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GUIDELINES FOR SPECIFYING UNDERWATER ELECTROACOUSTIC TRANSDUCERS

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Introduction

This paper describes fundamental principles and practical guidelines for specifying or selecting underwater transducers. Underwater transducers provide the essential link between the power amplifiers (generators) and the acoustic pressure output, or between the received acoustic pressure and the receivers (preamplifiers) as projectors or hydrophones respectively.

Expectations from a transducer involve a mixture of acoustical, electrical and mechanical considerations, such as beam pattern, impedance, corrosion resistance and weight. This unusual combination of disciplines with the added concern of cost, makes the specifying requirements, and trading-off between them a difficult task. In addition, standard terminology describing transducers is different from other widely known definitions. Since underwater transducer users come from various disciplines, the difficulty in the task of specifying or selecting the correct transducer is compounded even more. This is particularly true for new users.

Transducers are usually used as an integral part of acoustic systems and typically described as the " wet-end". Thus, the parameters for a transducer are usually obtained from the overall system requirements to achieve a certain task. A general knowledge of these parameters and their inter-relationships will make the task of transducer specification easier and faster. In addition, conveying and discussing these parameters with a transducer manufacturer then becomes simpler and more effective.

Parameters to Consider When Specifying an Underwater Transducer

Probably the first parameter to be considered is the exact task of the transducer: is it to be a **projector** (for transmitting), a **hydrophone** (for receiving), or a **transducer** (both for transmitting and receiving).

The **frequency** definition for a projector or a hydrophone has different meanings. Projectors are usually driven near their resonance frequencies where they provide the highest acoustic output. Hydrophones, on the other hand, are usually used at and below their resonance frequencies over a much wider frequency band.

The **beam pattern** shows the relative amplitude of the acoustic pressure (generated or received) as a function of direction relative to the transducer. For a spherical transducer this response is uniform in space providing an omnidirectional pattern. For many applications, i.e., to locate a target or to reduce the received ambient noise, directional beams which provide a main lobe may be required. This is achieved by using a particular shape and/or an array of transducers. In some cases an array may be housed in a single transducer unit. The width of the main lobe, in degrees, is defined as the **beam width.** Although different criteria may be used in the literature, the general tendency is to use the width between the " half power " or " -3 dB " points.

Parameters to Consider (Cont.)

Usually there are additional lobes around the **main lobe** called **side lobes**.The **maximum response axis (MRA)** or the **acoustic axis** of a transducer is defined as the direction in which the acoustic response has its maximum value. The levels of the side lobes may be reduced at the expense of broadening the main beam by applying different voltages to the elements of an array. This is called **amplitude shading**. In some cases the main lobe of an array may need to be steered to a certain direction; this is called **beam steering**. Beam steering is achieved by application of proper phase or time delays betwen the signals fed into the elements, and is called **phase shading**. In such transducers the output of each element may need to be brought out separately.

The **directivity index (DI)** simply shows the improvement in signal to noise ratio (in dB) by using a directive transducer rather than an omnidirectional one. This is achieved by overall concentration of power along the MRA where the main lobe is located, without explicitly involving the details of the beam shape or side lobes. DI is a special case of **array gain** (**AG**): it is true only when the signal is a unidirectional plane wave and the noise is isotropic, that is, when the noise power per unit solid angle is the same. As expected, the DI of a spherical transducer is zero. The DI of a transducer used either as a projector or a hydrophone is the same. Correct DI of a transducer may be found from its beam pattern.

For analysis and application purposes transducers may be represented as equivalent electrical circuits consisting of resistors, capacitors and inductors. Since piezoelectric transducers can be modeled much easier with parallel components, it is a common practice to use parallel **admittance** (**Y**) rather than series **impedance** (**Z**), which consists of **resistance** (**R**) and **reactance** (**X**); hence **conductance** (**G**) for the real part, and **susceptance** (**B**) for the imaginary part. The unit of Y, G or B is Siemens (S). R, X, G and B are related to each other by the following equations:

$$R = \frac{G}{G^2 + B^2}, \quad X = \frac{B}{G^2 + B^2} \qquad (1)$$

The existence of the imaginary part may give problems in matching an amplifier to a projector. Thus, a series or parallel inductor can be added to the input of a transducer to cancel this imaginary part. This is known as **tuning**. Transformers may also be used to match the output impedance of an amplifier to a projector. This is called **matching**.

The electroacoustic **efficiency** of a projector is defined as the ratio of the acoustic power generated to the total electrical power input. Efficiency varies with frequency and expressed as percentage. The power input to a transducer, in terms of electrical watts, can be easily calculated from:

$$P_{in} = V_{in} \cdot G, \qquad (2)$$

where V_{in} is the rms voltage input to the transducer. Since efficiency of a transducer is calculated from the measured parameters (DI from beam pattern, TVR and G) it may not be well defined and one is discouraged from specifying it.

For an input of 1 Vrms, the acoustic output of a projector referenced to 1 m is defined as the **transmitting voltage response** (**TVR**). The acoustic pressure at one meter is usually found through a measurement on MRA, in terms of μPa. TVR is expressed in decibel form, i.e., dB re 1 μPa.m/V. Thus, a projector with a 150 dB re 1 μPa.m/V produces a pressure of 31.6×10^6 μPa at 1 m with a 1 Vrms input.

The **mechanical quality factor** (**Q_m**) simply shows the sharpness of the resonance of an untuned transducer and can be found from the G curve:

$$Q_m = \frac{f_r}{f_u - f_l}, \qquad (3)$$

where f_r is the frequency of maximum G (the resonance frequency), and f_u and f_l are the frequencies where the value of G is one half the maximum of G, on both the upper and lower sides of f_r. At these frequencies the input power is the half of its value at f_r with constant voltage input. ($f_u - f_l$) is known as the **bandwidth**. The bandwidth calculated from the -3 dB points of a TVR curve is similar to the one found from G; however, it may be slightly different. This is due to increased DI at higher frequencies and beam pattern ripples.

Parameters to Consider (Cont.)

Rise time (or **buildup time**) of a projector is the time required for a pulse to reach its steady-state amplitude (actually, to 96%), and can be estimated by its Q_m:

$$\text{Rise Time} = \frac{Q_m}{f_r} \quad . \qquad (4)$$

In other words, it takes Q_m cycles for the amplitude to buildup to 96% of its final value. Similarly, it takes Q_m cycles for the amplitude to decay to 4% of its value at the time of the removal .

The actual drive voltage of a transducer may be much higher than 1 Vrms and result in a higher acoustic output than its TVR. This level is called **sound pressure level** (**SPL**). The SPL and the associated power input of a transducer is limited by various factors including:

- Voltage breakdown
- Electrical/mechanical stress
- Thermal effects (heat dissipation)
- Cavitation
- Acoustinc interation between projectors

Some of these limitations are related to the **pulse length** (**PL**) and the **duty cycle** (**DC**) which is defined as the ratio of the pulse length to the period. For example, a transducer transmitting a pulse of 100 msec. long every second has a DC of 10%. A DC of 100% is usually termed a **continuous wave** (**CW**).

For each transducer the lowest threshold of these factors listed above limits the maximum drive level, thus the SPL. In air, underwater transducers may not be driven with the same power levels as under water. The unit of SPL is dB re μPa.m. The SPL of a projector at a certain frequency can be found from:

$$SPL = TVR + 20 \log (V_{in}) = TVR - 10 \log (G) + 10 \log (P_{in}). \qquad (5)$$

In rare cases, instead of the TVR, the **transmitting current responce** (**TCR**) is used. The only difference between TVR and TCR is that in TCR the pressure at 1 m. is defined for an input of 1 Amp and shown as dB re μPa.m/A.

The relation between TVR and TCR is :

$$TCR = TVR + 20 \log \frac{1}{|Y|} = TVR + 20 \log |Z| , \qquad (6)$$

where $|Y|$ and $|Z|$ are the magnitudes of the transducer admittance and impedance, respectively:

$$|Y| = \frac{1}{|Z|} = \sqrt{G^2 + B^2} \quad . \qquad (7)$$

The receiving performance of a hydrophone is expressed as the **open circuit voltage receiving sensitivity** (**OCV**). This is the rms voltage output at the open circuit terminals of a hydrophone, in response to a pressure amplitude of 1 μPa. For a directional hydrophone this is usually given at the MRA. OCV is expressed in decibel form, i.e., dB re V/μPa. Thus, if a transducer has an OCV of -180 dB re V/μPa, it provides a voltage of 10^{-9} Vrms for a pressure amplitude of 1 μPa at the face of the hydrophone. If the incoming wave is 20 μPa, the voltage output is 20 times greater than 10^{-9} Vrms. Note that the less negative the OCV of a hydrophone the higher the output voltage for a given pressure level.

Usually the OCV of a hydrophone, consisting of a piezoelectric ceramic only, has a flat response below the lowest resonance frequency of the piezoelectric ceramic and extends down to very low frequencies.

The TVR and OCV are related to each other

$$OCV = TVR + 20 \text{ Log } |Z| + J, \qquad (8)$$

where J is the **reciprocity parameter**, and for spherical waves may be given as:

$$J = \frac{2d_0}{\text{Water Density} \cdot \text{Frequency}} \quad , \qquad (9)$$

where d_0 is the reference distance specified in the TVR of the projector (1 m). In MKS system with μPa reference pressure the J in Eq.(8) can be used as: $J = - 354 - 20\log(f_{kHz})$.

When a preamplifier is used with a piezoelectric ceramic to raise its OCV, coupling of the impedance of the ceramic into the preamplifier usually creates a fall-off in OCV below a certain **cut-off frequency**, also known as the **roll-off frequency**.

Proper impedance selection will control OCV levels at low frequencies. In many cases, a controlled roll-off is a desirable feature. If a preamplifier is used, the **noise** added to the system due to the additional electronic components may need to be considered. The total noise of the ceramic and the preamplifier may need to be below the ambient noise in the water. In this case the noise performance of the complete hydrophone (ceramic and preamplifier) must be compared with the expected ambient noise levels.

Other Application Concerns

The depth capability of transducers is limited basically by the failure of its pressure release material, degradation of the piezoelectric ceramic under hydrostatic pressure, and of course, by the stress limits of the ceramic and the structure. In addition to the acoustical and electrical parameters described above one should also consider:

- Cable type, length and connector
- Mounting scheme of the transducer
- Environmental conditions -- temperature, vibration, sea-state, exposure to sun, etc
- Weight and size limits
- Service life in the water

Certain performances can be achieved acoustically, electrically and mechanically, but cost limitations may prohibit an expensive design. Thus a balanced compromise may be needed between these parameters and their affordability.

When a transducer is completed it is calibrated to obtain a set of performance curves. These tests usually include the water admittance, TVR and/or OCV and beam patterns at specified frequencies. There are several ways of representing beam pattern data and these can affect the ease of interpretation. The TVR and OCV may be plotted against a linear or a logarithmic scale of frequency. The logarithmic scale is especially convenient for plotting the OCV which makes it possible to display a wide frequency band. Other parameters can be calculated knowing these basic data values.

Additional testing for shock, vibration, temperature and/or hydrostatic pressure effects may also be conducted for special transducers.

Conclusion

The task of specifying a transducer is simplified once the expected parameters are defined or considered in advance.

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