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RELIABILITY IN TRANSDUCER SYSTEMS

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This paper will concentrate on transmitting transducers as components in systems for converting electrical to acoustic power radiated into water. Achieving reliability of the whole system depends of course on ensuring reliability of the transducer itself, but the importance of making sure that the combination of both amplifier and transducer is also satisfactory is sometimes forgotten. In some applications an array of transducer elements is needed to meet the acoustic requirements, and in these cases further precautions may be necessary to prevent failure. This paper therefore discusses reliability in three stages:

a. transducer itself

b. transducer plus amplifier

c. multi-element arrays

The discussion will be generally based on piezolectric piston-type transducers, although the principles and methods should be relevant also to other transducer types. This paper concentrates on electrical aspects rather than watertightness, although the latter is much the most common cause of failure.

The most useful tool for considering the behaviour of a transducer is its equivalent electrical circuit. A typical electrical admittance diagram of a well-behaved transducer in air shows a well defined admittance circle characteristic of an element with a single major resonance frequency (f_r) in the band of interest, high mechanical Q-factor (Q_m), and high coupling coefficient (k). These electrical admittance characteristics may be represented by the equivalent circuit of Figure 1, in which the components are related to the admittance circle by the equations:

$$\omega_r^2 = (2\pi f_r)^2 = \frac{1}{L_1C_1}$$

$$Q_m = \frac{\omega_r L_1}{R_1}$$

$$k^2 = 1-\left(\frac{f_r}{f_p}\right)^2$$

$$= \frac{C_1}{C_0 + C_1} = \frac{C_1}{C_{LF}}$$

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This method is easily understood in terms of the equivalent circuit, since if the tuning coil and element capacitance together produce a high parallel impedance then the motional current (representing the mechanical displacement velocity) will be approximately equal to the controlled input current. However, although this is clear for a single frequency, it is necessary to consider how well the method works over a band of frequencies. For this we consider the impedance seen looking back into the transducer from the acoustic terminals (AB) in Fig 5; the motional current will be well controlled if this impedance (Z_s) is much higher than the acoustic impedance itself. Calculation of Z_s can be carried out again by the methods of electrical filter analysis, since the circuit is effectively a band pass filter which is terminated by the resistor R_s representing the output resistance of the amplifier.

It is convenient to normalise the parameters using the relationships:

$$y = \frac{1}{W}\left(\frac{f}{f_r} - \frac{f_r}{f}\right) \qquad \text{where} \quad W^2 = \frac{k^2}{1 - k^2} \approx k^2$$

$$R_N = \frac{W}{\omega_r C_1}$$

$$\rho = \frac{R_N}{R_S}$$

The magnitude of the impedance $|Z_s|$ is given by

$$|Z_s| = R_N \frac{\{\rho^2 + y^2(\rho^2 + y^2 - 1)^2\}^{\frac{1}{2}}}{\rho^2 + y^2}$$

Results are illustrated in Fig 6, which shows the variation of normalised impedance with the frequency parameter y for various values of the amplifier output resistance R_s. It is clear that $|Z_s|$ is maximised for small frequency deviations about resonance by making R_s large. However, if the application demands use of a frequency band exceeding that corresponding to $y \approx 0.8$ the value of $|Z_s|$ will fall to low values, and the 'velocity control' will then not be achieved. For these wider bandwidths a better compromise may be to use a source impedance given by $\rho \approx 1.5$. This would give less effective control for small frequency deviations but would be more effective for wider bands. The choice for any particular application should be made by consideration of typical values of the parameters involved, and of the bandwidth required. For a bandwidth of $1/Q_m$, it would probably be safer to avoid the risk of failure caused by excessive amplitudes at the edge of the band, at the expense of rather less control nearer resonance. Once again a safer solution is given by an approximately matched amplifier if wide bandwidth is wanted.

C_{LF} is the capacitance measured well below resonance.

The admittance diagram of a transducer in water shows a much smaller circle, owing to the higher radiation loading of the water, but if only a single resonance is dominant it is still possible to determine the components of the equivalent circuit. Component values in the slightly more detailed equivalent circuit shown in Figure 2 may thus be derived, distinguishing between those components representing the radiation impedance due to the water loading and those inherent in the transducer. Note that these values have all been derived from electrical measurements, and so far we have made no attempt to relate them to the mechanical construction of the transducer element. Derivation of the circuit from a knowledge of the construction has thus not been necessary; the only condition needed has been the 'good behaviour' of the element (ie a single well-defined resonance within the band of interest).

Testing: Element itself

a. In air

Measurements at low power in air are used to establish the basic characteristics of the transducer element - eg C_{LF}, f_r, k . These are important to confirm satisfactory assembly, consistency, and good matching for elements in an array (Ref 1); but for this paper we concentrate on establishing good performance at high power. For this we need to confirm that the transducer will withstand the maximum values of mechanical and electrical stress to be experienced during operation. One way of attempting this would be to immerse the transducer in water and drive it to its required power level (multiplied by some safety factor), monitoring its performance. However, it is often the case that the impedance of a single element in water is not equal to its impedance in operational conditions, because eg of different baffle conditions, or because the element is to form part of an array. In such cases merely driving the element in water is an inadequate test, since it will not readily combine the correct values of electrical and mechanical stress. It can also be difficult to apply the specified power level conveniently, because of the cavitation produced in the shallow water in a test tank, if required power levels have been set for deep operation. There is therefore considerable advantage in carrying out the tests in air, although this means that the mechanical and electrical stress have to be applied separately. Thus, the electrical test voltage is applied to the element in air well away from resonance, (preferably below resonance to avoid heating due to the dielectric loss, tan δ), so that only small mechanical displacement is produced. Conversely, the test mechanical stress is applied at resonance in air, where only low input power is needed because of the low impedance in air. The input current is calculated by making the current in the mechanical arm (L_1, C_1, R_1) of the equivalent circuit equal to that at the maximum operating power. The 'motional current' (i_m) is related to the required mechanical power in water (W_m) by:

$$W_m = i_m^2(R_1 + R_r) .$$

At resonance in air, for an element with sufficiently low internal losses, the mechanical impedance is usually much less than that of the parallel capacitance C_0, and the motional current is then only a little less than the total input current. It is then sufficient to make the input current equal to the value of i_m calculated from the equation above (times a safety factor). It is of course often necessary to place the transducer within a sound-proofed box to carry out this test satisfactorily. An allowance may readily be made in the calculations if the transducer contains a tuning coil. Failure of the test is indicated by a marked change in waveform and 'resonance' frequency.

A good conservative rule is to use a safety factor of two for both of these tests. If the element is driven by an amplifier where output is matched to the radiation impedance then the input current or voltage to the element should never exceed twice the nominal operating values. In practice very satisfactory reliability has been achieved by using such a safety factor.

In addition to the controlled test conditions achieved by these methods, there are considerable cost savings to be derived from avoiding production tests in water for every element. It is of course desirable, if circumstances permit, to carry out some in-water tests at both low and high power to confirm on a few elements the adequacy of the tests described above. And mention should be made of the vital necessity for careful pressure tests, since water leakage is generally the most frequent cause of failures. (Pressure testing can normally be carried out by batch methods, and is therefore much cheaper than acoustic tests in water.)

Finally, it is possible to simulate the full in-water loading on an element whilst it is in air by using the Dumiload technique (Ref 2). In this technique a 'dummy' transducer is used to load the element under test, the electrical parameters being adjusted to produce the required mechanical impedance at the piston face. When this condition has been achieved, full power testing can be carried out in the air. Although this can be a very useful design proving method, it is not very convenient as a production test to assure reliability.

Transducer plus amplifier

If the transducer is driven by an amplifier capable of delivering power well in excess of that required, there should be no real difficulty in operating the system reliably. All that is needed is to be able to apply the required voltage at the transducer terminals. However, in more demanding applications it may be important to obtain the maximum power from an amplifier system, and consideration of the overall performance is then necessary. Maximum power from a source is obtained by matching its output impedance to the load. This is usually achieved by connecting a parellel tuning coil (L_0 in Fig 2) across the transducer element to make its impedance resistive at the operating frequency - normally the resonant frequency. It is often convenient also to use the tuning coil as an autotransformer, so that the value of the input impedance may be adjusted to a convenient value by varying the turns ratio of the transformer. The output impedance of the driving amplifier may then be made equal to the transducer's input impedance. This is straightforward if operation at only a single frequency is needed, but if operation over a band of frequencies is needed a little more consideration of the optimum matching is needed.

Again, analysis of the performance is best carried out by considering the admittance diagram and equivalent circuits. Fig 3 shows the admittance loop for a transducer tuned by means of a parallel tuning coil to appear resistive at the resonance frequency. The shape of the admittance loop is determined by the parameter kQ_m. The amplifier must be designed to work reliably into a range of impedance values, a typical range of nominal values being 2:1 in modulus and load factor $\geqslant 0.8$. For these limits the maximum bandwidth is obtained when $kQ_m \approx 1.2$, as indicated in Fig 3. (Ref 3.)

In practice it is necessary to take into account also the variations in impedance arising from manufacturing tolerances, operating temperature, pressure, and aging. If the transducer is used in an array the effect on its impedance of interaction with the other elements of the array should also be included. An example is shown in Fig 4, from which it can be seen that the transducer load may well vary by 6:1 in magnitude and up to ± 60° phase angle for typically experienced variations. The amplifier must thus be designed to withstand such variations without failure, although the operational application may permit some relaxations (eg of the output power) at the extreme load values.

A very low amplifier output impedance (ie effectively a constant voltage source) would imply an input current into the transducer which would vary inversely as the modulus of the load impedance. In the example quoted above, this would result in a variability of 6:1 in input current, and a correspondingly large variation in power. Whether this is acceptable operationally depends on the particular application; what concerns us from the reliability standpoint is the implications for the input current (and consequent mechanical strain), and the need to increase the test current to ensure safety. A similar effect results if a high output impedance (constant current) amplifier is used, although in this case it is large variations in input voltage which need to be considered. A safer system is one in which the amplifier's output impedance is approximately matched to the nominal load. In this case neither the input current nor the voltage will exceed twice the nominal values (except for those rare occasions when the resistive component becomes negative because of array interaction effects). Usually the current and voltage will be well below this value of twice nominal, and the test value of twice the nominal value should then be adequate to ensure reliability. The input power is also restricted to a much smaller range, given by

$$W = W_0 \frac{4R_t/R_s}{(1 + R_t/R_s)^2 + (X_t/R_s)^2}$$

where W_0 is the nominal power, R_s is the source impedance, and R_t, X_t are the resistive and reactive components of the transducer impedance.

Multi-element arrays

Achievement of the required source level and directivity often demands the use of a number of transducers assembled into an array, and in these circumstances the acoustic pressure generated by each transducer element exerts a force on all others. The resulting acoustic interaction effects are particularly serious for low frequency arrays, where the inter-element spacing is often much less than half a wavelength, and the variations in impedance can lead to catastrophic failure of the array. The greatest danger is that elements having very low acoustic impedance will be driven to excessive displacements, causing mechanical failure, and efforts to apply 'velocity control' to avoid this failure mode have been described (Ref 4). The basic method is to use a parallel tuning coil and a high impedance (constant current) driver amplifier for each element. (Although several alternative versions of the method have been proposed.)

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Comments

Many simplifying assumptions have been made for this paper, in order to give a reasonably concise discussion of the means of seeking reliability in transducer systems. The aim has been to show how analysis of the behaviour can be carried out by using quite simple equivalent circuits, and it is believed that the general approach and conclusions remain applicable even if more accurate representations of real systems are sought. It is not usually necessary to make the equivalent circuit much more detailed than that considered in Fig 2 for adequate analysis of testing methods. Testing of transducers in air is generally sufficient and preferable to acoustic testing in water. Matching of the output impedance of the driving amplifier to the nominal transducer impedance is usually advantageous; the amplifier must also be capable of operating safely into a wide range of impedance values.

This paper has concentrated on electro-mechanical aspects of reliability, but the importance of adequate tests to confirm watertightness of the transducer must again be re-emphasised. Ensuring good design against leakage involves a combination of common-sense, attention to detail and careful manufacture - but testing should never be neglected.

The methods described above have been applied over a number of years to transducer arrays designed by AUWE for MOD applications. It is difficult to quantify results, but as an example well over 20,000 transducers of one type have been manufactured, and experience in service has shown that over 90% have operated safely over 12 years or more. Although the methods described may involve some extra costs during manufacture, they are far exceeded by the savings in repair costs (including docking etc) which would be associated with transducer failures and replacements.

Acknowledgement

These methods were developed and applied in association with various other members of the Transducer Design Section at AUWE Portland, to whom grateful acknowledgement is given.

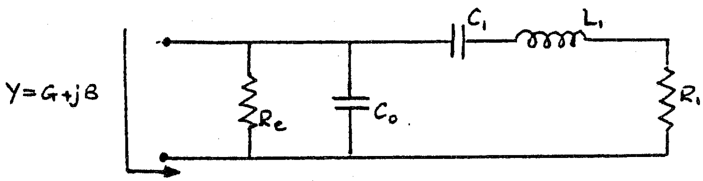

Fig 1 Equivalent circuit in air

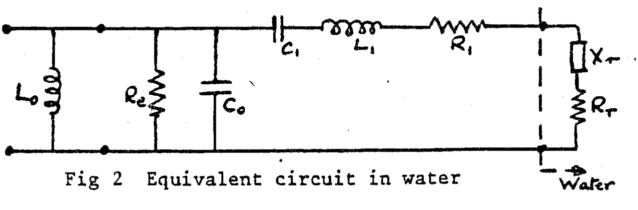

Fig 2 Equivalent circuit in water

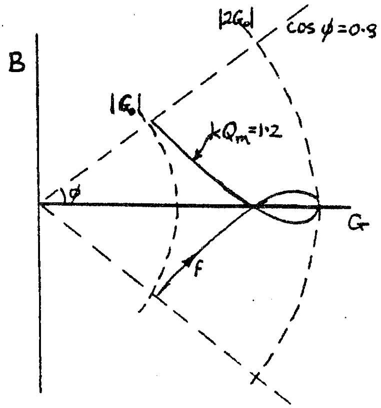

Fig 3 Optimum admittance loop

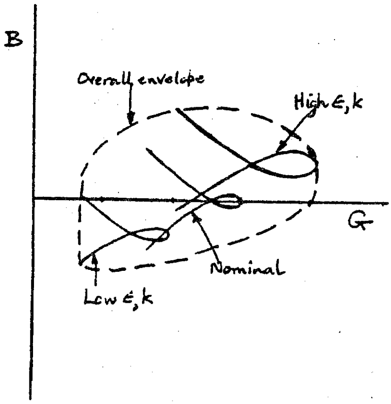

Fig 4 Typical effects of environmental variations, etc

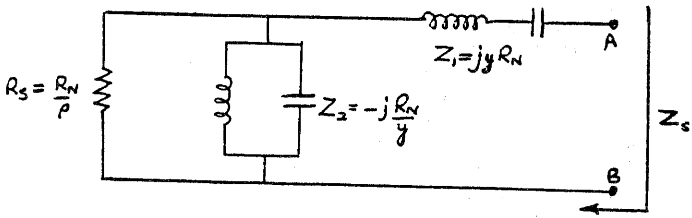

Fig 5 Equivalent circuit from acoustic terminals, as filter network

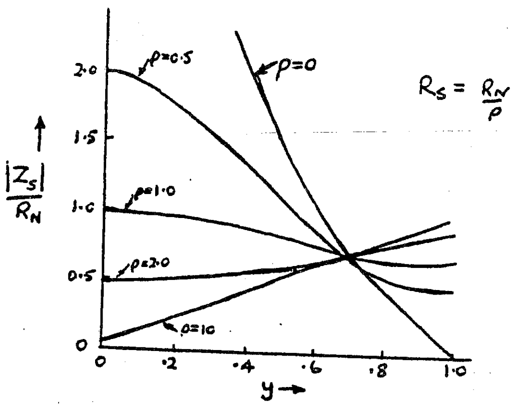

Fig 6 Variation of $|Z_s|$ with frequency (y)