current are found as being:

$$S_p^2 = \frac{\rho f d_1 d_3}{2 d_2} \frac{Z_{ph} Z_{pt}}{Z_{ht}} \qquad (11)$$

$$S_t = \frac{\rho f}{2} M_t \qquad (12)$$

Note 1: It is even possible to calculate the hydrophone sensitivity of the projector and the projector sensitivity of the hydrophone with these equations, although these transducers never were used as such.

Note 2: If the projector P is also reciprocal, it can be used as hydrophone and the transfer impedance $Z_{pt}$ can be measured with the transducer T transmitting and the projector P receiving. Then it should turn out that $Z_{pt} = Z_{tp}$. This is a check if the transducers are really reciprocal and what kind of errors can be expected at these measurements. If also the hydrophone H can act as a reciprocal transducer, two more measurements can be done, with the hydrophone H as a transmitter and either the projector P or the transducer T as receiver. In this way each transfer impedance is measured twice and again a check is obtained in how far the reciprocity is really true.

In summary: By measuring the ratio of a voltage to a current at three different transducer pairs the absolute sensitivity of all participating transducers can be calculated. No acoustic standard is needed.

## 5. Limitations

### 5.1 Test distance and frequency limit

It is necessary that the measurements are performed in the far field of the transducers, which means that for each pair of transducers the distance d should be larger than the total near field distance:

$$d > \frac{1}{\lambda} (a_1^2 + a_2^2) \qquad (13)$$

where $a_1$ and $a_2$ are the largest linear dimensions of the active faces of both transducers. See figure 3.
Simultaneously the distance must be larger than these dimensions too:

$$d > a_1 + a_2 \qquad (14)$$

which becomes effective at low frequencies where the near field is short. The near field grows with increasing frequency, creating an upper frequency limit where eq. 13 requires a distance larger than available in the body of water where the calibration is being performed.

## 5.2 Tank size

Unless the test distance d is small compared to the depth of the transducers under water, all underwater measurements suffer from reflections against the surface. See figure 4. Using the different times of arrival of the direct sound and the reflected sound, with short sound bursts the direct signal can be separated from the reflected signal if the pulse duration is shorter than that time difference. Then the problem is solved if the calibration is performed in an outdoor test facility like a lake of sufficient depth. But using an indoor tank the reflections against the walls and the bottom have to be taken into account. Using a pulse length of t seconds the reflected path should be Δ metre longer than the direct path:

$$\Delta \geqq 1500\ t \qquad (15)$$

Then the length of the tank should be

$$L > d + \Delta \qquad (16)$$

and the width and depth of the tank is

$$W > (d + \Delta)^2 - d^2 \qquad (17)$$

In order to limit the required size of the tank, the pulse length t should be as short as possible. However, each transducer and power amplifier suffer from transients at the beginning and the end of the pulse.
The steady state response should last at least several periods of the sinussoidal wave train, so that the pulse duration should correspond with, say at least ten periods:

$$t \geq \frac{10}{f} \qquad (18)$$

where f is the signal frequency in hertz.
Hence the required tank size depends on the size of the transducers and the frequency range.

The received signal at the hydrophone consists of the direct pulse, contaminated by transients, followed by reflections against the water boundaries.
A gating system may be required which selects the steady-state portion of the direct signal, thus eliminating all unwanted signals.

## 6. Measuring procedure

The calibration of hydrophones consists of the measurement of three voltages, three currents and three distances. Voltage- and current meters would have to be calibrated separately and the linearity has to be good.
Another unknown factor is the gain of the several amplifiers in the receiver chain, of which also the linearity has to be good.

These drawbacks can be overcome, making use of the fact that not the absolute values of voltage and current are to be known, but only their ratios. Current and voltage further can be interchanged by means of a resistor, so that the ratio of voltage to current can be measured with the same instrument, being either a voltmeter or a current meter.
A measuring procedure will be given where the gain and the linearity of the amplifiers is not important, and which uses uncalibrated current meters.

Note: Current meters were selected because nowadays reliable and precise current probes are available which do not require galvanic contact with the circuit, thus avoiding errors due to changing ground connections. The system is shown in the diagram of figure 5.

A frequency oscillator with a gating system generates short tone bursts which alternately go to a power amplifier to drive the projector or go through an attenuator W-W' to a small resistor in series with the low terminal of the hydrophone. A switch S5 connects in position 1 the hydrophone output to an amplifier with bandpass filter and to an oscilloscope. Alternately the hydrophone receives an acoustic signal from the projector and an electric signal from the series resistor. With the variable resistors W and W' both signals are made equal. These resistors need not to be calibrated.

The current through the projector $I_p$ and the current through the series resistor $I_r$ are measured through two identical current probes. With the switch S5 in position 2 these two current values are alternately presented on the oscilloscope. By means of a calibrated attenuator the presented values are made equal.

If the attenuator has to be set to an attenuation A ($A \geq 1$) this means that

$$I_p = A\, I_r \tag{19}$$

The voltage at the hydrophone, caused by the sound pulse, is equal to

$$E_{hp} = \frac{M_h\, S_p\, I_p}{d} \tag{20}$$

By means of attenuator W-W' this voltage is made equal to the voltage $E_r$ caused by the current $I_r$ through the series resistor:

$$E_{hp} = E_r = 10\, I_r \tag{21}$$

Now it follows that

$$\frac{M_h\, S_p}{d} = \frac{10}{A} \tag{22}$$

which is equal to $Z_{hp}$ (eq. 4).

Any preamplifier with an unknown gain G in the hydrophone chain does not change the result, because the voltage $E_{hp}$ and $E_r$ are amplified by the same factor. Hence the required value of $Z_{hp}$ is solely determined by the attenuation A. Because each time pulses of equal level are compared, the linearity of the amplifiers is not important. The series resistor of 10 ohm has to be known with a high precision, but that can be measured easily.
The two current probes have to be identical. This can be checked by hooking them on the same wire: Their responses should be equal.

Note: The values of $I_p$ and $I_r$ may differ largely. The dynamic range of the current probes might be not sufficiently large to cover this difference. However, the probes used at the experiments had selector switches to set the magnitude of the current to be measured, in the ratios 1, 2, 5, 10, etc. The calibrated attenuator has steps of 1 dB and 0.1 dB. In combination with the range switches of the current probes any value of the transfer impedance can be measured. The attenuation A (eq. 19) is then a combination of the attenuator setting and the ratio of the two range switches of the current probes.

The switches 1, 2, 3 and 4 are of the electro-optical type. They consist of a light emitting diode optically coupled with a photosensitive diode and they are commanded by a separate timing unit (IC type SN7474) which is triggered by the gating system BK4440. Switch 1 and 3 open simultaneously while switch 2 and 4 are closed, and vice versa. See figure 6.
It was not necessary to gate the received acoustic signals, because visually it was possible to select the steady-state portion of the signal on the oscilloscope to compare it with the other pulse for equalisation.

For each pair of transducers the values of $Z_{hp}$ are measured at a number of pre-determined frequencies. For transducers with a flat or monotonous frequency response curve these frequencies may be selected one third octave apart, using the standard IEC frequencies. When resonance occurs the frequencies should be selected closer together with smaller intervals.
After the measurements over the whole frequency range the measurements are repeated with another pair, using the same frequencies. In order to reproduce each time exactly the same frequency, the use of a frequency synthesiser as a signal generator is indispensable.

## 7. Precautions

### 7.1 Orientation of hydrophones

During the measurements each time the transducers should be positioned facing each other in such a way that each transducer is placed on the acoustical axis of the other. For flat transducers this may not give any problem. However, cylindrical or spherical transducers do not have one single axis. They are called "omnidirectional" in one or more planes. But no transducer is really omnidirectional. The sensitivity may change a few decibel with the direction. Therefore a mark on the transducer should indicate the direction of an assumed acoustical axis which is respected at each measurement. This direction can be chosen arbitrarily but preferably initial directivity measurements are to be performed at a number of frequencies, and the direction of maximum sensitivity be selected as reference axis.

### 7.2 Wetting

Repeatedly it can be observed that slight traces of fat or grease adhere to the surface of transducers, impeding a proper acoustical contact between the transducer and the water. Therefore each time before immersion the transducer should be properly cleaned with soap or a detergent so that, when taken out of the water, an uninterrupted film of water should adhere to the surface.

### 7.3 Grounding

Generally, most electronic instruments are provided with a ground connection through the power plug, which is also connected to the lower input terminal. This provision may cause interference in the hydrophone amplifier, because the hydrophone makes contact, either galvanic or capacitive, with the mass of water, possibly having another earth potential. This closed ground loop might pick up magnetic interference. Also ground currents may flow between the two different earth connections. This can be avoided when all ground connections are disconnected and the whole electronic circuit is earthed to the unique ground terminal of the hydrophone. If it is not possible to remove all power plug ground connections a screened isolation transformer has to be inserted in the circuit to separate the ground connections. The use of a monitor loudspeaker at the hydrophone amplifier is indispensable.

## 8. Format

The result of the calibration can be shown as a graph of the sensitivity level in decibel with respect to the reference level of 1 volt per micropascal, as a function of the frequency on a logarithmic scale.
IEC normalisation requires that for this kind of plots the scale proportion shall be those for which the length for a 10:1 frequency ratio is equal to the length for a level difference of 10 dB, 25 dB or 50 dB on the ordinate scale. See IEC Publication 263.

Most commonly the ratio of 25 is used for hydrophone calibrations, but when a flat frequency response has to be shown (e.g. for a standard reference hydrophone) the ratio of 10 is chosen. If then the length of one frequency decade is 50 mm, the decibel scale will be 2 mm/dB or 5 mm/dB respectively.

## 9. Computer processing

The calculation of the transducer sensitivities and the plotting of the frequency response curves is preferably done by a desk top mini-computer. The input values are the frequency and the setting of the attenuator. The frequency information can be taken from the signal generator or a frequency counter which should have a digital frequency output. The knobs of the attenuator with steps of 10 dB, 1 dB and 0.1 dB and the range switches of the current probes can be provided with a digital read-out provision giving the positions of the knobs in a digital form.

Then each measurement consists of:

1. Frequency setting;
2. Equalising the two pulses on the oscilloscope screen by means of the calibrated attenuator, if necessary aided by changing the range setting of one of the current probes;
3. Giving a command to the computer to read these settings.

After the whole frequency range has been covered, one of the transducers is replaced by the other one and the same sequence of frequencies is repeated. If the signal generator is of the synthesiser type, the frequency setting can be commanded by the computer itself.

## 10. Accuracy

The following accuracies of the different parameters are assumed:

Error in the hydrophone series resistor: 1%
Error in the calibrated attenuator: 1%
Equality of the current probes: 3%
Error in the visual equalisation: 2%
Hence the total error in the value of $Z_{hp}$ (eq. 4) is: $(1^2 + 1^2 + 3^2 + 2^2)^{\frac{1}{2}} =$ 4%
Error in the separation distance: 1%
Error in the water density: 1%
Error in the signal frequency: 0.1%
Hence the total error in the value for $M^2$ (eq. 10) is:
$(1^2 + 1^2 + 1^2 + 0.1^2 + 1^2 + 4^2 + 4^2 + 4^2)^{\frac{1}{2}} =$ 7.2%
The error in the value for M is then: 3.6%
Expressed in decibel this error in the final result is 0.3 dB.

## 11. Conclusion

By means of the reciprocity principle the absolute sensitivity of underwater sound transducers can be measured without a standard reference transducer if at least three transducers are used for the measurements, one of which acting as sound source, one as receiver and at least one should be reversible and reciprocal.
With normal laboratory equipment and skilfull care the accuracy of the result allows a probable error of 4% or 0.3 dB.
If the sound source can be used as a receiver, if the receiver can be used as a source or if more than three transducers are used more than one result is obtained as the most probable value for the sensitivity of the transducer in question. The spread of these values indicates the reliability of the results while its average value gives the most probable calibration figure.
The numerous individual measurements and the associated calculations require the use of a desk top computer with sufficient memory space to store all the data for further processing.

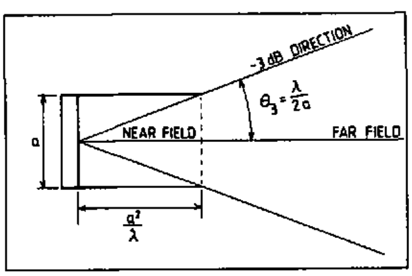

FIGURE 1: NEAR FIELD DEFINITION

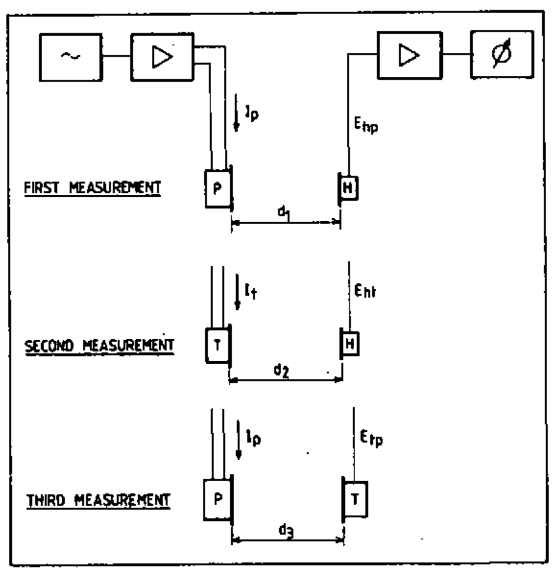

FIGURE 2: SEQUENCE OF 3 MEASUREMENTS

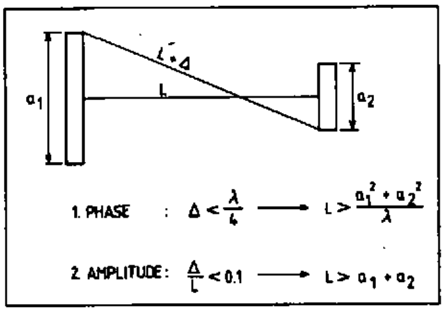


FIGURE 3: NEAR FIELD CONDITIONS

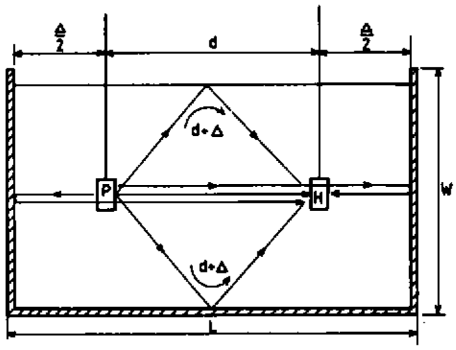


FIGURE 4: ACOUSTICAL TANK

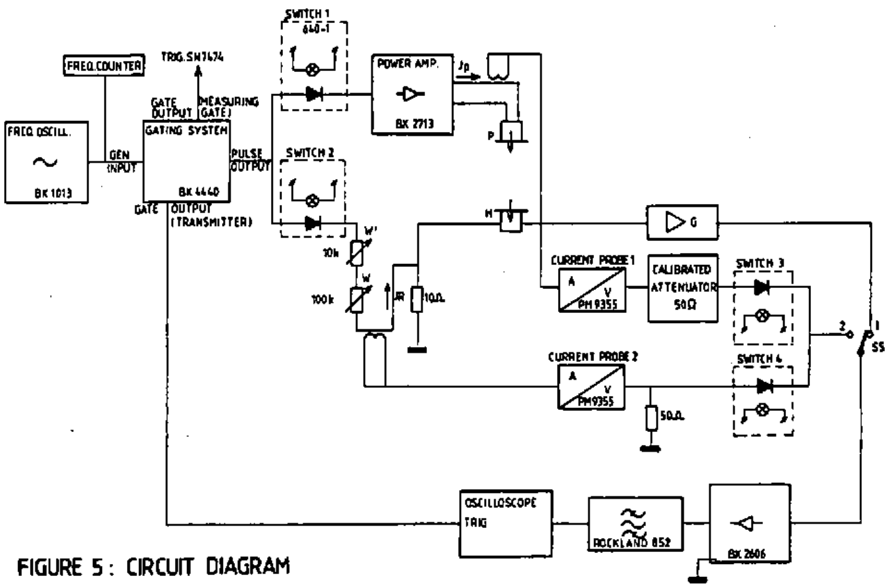


FIGURE 5: CIRCUIT DIAGRAM

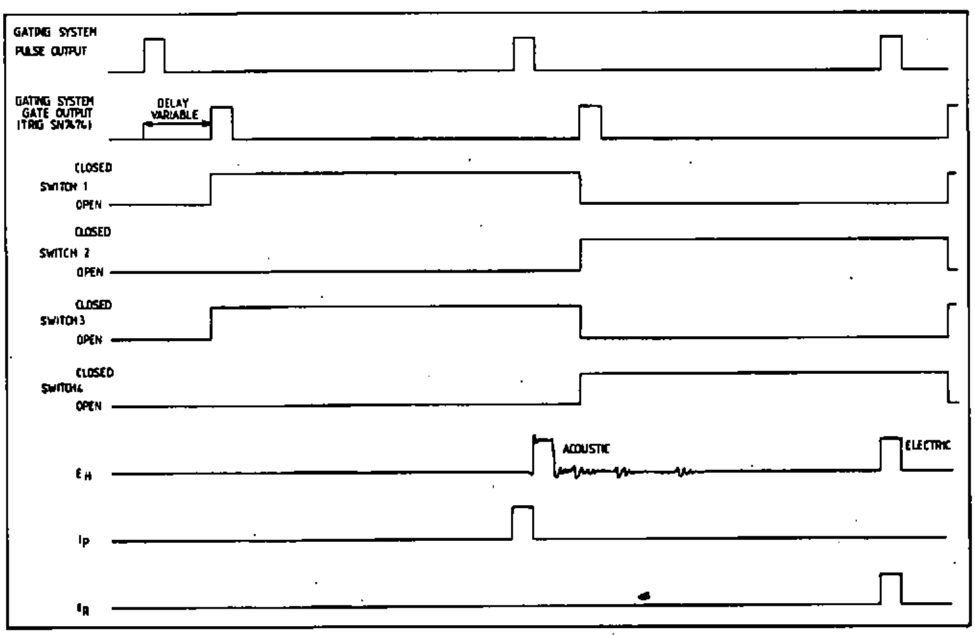


FIGURE 6: TIME SEQUENCE OF PULSES AND SWITCHES