Self-reciprocity calibration of a transducer

You can calibrate a test transducer using nothing more exotic than the still water interface of an acoustic test tank and some simple electronics. The method is called self-reciprocity[1]. It involves suspending the test transducer at some depth in the tank, facing upwards, transmitting short CW pings, and measuring the drive current and the echo amplitude.

There are, of course several factors that must be considered and accounted for. First, this method requires that the transducer be linear, passive, and reversible. These properties are impossible to measure, of course; the proof of their existence is largely shown by the plausible nature of the results. For calibration of TAPS systems, I use broadband transducers designed for non-destructive test and evaluation. These heavily damped transducers have almost no resonant responses and, thus, appear to be linear, passive, and reversible over the entire useful frequency range of interest. Lightly-damped transducers may not be as satisfactory in the vicinity of their (often numerous) resonances.

In addition, these measurements should be made in the far-field of the transducer. Since we are using the surface reflection to produce an image of the source at twice the depth of the transducer, we should ensure that the farfield criteria for two transducers of equal diameter, D, is met:

$$R_{ff} \geq \frac{(2D)^2}{\lambda}$$

Where R_{ff} is the range from the source to the image receiver (twice the depth of the transducer) and λ is the wavelength.

If these (and certain other) criteria are met, then it is true that the ratio of the receiving response, Mo, and the transmitting current response, So, is a constant, J, called the reciprocity parameter, viz,

$$\frac{M_o}{S_o} = J$$

$$J = \frac{200\lambda}{\rho c} 10^{-14}$$

Moreover, we can measure M_o and S_o separately by measuring the transmitter current, I_t, and the surface echo, V_r. The relevant equations are:

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[1] Carstensen, E. L., 1947. Self-Reciprocity Calibration of Electroacoustic Transducers. J. Acoust. Soc. Am. (19)6: 961-5.

$$S_o = \sqrt{\frac{V_r 2r}{I_t J}}$$

$$M_o = \sqrt{\frac{V_r}{I_t} 2J}$$

where the units of S_o are μPa/A at 1m and M_o are V/μPa. The units of J are W/μPa^2. All distances are measured in meters.

There is an Excel spreadsheet available here. This spreadsheet contains actual calibration data from two Panametrics transducers that I use for TAPS calibrations.

Note that the transducer drive voltage, V_t, doesn't appear in these equations. The ratio that is used in both equations is the received echo voltage divided by the drive current. (Note that you could use peak-to-peak measurements here since they appear as a ratio.) I have included V_t as a measured quantity as a way of checking the results (see below).

Note also that the surface echo voltage is the **open-circuit voltage** from the transducer. This is a bit tricky to obtain in normal calibrations since the transducer will be loaded by the output impedance of the driver, usually 50 Ω from a signal generator. There are a couple of ways to decouple the transducer from this impedance. A pair of back-to-back[2] diodes in series with the transducer will largely decouple the transducer and source if the echo voltage is well below the forward voltage drop of the diodes. Sometimes series pairs of diodes can be hooked back-to-back to increase the net forward voltage drop.

A better way is to completely disconnect the transducer from the driver using a relay. Small DIP relays usually respond quickly enough to let the contacts settle in time to measure the surface echo a few hundred microseconds after the end of the transmitted ping. A suggested schematic can be found here.

While So is a perfectly good way to characterize the transmitting response of a transducer, it is usually easier to measure the drive voltage during calibrations. In this case, the S/V (source per volt) response is required. This can be obtained from the source per amp quite easily:

Suppose we drive the transducer with voltage E and obtain current I. The resistance of the transducer is R = E/I. The source level, SL, for this drive condition is

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[2] Take two diodes. Arrange them so the anode of one connects to the cathode of the other and vice versa. Voila', back-to-back diodes!

$$SL = S_o + 10\log(I^2 R)$$

$$SL = SPV + 10\log(\frac{E^2}{R})$$

We can equate the two equations, find that the R terms cancel, and obtain

$$SPV = S_o - 20\log(\frac{E}{I})$$

Thus, the source per volt can be obtained from the source per amp quite simply.

Some caveats: I don't trust the temperature stability of NDE broadband transducers for calibration purposes. Before a calibration run, I like to verify that the transducer is producing the same results as previously. One way to do this is to conduct a full calibration on the test transducer. I have done this but it is tedious.

Another way is to setup the transducer for the calibrations (the setup I use is identical to that for calibrating the test transducer) and ping at the surface. To simplify the setup, I just ping using a gated signal generator and ignore the loading effect of the sig gen driver on the received echo. If I get the same values as I got with this setup taken just after I did the complete calibrations, then I am happy that I can use the same calibration values.