Acoustic calibration in reverberant environments: 
a survey of USRD measurement methodology

S. E. Forsythe & P. L. Ainsleigh
Naval Undersea Warfare Center
1176 Howell Ave
Newport, RI 02841

Abstract: The use of pressure- and temperature-controlled tanks for calibration of Navy projectors is a cost-effective alternative to open-water or at-sea measurements. The Underwater Sound Reference Division (USRD) of the Naval Undersea Warfare Center maintains a large closed tank that is temperature- and pressure-controlled. This tank, like all closed vessels, suffers from a major drawback: it is highly reverberant, especially at low-frequency operation, which precludes the possibility of making steady-state projector response measurements (especially for highly resonant projectors with low-frequency resonances) as would be possible in a large body of open water. Three broad categories of approaches for overcoming this drawback are discussed: (1) estimating the steady-state response using a model that represents only the pre-echo portion of the received data (transient modeling), (2) estimating the echo-free steady state using a multiple-arrival model that accounts for echoes in the received data (multipath modeling), and (3) characterizing the wavefield using multiple hydrophones to separate the direct wavefield from the wavefield due to echoes (spatial processing).

INTRODUCTION

In 1950, USRD acquired its first environmentally controlled tank, called the Anechoic Tank Facility (ATF). The finite inner volume (8 meters long by 3.2 meters diameter) limits its use in making direct low-frequency far-field measurements to frequencies of 2 kHz and above (the limit for higher-Q transducers can be 4 kHz or more). The tank has an "anechoic" lining, but this is intended only to reduce the ring-down time constant of the tank; moreover, the lining significantly reduces the effective volume of the tank at lower frequencies, where the lining is somewhat reflective. For projector response measurements in such a tank, the ideal scenario is when there is a time window representative of steady-state echo-free response from the projector available before echoes from the tank walls contaminate the measurement. If such a time window is not available, indirect methods must be used. While a larger pressurized tank that was brought on line in 1991 partially alleviates this problem, it does not fully overcome the previous limitations, especially for projectors whose resonances are at frequencies lower than 1 kHz.

TRANSIENT MODELING OF PROJECTORS

Variations and extensions of the Prony method were developed and tested in the ATF by J. D. George, et al. These methods all assume that a pole-zero model of relatively low order can model the projector under test. The object of these methods is to match the calculated transient response of the projector with the observed response to input signals, which consist of stepped sinusoids over a range of frequencies. The major technical issues for these methods are

1. selection of model (poles-only or pole/zero model);
2. use of linear (e.g., Prony) vs. nonlinear least-squares techniques to determine model parameters;
3. selection (or automated determination) of model order, as well as distinguishing signal poles from noise poles;
4. sensitivity to experimental artifacts such as noise and unwanted DC bias in the input data;
5. time duration of the transient signal uncorrupted by echoes;
6. sensitivity to model accuracy;
7. selection of a correct start time for the signal measured by the reference hydrophone;
8. computational efficiency.

All of the above transient methods assume a point projector, i.e., one with no spatial extent; exactly modeling an extended projector with a small number of poles and zeros is not feasible (issue 6 above). It is critical for all methods that DC bias be removed from the hydrophone signal or added to the model as an adjustable parameter (issue 4 above); a constant DC bias cannot be modeled by the pole-zero method, thus introducing a statistical bias in the
pole/zero parameters. Similarly, an incorrect choice of start time leads to a statistical bias because of the resulting phase shift in the frequency domain that is not modeled in the pole-zero model (7 above).

WALL ECHO MODELING

At low frequencies, the limited time available before echoes contaminate the measurement (often less than one cycle) reduces the independence of the basis functions used to form the pole-zero models described above; especially for driving frequencies near resonance, the close proximity of a natural-response pole to the forced-response pole make them very difficult to distinguish in a short time. This makes the estimation of high-Q resonances particularly difficult. In order to make more data available to incorporate into the model, the above techniques were modified to include a general model of the echo responses including both time delays and amplitude- and phase modification in the echo signals. The so-called multipath modeling method was used to calibrate a highly resonant ($Q=12$), low-frequency ($f_0=1$kHz) projector when there was not enough echo-free time to produce an acceptable calibration by transient methods. The projector's calibration curve by this method agreed with the open-water calibration except in the region around resonance, where there was a 1-2 dB error; this error may have been caused by radiation impedance changes due to wall interactions. It was also found that the parameter estimates are highly sensitive to the estimate of the echo arrival times since phase and arrival time estimates can offset each other in the model.

SPATIAL PROCESSING

Recently, a set of techniques loosely referred to as "spatial processing" has been investigated. The common approach in these techniques is to use spatial variation of the reference hydrophone to provide some measure of discrimination between direct signal and echoes in a manner analogous to the use of a line array for beamforming. The technique is easiest to visualize in steady state. For a given frequency, the pressure field produced by a projector is measured at $N$ hydrophone locations, giving pressures $h_n$. A set of weights is calculated such that the pressure that would be seen in open water at one meter is the weighted sum of the pressures at the hydrophone locations. The problem is to find a set of weights that simultaneously gives the correct pressure at one meter and causes the echo contributions of the weighted hydrophone responses to sum to zero. The calculation of the weights is based on simple geometrical acoustic properties. Because the large number of echo terms, this is in general a least-squares problem. Several candidate geometries for the hydrophones have been tried for a rectangular tank located at NUWC Newport. For the rectangular tank, there is an exact solution for the problem in terms of images. This makes it easy to formulate a linear least-squares design to calculate the weights. Testing of candidate geometries for the hydrophone array and of weighting techniques is currently underway.

ACKNOWLEDGEMENTS

The Office of Naval Research supported the majority of the work described here.

SELECTED REFERENCES

Limited space precludes listing a full set of references covering two decades of related work. The references below are chosen as representative of the work; their reference lists point to most of the other work done by USRD on projector calibration.

1. Bobber, Robert J., Underwater Acoustic Measurements, Los Altos, CA, Peninsula Publishing, 1988. (This reference covers measurement basics and describes some of the problems that the above acoustic modeling techniques were designed to overcome.)
