EXPERIMENTAL STUDY OF THE ULTRASONIC TRANSDUCER NON-LINEAR VIBRATIONS

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A simple method that makes it possible to measure transducer characteristics in a non-linear regime is described. The method is illustrated by several measured characteristics, from which conclusions regarding the design of a driving power generator may be drawn.

1. INTRODUCTION

To simplify the design of an ultrasonic transducer and an associated driving power generator it is usually assumed that the transducer operates in a linear manner [1–5]. However, there are some applications where the transducer is driven at such high power levels that its vibrations become non-linear and the assumption of linearity is violated. It may then be desirable to know the transducer behaviour under these conditions. The purpose of this paper is to describe a simple method that makes it possible to measure characteristics of the transducer operated in the non-linear regime. The method is illustrated with several measured characteristics.

2. EXPERIMENTAL SET-UP

A block diagram of the measuring apparatus is shown in fig. 1. A harmonic signal of an amplitude U_0 and at a frequency f is produced by a signal generator *SG*, amplified by a power amplifier *PA*, and then fed to the ultrasonic transducer. The frequency set on the signal generator is checked by the frequency counter *FC*. The transducer is connected to the amplifier via the resistor R which serves to derive the voltage U_I proportional to the transducer current I. Its resistance $R = 1\,\Omega$ is negligible in comparison with the minimum transducer impedance $Z_{\min} = 130\,\Omega$. A pick-up (small piezoelectric ceramic disc) is cemented to the upper transducer face. The open-circuit voltage of the pick-up U_p is directly proportional to the transducer acceleration. The voltages U_I, U_p and U (at the transducer terminals) are measured by the low-frequency millivoltmeters mV_1 and mV_2. The magnitude of the current I is determined from U_I ($I = U_I/R$). The phase angle φ between the voltage U and current I, and the phase angle φ_p between the voltages U and U_p are measured

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by the phase-angle meter *PM*. In fig. 1 several auxiliary circuits were omitted. Among these are: the tuned impedance transformer which matches the power amplifier to the transducer, the preamplifier and the voltage divider which adjust the voltages U_I and U respectively for the phase-angle meter and the oscilloscope.

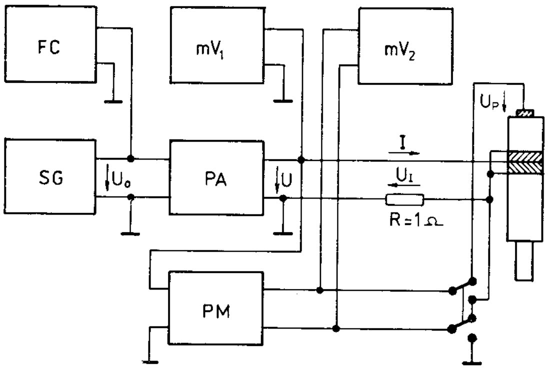

Fig. 1. Block diagram of the measuring apparatus.

For this measurement a composite (sandwich) ultrasonic transducer was available. Two piezoelectric ceramics separated by a thin metal electrode served as active elements of the transducer. To these a quarter-wave resonator and a double quarter-wave cylindrical step velocity transformer were attached. The resonator and the velocity transformer were made of titanium alloy. The transducer was clamped at the node to the stand. The low power level characteristics were measured with the transducer radiating in air. During the measurement at higher power levels the working face of the velocity transformer was submerged 10 mm in water.

3. TRANSDUCER CHARACTERISTICS

The experimental set-up described makes it possible to determine the transducer frequency response characteristics $U = U(f)$, $I = I(f)$, $\varphi = \varphi(f)$, $U_p = U_p(f)$, $\varphi_p = \varphi_p(f)$, $Z = Z(f)$ and $P = P(f)$ for a very large extent of power levels. The measurement proceeds in the following way: (1) the magnitude of the voltage U_0 is set at a certain value and kept constant during the measurement of each characteristic; (2) the frequency f is slowly varied in one direction; (3) the values of U, I, φ, U_p are read at selected frequencies and used to calculate the complex impedance of the transducer, $Z = U/[I \exp(j\varphi)]$, and the useful power the transducer draws from the amplifier, $P = UI \cos \varphi$. If a jump occurs in the characteristic, points (2) and (3) are repeated with the frequency f varying also in the opposite direction.

Though the voltage U_0 was immediately available, we decided to use the maximum power the transducer drew from the amplifier, $P_{\max}$, as a parameter of the characteristics. The characteristics are measured for values of $P_{\max}$ ranging from 82 mW to 95 W; that is, $P_{\max}$ is varied more than 10^3 times.

In this work the absolute amplitude of the transducer vibrations was not measured directly; instead the voltage U_p at the pick-up terminals was used as the relative measure of the transducer vibrations. It was found that the characteristics $U_p(f)$ and $I(f)$ have almost the same form (except for the factor ω^2). The phase difference between the current I and voltage U_p was 90°. This corresponds to the time the ultrasonic wave needs to propagate through the quarter-wave resonator. From the similarity between the characteristics $U_p(f)$ and $I(f)$ it follows that the value of current I may also be used as the relative measure of the transducer vibrations.

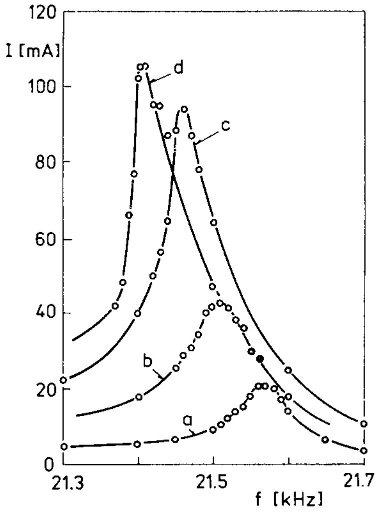

Fig. 2. Transducer characteristics $I(f)$ at different power levels: a — $P_{\max} = 82$ mW; b — $P_{\max} = 0{\cdot}49$ W; c — $P_{\max} = 1{\cdot}83$ W; d — $P_{\max} = 3{\cdot}15$ W; the transducer is radiating in air.

From the many measured and calculated characteristics only some more interesting ones will be given here. An example of the characteristics $I(f)$ corresponding to the low power levels is given in fig. 2. At the mechanical resonance the transducer draws the maximum power from the amplifier and the current reaches its maximum value $I_{\max}$. It may be seen that if the power supplied to the transducer is increased, the curve $I(f)$ leans and shifts towards the lower frequencies and thus the resonance ($I_{\max}$) also sets in at lower frequencies. It follows from this that the transducer represents a sub-linear vibration system otherwise known as a "soft-spring" [6]. The higher the power level, the more the curve $I(f)$ is bent, and after exceeding a certain limit P_L the curve $I(f)$ would become so bent as to become theoretically multiple-valued. In fact, the so-called "jump phenomena" [6] will set in (see fig. 3): in unstable points of the resonance curve, a very small change of frequency will cause quite a large change in the amplitude, so that there will be a jump from one branch of the curve to the other.

The limit P_L mentioned above may be used to classify the non-linear vibrations: if $P_{\max} < P_L$, the transducer performs weak non-linear vibrations for which the resonant frequency varies with the level of excitation but no jumps set in; if $P_{\max} > P_L$,

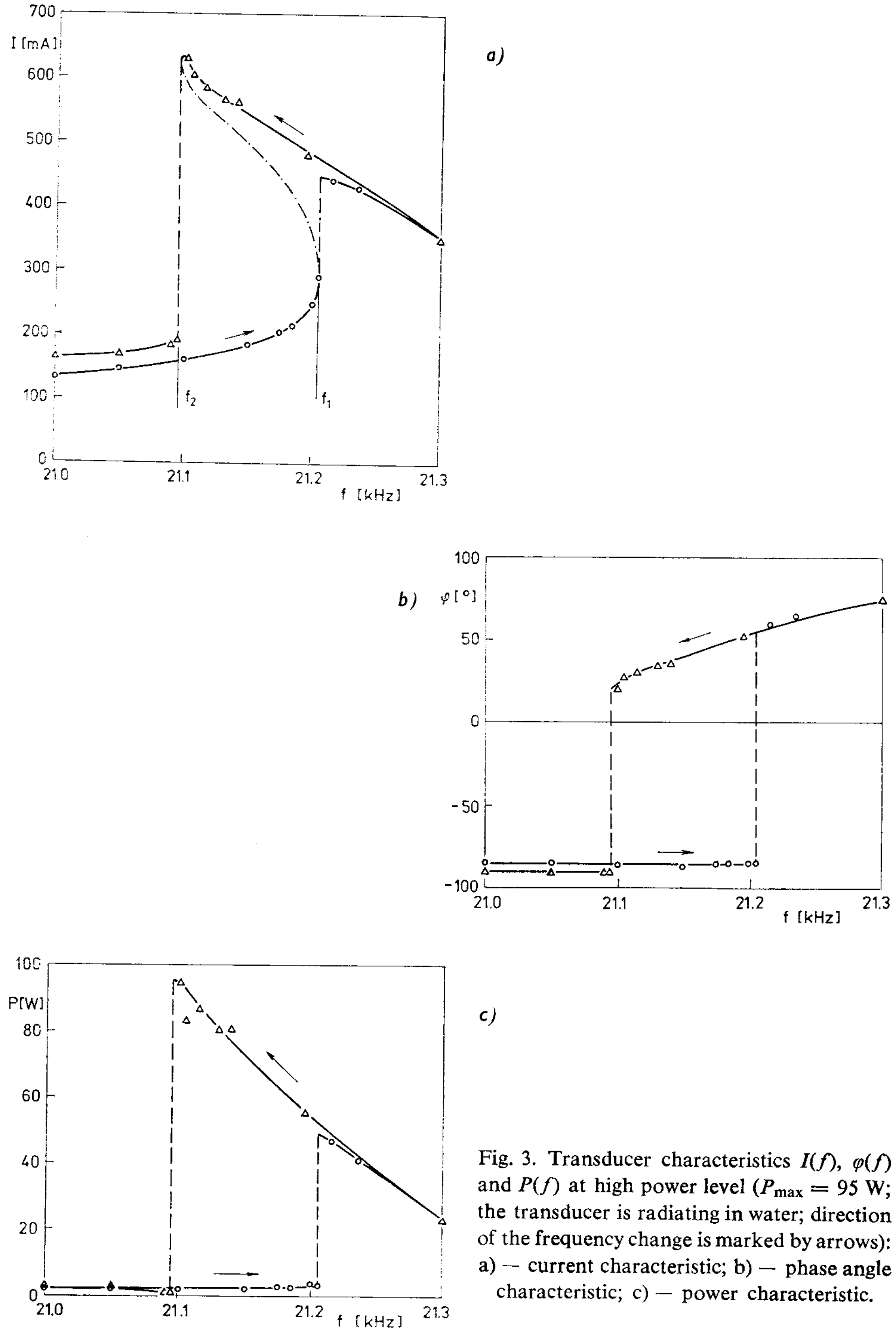

Fig. 3. Transducer characteristics $I(f)$, $\varphi(f)$ and $P(f)$ at high power level ($P_{\max} = 95$ W; the transducer is radiating in water; direction of the frequency change is marked by arrows): a) — current characteristic; b) — phase angle characteristic; c) — power characteristic.

the transducer performs strong non-linear vibrations accompanied by jump phenomena.

The characteristics $I(f)$, $\varphi(f)$ and $P(f)$ corresponding to the strong non-linear operating regime are given in fig. 3. The direction of the frequency change is marked by an arrow. When the frequency increases, the jump occurs at point f_1, and when the frequency decreases, the jump occurs at point f_2 ($f_1 > f_2$), so that the response exhibits frequency hysteresis. It is not possible to measure the middle branch of the characteristics; in fig. 3 an estimated form of this branch is plotted by the chain line.

It should also be noted here that it was not possible to maintain constant conditions during the measurement at the high power levels. When going through the "hysteresis curve" repeatedly, the values of f_1 and f_2 and the form of the curves slightly varied from one cycle to another.

4. CONCLUSION

The method introduced proved to be useful in obtaining information on transducer behaviour at high power levels. With respect to ultrasonic generator design several conclusions may be drawn from the transducer characteristics. First, it was found that the current and the pick-up voltage characteristics are equivalent with respect to the information content on the transducer vibrations. Therefore, the feedback signal may be derived both from the current I and from the voltage U_p.

It was also found that the resonance frequency of the transducer f_r varies strongly both with the power level and with the mechanical load. However, it is the resonance phase angle φ_r that is almost independent of these external changes.

Lastly, because of the jumps, the transducer may be tuned to the resonance only by lowering the frequency f starting from an arbitrary frequency higher than f_1. In designing a feedback system this requirement should be taken into account.

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