Proceedings of The Institute of Acoustics

RECEIVING ACTION OF ULTRASONIC TRANSDUCERS

Z. Jagodzinski

Institute of Telecommunications, Technical University, Gdansk, Poland

INTRODUCTION

The hydroacoustic transducer is a reversible device. However in the bibliography, while its input admittance and transmitting action are discussed rather thoroughly, the receiving action is treated in a very general, even superficial or marginal way. This may be understood, since in view of the sonar system requirements, the receiving sensitivity is less important because the signal-to-noise ratio is determined by the water noise (mainly noise from turbulence) i.e. which originates outside the receiving transducer. With a good, low noise amplifier, the low sensitivity of the receiving transducer may be compensated with suitable amplification [1, 2].

Nevertheless in the receiving action of the transducers there are some interesting questions that need explanation for better understanding of the physical facts, and sometimes for practical applications too.

THE ELECTROMOTIVE FORCE

The first question is how the electromotive force (EMF) is induced in the transducer and, later, what is its response in the frequency domain?

To make it clear it is convenient to imagine a transducer T that touches the loading liquid medium (water or even oil) with one of its vibrating faces only (fig 1).

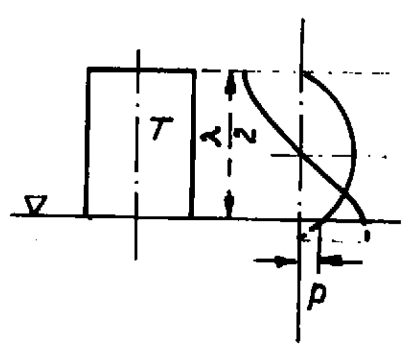

Fig 1.

When the transducer is unloaded, at the half-wave resonance frequency, pressure nodes and displacement (or particle velocity) antinodes exist on both of its vibrating faces.

When it is loaded, some pressure must exist on its loaded face, as shown in fig 1.

This is the necessary condition for the transfer of energy through the boundary between the transducer and medium.

To fulfil the continuity principle the pressure and velocity on both sides of the boundary must be equal. Thus the quotient of pressure and velocity on the transducer side of the boundary must be equal to that in the loading medium

$$Z_b = \frac{p_o}{v_o} = \rho C \qquad (1)$$

where ρC is the specific acoustic impedance of the loading medium.

In the terminology used in the general principles of acoustics, a transducer, treated as a solid block and vibrating because of the incident wave that reaches its surface, may be called a "pressure microphone", or, in this case, a "pressure hydrophone".

According to the Hooke's law the pressure of the incident wave causes displacement ξ, and vibrations with the velocity

$$v = \frac{d\xi}{dt} \qquad (2)$$

or, for harmonic vibrations

$$\bar{v} = \bar{\xi}.\omega \qquad (3)$$

where ω is the angular frequency, and $\bar{v}$ and $\bar{\xi}$ denote the amplitudes of velocity and displacement, respectively. There is however a definite difference in the way that the electromotive force is induced in the two types of transducers used - the piezoelectric (P-E) and piezomagnetic (P-M) ones. Both types must be pre-polarized, of course.

In the P-M transducer, the core of which is magnetically polarized with ferrite pieces (fig 2), the EMF is proportional to the change of magnetic flux and consequently to the particle velocity in the core.

$$e = k\frac{d\phi}{dt} = kv \qquad (4)$$

where k is the proportionality factor.

In each turn of the winding a "unit" EMF - e_1 - is induced and as the windings are connected in series with the proper winding directions observed, the unit EMFs sum-up and total EMF e, or voltage on the open electrical terminals is

$$e = ne_1 \qquad (5)$$

where n is the number of turns.

In accordance with Thevenin's theorem such a transducer may be represented as a source of EMF $\bar{e} = U$ and the internal, inductive impedance L, is proportional to the square of the number of turns

$$L = \gamma n^2 \qquad (6)$$

where γ is a constant depending on the geometry and permeability of the core (fig 2).

RECEIVING TRANSDUCERS

It is evident that increasing the number of turns will increase the sensitivity, but at the same time the internal inductance increases with the square of the number of turns.

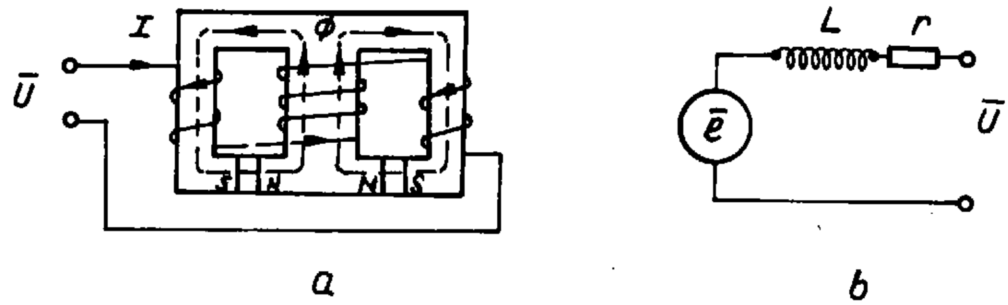

Fig 2.

This does not matter when the receiving action only is needed and the transducer is connected to a high input impedance amplifier.

In the other case, when the transducer is used as a transmitter too (and this is the usual situation), a low inductance is usually preferred. That is why P-M transducers are wound with a low number of thick wire turns. Then, for receiving, the low impedance transducer may be connected to a step-up, often resonant transformer (fig 3). The sensitivity, related to the transformer output terminals is then high, corresponding to the high number of winding turns. The step-up ratio is limited only by the inter-winding capacity of the secondary side of the transformer, and a long cable may be used between the transducer and transformer (fig 3).

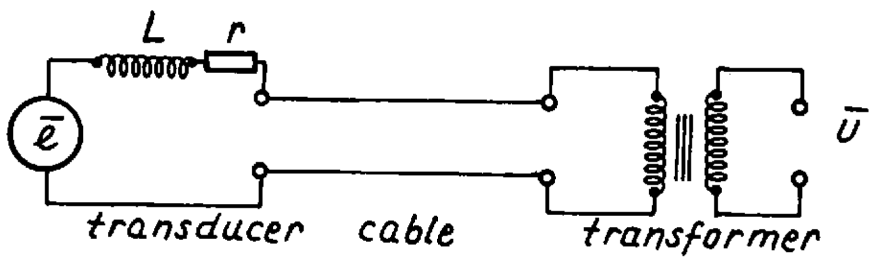

Fig 3.

In view of fig 3 the notion, or definition of the sensitivity, of a P-M transducer is somewhat ambiguous. One may ask whether it is related to the open terminals of the transducer itself or to the terminals of the transformer.

In practice this must be clearly stated, though it seems that the reference to the transformer output is more reasonable since the transformer is a non-active element, and the voltage on its output makes a starting point for the design of the amplifier.

RECEIVING TRANSDUCERS

In the piezoelectric transducers, which are electrically polarized, the EMF is proportional to the change of polarizing field and consequently to the displacement ξ.

$$e = k\xi \tag{7}$$

where k is a proportionality factor.

There is no summing-up action as in the P-M transducer because the elementary EMFs induced at each point of the vibrating face are connected in parallel.

In the simple but most important case when the wave reaches the face of the transducer in a perpendicular direction these elementary EMFs have also the same phase, as shown in fig 4. The result is that the open circuit voltage does not depend on the surface area of the receiving face, and only the internal, capacitive impedance in the Thevenin's equivalent circuit decreases when the transducer has a greater receiving face, as shown in fig 5, for a transducer at its resonance frequency, where $\bar{\varepsilon}$

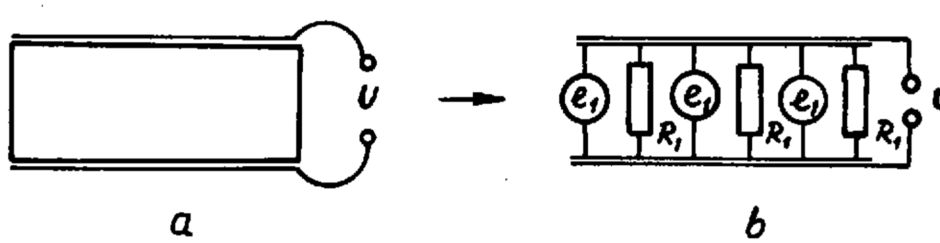

Fig 4

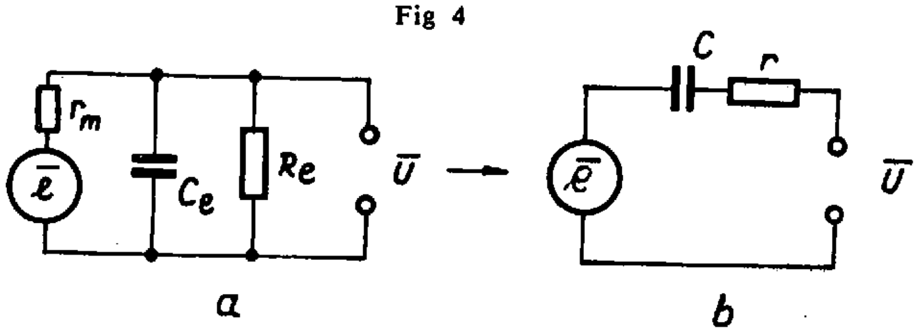

Fig 5.

is the total EMF, C_e the static capacity and r the total loss resistance of the transducer. When the area of the receiving face is increased the static capacity and the loss conductance increase too, or in the Thevenin's circuit (fig 5b) the internal series impedance is decreased, but the total electromotive force remains constant.

In practice, the internal impedance of the P-E transducer is higher than that of the P-M one. There are no means to increase the output voltage as is possible in the P-M transducer by increasing the number of turns or using a transformer.

When the incident wave is not perpendicular to the transducer face the elementary EMFs change their phase and the directivity pattern is formed.

RECEIVING TRANSDUCERS

The sensitivity definition, as shown in fig 5 is clear and not ambiguous.

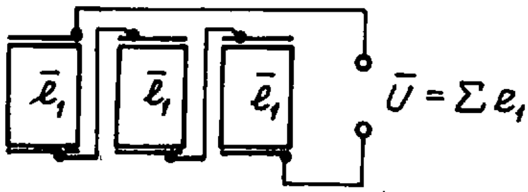

Fig 6

To increase the sensitivity it is possible to cut the transducer or its metallic plates into sections and to connect them in series (fig 6). The total sensitivity will then be multiplied by the number of sections, and the internal impedance will be respectively increased too. For transmission, the low impedance corresponding to parallel connection is definitely more suitable and then such a proposition (or even switching) does not seem reasonable. It may be accepted only when reception is needed, e.g. in hydrophones.

THE BAND-WIDTH

The frequency dependence and the band-width of the receiving transducer is usually calculated from the vibration equations in a simple, but convincing manner.

In the P-E transducer where the EMF is proportional to the displacement ξ (2) the vibration equation takes the form

$$M \frac{d^2\xi}{dt^2} + R\frac{d\xi}{dt} + \frac{1}{K}\xi = F(t) \qquad (8)$$

where M, R, K are the mass, losses and compliance of the vibrating block, respectively, and F(t) is the driving force of the incident wave.

For harmonic vibrations with angular frequency ω this equation takes the form

$$\omega^2 M\bar{\xi} + j\omega R\bar{\xi} + \frac{1}{K}\bar{\xi} = F'(\omega) \qquad (9)$$

where $\bar{\xi}$ is the displacement amplitude.

It is at once apparent that below the resonance frequency ω_0 i.e. when the elastic component $\bar{\xi}/K$ is dominant, the vibrations do not depend on frequency. Similarly for the P-M transducer where the EMF is proportional to the particle velocity v, the vibration equation takes the form

$$\omega M\bar{v} + R\bar{v} + \frac{1}{\omega K} = F(\omega) \qquad (10)$$

It is apparent that the sensitivity versus frequency characteristic is symmetrical around the resonance frequency.

This simple interpretation that can be found in nearly all text books is clear but does not show the band-width and characteristics around the resonance frequency and, in case of the P-E transducer, the relation between the flat part and the resonance peak of the characteristic.

As it may be useful in some practical applications and transducer design it is worthwhile to examine the sensitivity characteristic in terms of the mechanical impedance of the transducer block:

$$Z_m = \frac{F}{v} \qquad (11)$$

where

$$Z_m^2 = r^2 + (\omega M - \frac{1}{\omega K})^2 \qquad (12)$$

When the normalizing factor, relative to the resonance frequency, is introduced

$$\frac{\omega}{\omega_o} = \delta, \text{ where } \omega_o = \frac{1}{\omega K} \qquad (13)$$

$$Z_m^2 = r_m^2 + (\delta\omega_o M - \frac{1}{\delta\omega_o K})^2 \qquad (14)$$

or, after some simple rearrangements

$$Z_m^2 = r^2[1+Q_m^2(\delta - \frac{1}{\delta})^2] \qquad (15)$$

at the resonance frequency $\delta=1$ and $Z_{mo} = r$

Now, for the P-M transducer

$$\bar{v} = \frac{\bar{F}}{Z_m}; \quad \frac{\bar{e}}{\bar{e}_o} = \frac{\bar{v}}{\bar{v}_o} = \frac{\frac{\bar{F}}{Z_m}}{\frac{\bar{F}}{Z_{mo}}} = \frac{r}{Z_m} \qquad (16)$$

consequently

$$\frac{\bar{e}}{\bar{e}_o} = \frac{1}{\sqrt{[1+Q_m^2(\delta - \frac{1}{\delta})^2]}} \qquad (17)$$

At resonance, where $\delta=1$, obviously $\frac{e}{\bar{e}_o} = 1$

For any other frequency, when $\delta \neq 1$, $Q_m^2(\delta - \frac{1}{\delta})^2 > 1$

Far enough off-resonance, where $Q_m^2(\delta - \frac{1}{\delta})^2 \gg 1$

$$\frac{\bar{e}}{\bar{e}_o} = \frac{1}{Q_m(\delta - \frac{1}{\delta})} \qquad (18)$$

Thus below resonance, when $\delta \ll 1$

RECEIVING TRANSDUCERS

$$\frac{\bar{e}}{\bar{e}_o} = \frac{\delta}{Q_m} = \frac{\omega}{\omega_o Q_m} \qquad (19)$$

and above resonance, when $\delta \gg 1$

$$\frac{e}{e_o} = \frac{1}{\delta Q_m} = \frac{\omega_o}{\omega Q_m} \qquad (20)$$

The sensitivity characteristic is symmetrical around the resonance frequency as shown in fig 7.

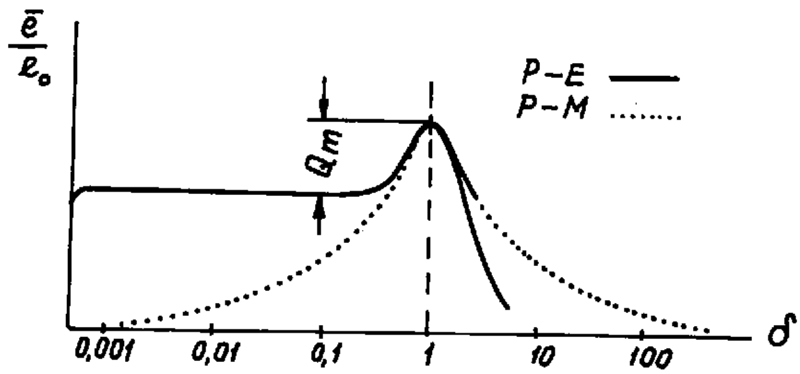

Fig 7

With the P-E transducer the sensitivity characteristic is different. Here $\frac{\bar{e}}{\bar{e}_o} = \frac{\bar{\xi}}{\bar{\xi}_o}$ and,since $v = \frac{d\xi}{dt}$ or, for harmonic vibrations $\bar{\xi} = \frac{\bar{v}}{\omega}$,

$$\frac{\bar{e}}{\bar{e}_o} = \frac{\frac{\bar{v}}{\omega}}{\frac{\bar{v}_o}{\omega_o}} = \frac{\bar{v}}{\bar{v}_o \delta} = \frac{r_m}{\delta Z_m} \qquad (21)$$

This δ in the denominator shows the difference between the P-M and P-E transducers.

Therefore

$$\frac{\bar{e}}{e_o} = \frac{1}{\delta\sqrt{[1+Q_m^2(\delta-\frac{1}{\delta})^2]}} \qquad (22)$$

For a detuned circuit $\delta \neq 1$ when $Q_m^2(\delta-\frac{1}{\delta})^2 \gg 1$

$$\frac{\bar{e}}{e_o} = \frac{1}{Q_m(\delta^2-1)} \qquad (23)$$

and below resonance, when $\delta^2 \ll 1$

$$\frac{\bar{e}}{\bar{e}} = \frac{1}{Q_m} \tag{24}$$

the sensitivity characteristic is flat, independent of frequency, and the sensitivity is Q_m times lower than at the resonance frequency.

Above resonance, when $\delta^2 >> 1$

$$\frac{\bar{e}}{\bar{e}_o} = \frac{1}{\delta^2 Q_m} = \frac{\omega_o^2}{\omega^2 Q_m} \tag{25}$$

the sensitivity characteristic drops down with the square of frequency.

In this way, instead of point-by-point measurement, it is enough to measure the e_o, or sensitivity in terms of V/Pa at the resonance frequency, then to find the Q_m corresponding to the 3 dB drops around the resonance, and the whole sensitivity characteristic may then be easily calculated for both P-M and P-E transducers.

CONCLUSION

Some properties only of receiving transducers are discussed in this paper. The author is aware that not all the questions are answered clearly enough. Some fragments need a deeper study, supplements or, perhaps, even corrections. Only most fundamental questions have been discussed. Some interesting problems which may have also a practical significance, especially that of the relation between the efficiency in the transmitting action and the sensitivity in the receiving action of the transducer, and also the mechanism of the formation or the directivity pattern and its interpretation in the receiving action are not even started, because they cannot bekept within the limits of time and space of this conference.

REFERENCES

[1] R J Urick, Principles of Underwater Sound, McGraw-Hill, New York (1962)
[2] Y Kikuchi, Ultrasonic Transducers, Tokyo (1969)
[3] Z Jagodzinski, "Radiation Efficiency of Ultrasonic Transducers", Archiwum Akustyki (Warszawa) Vol.7, 2, (1972)