TRANSFER COUPLER RECIPROCITY

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1 INTRODUCTION

In a reciprocity calibration, three electroacoustic devices are required: a sound source, a reciprocal transducer, and a hydrophone to be calibrated. In free-field reciprocity the required measurements are electrical voltages out of the transducer and the hydrophone, the electrical currents into the sound source and the transducer, the test distances under which the measurements are made, the frequency of operation, and the density of the medium in which the measurements are made. The frequency f and the density ρ are used to calculate the free-field reciprocity parameter $J = 2/\rho f$ at one meter.[1]

Conventional coupler reciprocity is similar to free-field reciprocity except that the three electroacoustic devices are placed in an acoustic coupler. An acoustic coupler is a small fluid-filled chamber in which the sound field generated by one electroacoustic device is uniform throughout the volume of the chamber. The electrical measurements required are the same as in free-field reciprocity. No test distances are required. The reciprocity parameter is different than in free-field reciprocity and is given by $J = 2\pi f C$ where C is the acoustical compliance of the coupler and includes the compliances of the fluid, the coupler walls, and the devices inside the coupler.[1] Thus, only hydrophones whose acoustical compliance is known or negligible can be calibrated in the coupler. Also, devices that include a pressure release material cannot be calibrated in a coupler because of the pressure gradient in the vicinity of the pressure release material. Note that the acoustic sensitivity measured in a coupler is the voltage output of a hydrophone for a unit acoustic pressure at the hydrophone location. This is not necessarily equal to the free-field sensitivity of a hydrophone.

The transfer coupler reciprocity technique is an improvement over the conventional coupler reciprocity in that it can provide absolute calibrations for hydrophones that are not specifically designed for use in a coupler and it can do so with very high accuracy. There are several methods of implementing the transfer coupler reciprocity technique. These methods use two couplers to perform the calibration. In the method used by the author, the first coupler or reference coupler uses two similarly constructed reciprocal transducers. The acoustic compliance of this coupler is precisely known so that the reciprocity parameter is well known. The transfer impedances of the two transducers in this coupler are measured. This is the only measurement in which these transducers are electrically driven. This is desirable because transducers are more stable when used as hydrophones than as transmitters. The second coupler or transfer coupler uses the same two transducers as the first coupler as well as the hydrophone under test and a sound source. The two transducers from the first coupler as well as the hydrophone under test are symmetrically positioned in a circular arrangement with the sound source at the center of the arrangement. This arrangement provides the most uniform ensonification of the two transducers from the first coupler as well as the hydrophone under test. Using this technique an uncertainty approaching 0.1 dB can be achieved. Three different methods of implementing transfer coupler reciprocity are discussed.

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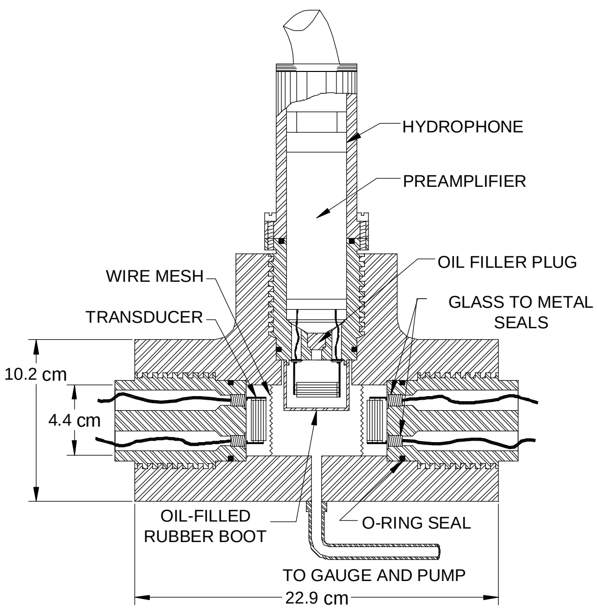

Figure 1. Reciprocity coupler.

A conventional reciprocity coupler similar to the one described by Sims and Henriquez[2] is shown on Figure 1. This figure shows three transducers mounted in a stainless-steel pressure vessel. A port for evacuation, filling with a coupling fluid, and pressurization is shown at the bottom of the figure. The fluid couples the sound generated by one of the transducers to the other transducers. Information on conventional coupler reciprocity can be found in Bobber[1] and in ANSI S1.20-1988[3]. In this procedure a reciprocal transducer T, a linear sound source P, and a hydrophone H to be tested are placed in a coupler as shown on Figure 2. The projector and the transducer are, in this case, of identical construction and are both reciprocal. The acoustic pressure sensitivity of the hydrophone is determined from the reciprocity parameter of the coupler and simple electrical measurements. At low frequencies, the acoustic pressure sensitivity of a hydrophone is the same as the free-field voltage sensitivity. First, the reciprocal transducer T is driven with an electrical current I_{T} and the output voltage U_{TH} of the hydrophone under test is measured. The electrical transfer impedance Z_{TH} is defined by

$$Z_{\mathrm{TH}} = \frac{U_{\mathrm{TH}}}{I_{\mathrm{T}}} \quad . \tag{1}$$

Next, the projector P is driven electrically and the output voltage U_{PH} of the hydrophone under test and the output voltage U_{PT} of the reciprocal transducer are measured. The transfer impedances Z_{PH}, and Z_{PT} are defined in a manner similar to Z_{TH} above. The hydrophone sensitivity M_{H} is given by

$$M_{\mathrm{H}}^{2} = J\,\frac{\left|Z_{\mathrm{PH}}\right|\left|Z_{\mathrm{TH}}\right|}{\left|Z_{\mathrm{PT}}\right|} \quad , \tag{2}$$

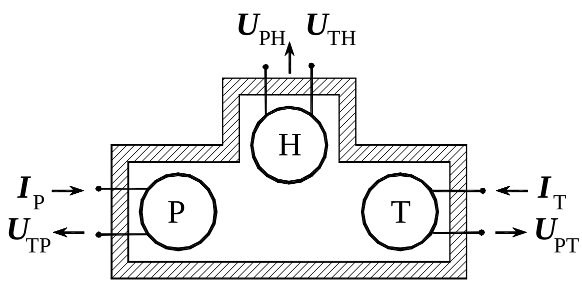

Figure 2. Diagram of a reciprocity coupler showing the three transducers and the relevant electrical quantities.

where the reciprocity parameter J is equal to ωC_{t}, $\omega = 2\pi f$, f is the frequency of operation and C_{t} is the acoustical compliance of the coupler. The acoustical compliance of the coupler is the compliance of the fluid in the coupler plus the acoustical compliance of the coupler walls plus the acoustical compliance of the transducers and hydrophones in the coupler. Since P is also reciprocal, the roles of P and T can be interchanged to check for consistency and the two results can be averaged to improve the accuracy of the measurement.

The fundamental assumptions in the derivation of Equation 2 are that the acoustic pressure is uniform within the coupler and that the acoustic compliance is accurately known with the hydrophone under test in the coupler. As the frequency of operation is increased, small corrections can be made using approximations for the field nonuniformity[4,5]. For higher frequencies or for more exact corrections, finite element calculations can be performed. An arbitrary hydrophone in the coupler presents a more difficult problem. Its compliance may not be known so that a good estimate for C_t, and hence J, cannot be made. Also, the point where the cable is brought out of the coupler has a large but undefined compliance so its contribution to the coupler compliance is not known. The solution to the problem of coupler compliance uncertainty is to use one of the versions of transfer coupler reciprocity described below.

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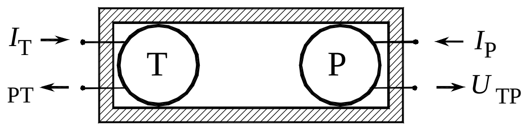

Figure 3. Diagram of reference coupler with two transducers showing the relevant electrical quantities.

The idea behind transfer coupler reciprocity is that the projector and transducer are first placed in a well-characterized coupler (the reference coupler), as shown in Figures 3 and 4, that doesn't contain the hydrophone to be calibrated, and the transfer impedance Z_{TP} is measured. Then when the projector and transducer are transferred to another coupler (the transfer coupler) as shown in Figure 5, the reciprocity parameter of the

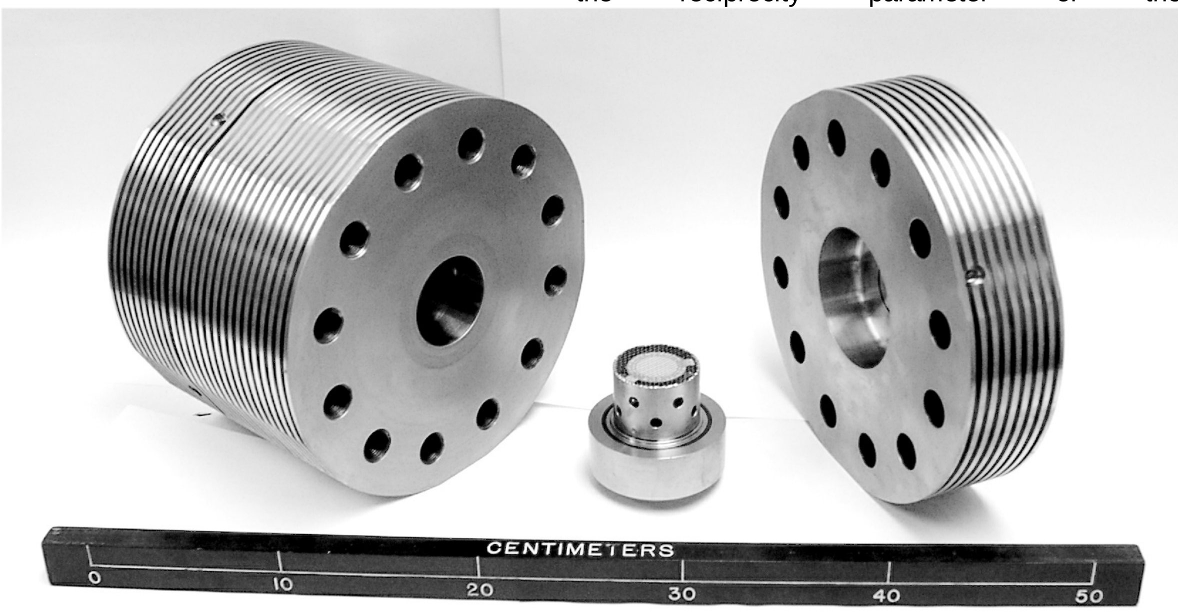

Figure 4. Photograph of reference coupler

transfer coupler J' can be calculated from the reciprocity parameter J in the reference coupler, the transfer impedance in the reference coupler Z_{TP}, and the transfer impedance Z'_{TP} measured in the transfer coupler. This relationship can be shown to be[4]

$$\frac{J'}{J} = \frac{|Z_{\mathrm{TP}}|}{|Z'_{\mathrm{TP}}|} \ . \tag{3}$$

The transfer coupler will contain the hydrophone to be calibrated and its reciprocity parameter will be determined with the hydrophone in place. Now the projector and transducer can be used in the transfer coupler with a known reciprocity parameter to perform a reciprocity calibration of the hydrophone. The equation for the sensitivity of the hydrophone is

$$M_{\mathrm{H}}^{2} = J\,|Z_{\mathrm{TP}}|\left(\frac{|Z'_{\mathrm{PH}}|}{|Z'_{\mathrm{PT}}|}\right)\left(\frac{|Z'_{\mathrm{TH}}|}{|Z'_{\mathrm{TP}}|}\right) \ , \tag{4}$$

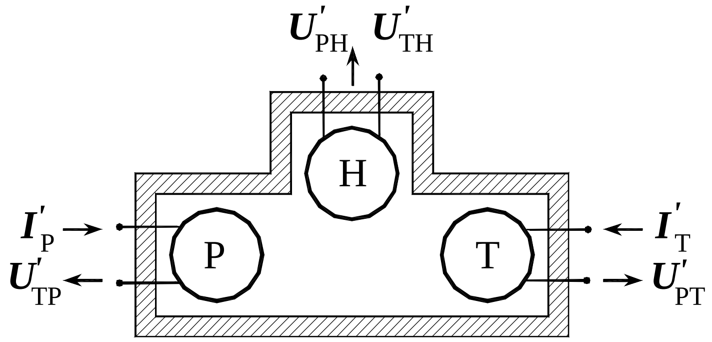

Figure 5. Diagram of transfer coupler with three transducers showing the relevant electrical quantities.

where the primed quantities refer to the transfer coupler. Again, since P is also reciprocal, the roles of P and T can be interchanged to check for consistency and the two results can be averaged to improve the accuracy of the measurement.

3.1 Transfer reciprocity using a separate sound source along with the projector and transducer

For maximum stability of the reciprocal transducer T, it would be desirable that T not be electrically driven in order to perform the hydrophone sensitivity measurement. In Equation 4 the first set of parentheses is just the ratio of voltages out of H and T when in the sound field produced by P. Since there is a uniform acoustical field in the coupler, this ratio is the same no matter what sound source performs the ensonification. A similar argument holds for the second set of parentheses. Therefore, a fourth element, a sound source S, can be added to the transfer coupler in such a way as to equally ensonify H, T, and P as shown in Figures 6 and 7. This sound source can replace both P and T as sound sources for determining the two impedance ratios in Equation 4. In this case the sensitivity of the hydrophone is given by

$$M_{\mathrm{H}}^{2} = \omega C_{t}\,|Z_{\mathrm{TP}}|\left(\frac{|Z'_{\mathrm{SH}}|}{|Z'_{\mathrm{ST}}|}\right)\left(\frac{|Z'_{\mathrm{SH}}|}{|Z'_{\mathrm{SP}}|}\right) \ , \tag{5}$$

where the subscript S refers to the sound source. Again, since P is also reciprocal, the roles of P and T can be interchanged to check for consistency and the two results can be averaged to improve the accuracy of the measurement.

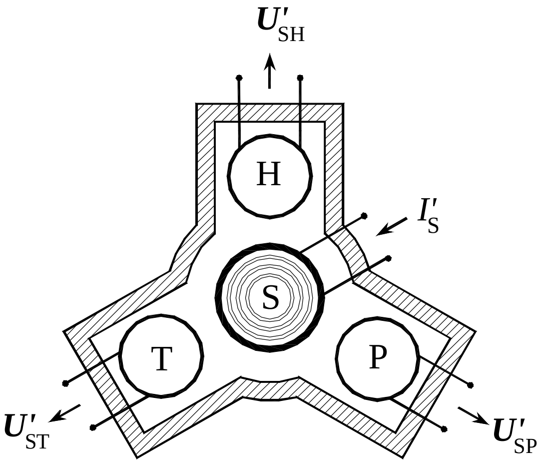

Figure 6. Diagram of transfer coupler with four transducers showing the relevant electrical quantities.

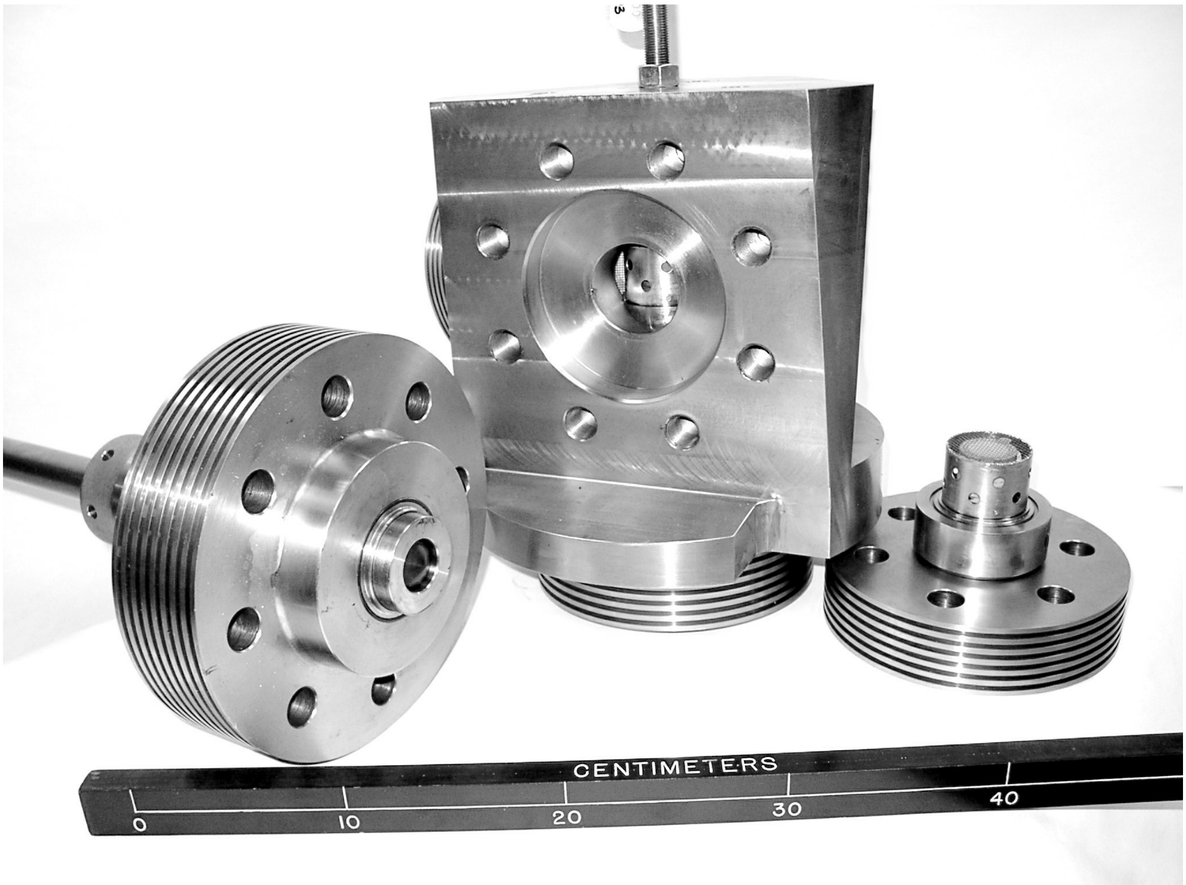

Figure 7. Photograph of transfer coupler with a separate sound source.

3.2 Transfer reciprocity using a reference coupler with an auxiliary hydrophone

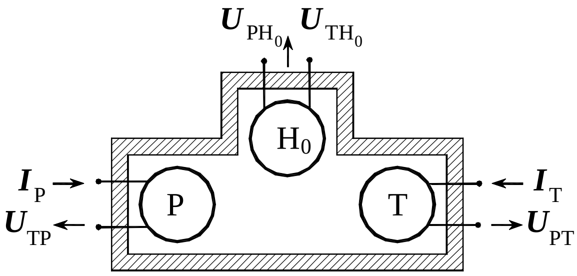

Figure 8. Diagram of reference coupler with the added hydrophone showing the relevant electrical measurements.

In the previous example of transfer reciprocity, a transfer coupler containing four transducers is required. This is a complicated and expensive device to fabricate. There is another approach that only requires three transducers in the transfer coupler. This technique requires that an auxiliary hydrophone H_0 be placed in the reference couple. A reference coupler with a hydrophone is shown in Figure 8. Three transfer impedances Z_{PT}, Z_{TH_0}, and Z_{PH_0} are measured in the reference coupler. There are two approaches to the transfer coupler. In the first approach, the transfer coupler is set up as shown in Figure 5. Equation 3 is true independent of the hydrophone. Therefore, from Equation 2,

$$M_{H_0}^2 = J\frac{|Z_{PH_0}||Z_{TH_0}|}{|Z_{PT}|}. \quad (6)$$

Since the transducer T is ensonified at the same level as H_0, its pressure sensitivity M_T is given by

$$M_T = M_{H_0}|Z_{PT}|/|Z_{PH_0}| \ . \quad (7)$$

In a transfer coupler as shown in Figure 5, the sensitivity M_H is given by

$$M_H = M_T|Z'_{PH}|/|Z'_{PT}| \ . \quad (8)$$

Combining Equations 6, 7, and 8 yields

$$M_H = \left\{ J|Z_{PT}|\frac{|Z_{TH_0}|}{|Z_{PH_0}|}\right\}^{1/2}\left(\frac{|Z'_{PH}|}{|Z'_{PT}|}\right) \ . \quad (9)$$

The quantity in parentheses in Equation 9 is the only quantity measured in the transfer coupler. This quantity is just the ratio of the outputs of H and T ensonified by P. This ratio is independent of the sound source. Therefore, P can be replaced by a sound source S in the transfer coupler. This is the second approach and is shown in Figure 7. In this case Equation 7 becomes

$$M_H = \left\{ J|Z_{PT}|\frac{|Z_{TH_0}|}{|Z_{PH_0}|}\right\}^{1/2}\left(\frac{|Z'_{SH}|}{|Z'_{ST}|}\right). \quad (10)$$

Again, the ratio in parentheses is the only quantity measured in the transfer coupler. Neither the projector P nor the transducer T are electrically driven after they are moved to the transfer coupler. Now the roles of the projector and transducer can be interchanged to check for consistency and the

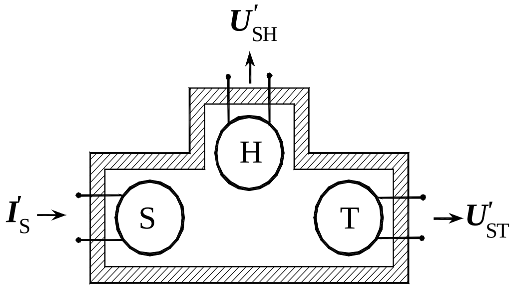

Figure 9. Diagram of transfer coupler with three transducers showing the relevant electrical quantities.

results can be averaged to improve the measurement accuracy. The arrangement of the three transducers in the transfer coupler is shown on Figure 9.

4 DISCUSSION

Coupler reciprocity is a powerful and accurate method for calibrating hydrophones at low frequencies but Is limited to specially constructed hydrophones in order that the acoustical compliance of the coupler be precisely known. Transfer coupler reciprocity is an extension of the reciprocity coupler technique that permits calibration of small more general-purpose hydrophones. Stuffing boxes can be used to bring hydrophone cables out of the coupler without seriously degrading the performance of the coupler, but there will be a small pressure gradient in the region that the cable penetrates the coupler. Hydrophones with preamplifiers are usually calibrated with the preamplifier external to the coupler and only the active element of the hydrophone in the acoustic field. Three different types of transfer coupler reciprocity systems have been discussed. Each may have advantage over the others in certain instances depending on cost, hydrophone configuration, ultimate accuracy desired, and simplicity of use.

Calibrations on several hydrophones have been performed over a time period of seven years. The acoustic receiving sensitivity for each hydrophone fell within a ±0.1 dB envelope over the frequency range of 100 Hz to 2.0 kHz. Aging of the ceramic in the hydrophones accounts for some of this difference over that time period. The estimated uncertainty achieved in the calibrations is 0.2 dB.

Currently, a reference coupler containing four transducers is being tested for use on general-purpose transducers. It is expected that the uncertainty will approach 0.1 dB.

5 ACKNOWLEDGEMENT

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