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ULTRASONIC TRANSDUCERS USING RADIAL VIBRATIONS OF A PIEZOELECTRIC DISK

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Suggestions concerning the use of radial vibrations of a piezoelectric disk in ultrasonic transducers working in the frequency range below 100 kHz are presented. Experimental data from investigations of two types of transducers are given, one using axial coupling of a piezoelectric disk with a metal rod vibrating in the longitudinal mode, the other using circumferential coupling of a piezoelectric disk and a metal plate. The amplitude and phase characteristics of admittance, the resonance curves, the temperature characteristics of impedance and the resonance displacement amplitudes are presented.

1. Introduction

Piezoelectric plates used for ultrasound generation most often work in the thickness mode. Radial vibrations of piezoelectric disks [8] have been used comparatively rarely to date. Use of these vibrations is of interest because of the possibility of ultrasound generation in air at frequencies of several tens of kHz. In addition, a piezoelectric disk vibrating in the radial mode has a low electrical imput impedance (typically a few ohms), which in turn is of interest from the viewpoint of matching to transistor supply systems.

It is possible to build vibrating structures with a piezoelectric disk vibrating in the radial mode as the active resonator. The disk can be coupled with such resonators as a cylinderplate or rod with the resonators being excited to flexural, radial or thickness vibrations with directional conversion or without it. Table 1 shows the manner of building the resonance coupled structures.

This paper presents experimental data of investigations of two types of coupled structures — denoted in Table 1 as transducers *c* and *f*. The transducer *c* is a resonance system with directional R-L conversion, where the piezoelectric disk is axially coupled with a rod vibrating in the longitudinal mode. The transducer *f* is a piezoelectric disk circumferentially coupled, without conversion,

Table 1. Manners of building the coupled resonance structures using the radial vibrations of a piezoelectric disk

	Rod			Plate			Cylinder		
	F	R	L	F	R	L	F	R	L
Disk	a	b	c	d	e	f	g	h	i

F – flexural, R – radial, L – longitudinal
a, b, ..., i – transducers

with a metal plate, creating a transducer vibrating in the longitudinal mode. For practical reasons it is advisable to build the simplest single or two-resonance structures, e.g. the transducers described in the sequel.

2. Transducer using axial coupling with conversion

Resonators with directional R-L conversion were designed by K. Ito and E. Mori [5, 6] who suggested R-L type converters in the form of uniform resonance structures requiring ultrasonic energy supply from outside. Such a solution is troublesome since it requires additional vibration sources. A considerably simpler design for an R-L type converter [2] is presented in Fig. 1.

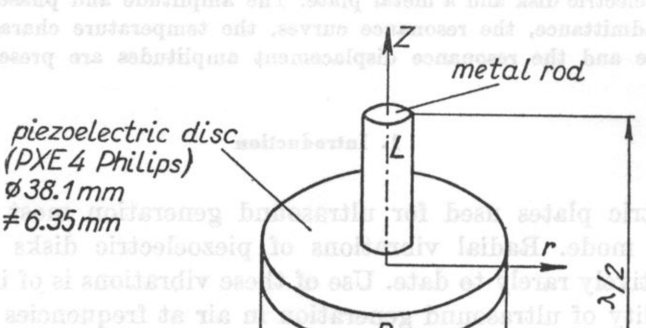

Fig. 1. A non-uniform R-L type converter

The converter is a non-uniform system made of a piezoelectric disk acting as a half-wave radial vibration resonator and a metal rod acting as a half-wave longitudinal vibration resonator, connected with a Hottinger Z-70 cyanoacrylate glue. The rod length is chosen so that its fundamental resonance frequency lies in the radial resonance range of the disk.

The piezoelectric disk and the rod are coupled together at the velocity node of radial vibration for the disk, and that of longitudinal vibration for the rod. With a suitable choice of dimensions, such a system permits comparatively large amplitudes of rod surface vibrations to be obtained. Energy transmission from the disk to the rod occurs due to a Poisson effect in the mechanically coupled common part of the converter. When the free vibration frequencies of individual resonators are different from each other, each of them vibrates as a free system, whereas when these frequencies are close to one another, there is an interaction of the two resonators [9].

One characteristic of such a converter is its electrical input admittance. An example of a graph of the admittance modulus is presented in Fig. 2.

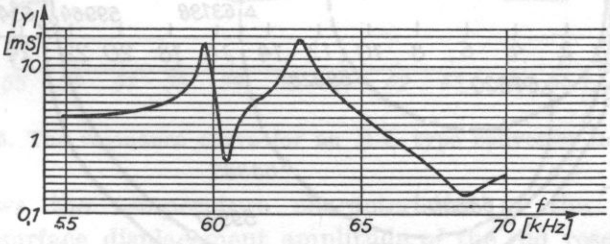

Fig. 2. The modulus of electrical admittance for a nonuniform R-L type converter

The maxima of this graph correspond to the free vibration frequencies of the converter. The gap between the frequencies depends on the dimensions of the part common to both resonators and is the longer the bigger the dimensions are [9]. The maximum values of the modulus of the electrical admittance of the converter depend on the resonator length and are equal for an aligned converter.

Fig. 3 shows the amplitude and phase characteristics of the electrical admittance of an R-L type converter without loading and with unilateral water loading. An example of the dependence of the modulus of electrical impedance, the argument, and the frequency of the minimum modulus of the impedance, on temperature is shown in Fig. 4. It is noteworthy that the modulus of the impedance changes only slightly in the given temperature range. This assures a stable matching of the supply generator over this temperature variation. The values of the modulus of electrical impedance on the curve apply to a converter working in air.

Fig. 5 presents the curve of the dependence of the surface displacement amplitude in a longitudinal vibration resonator on the frequency. Measurements were made using an MM004-type Brüel-Kjaer capacitance sensor. The characteristic has two maxima corresponding to the converter resonance frequencies. These maxima correspond to maximum values of the graph of modulus of the converter admittance against frequency.

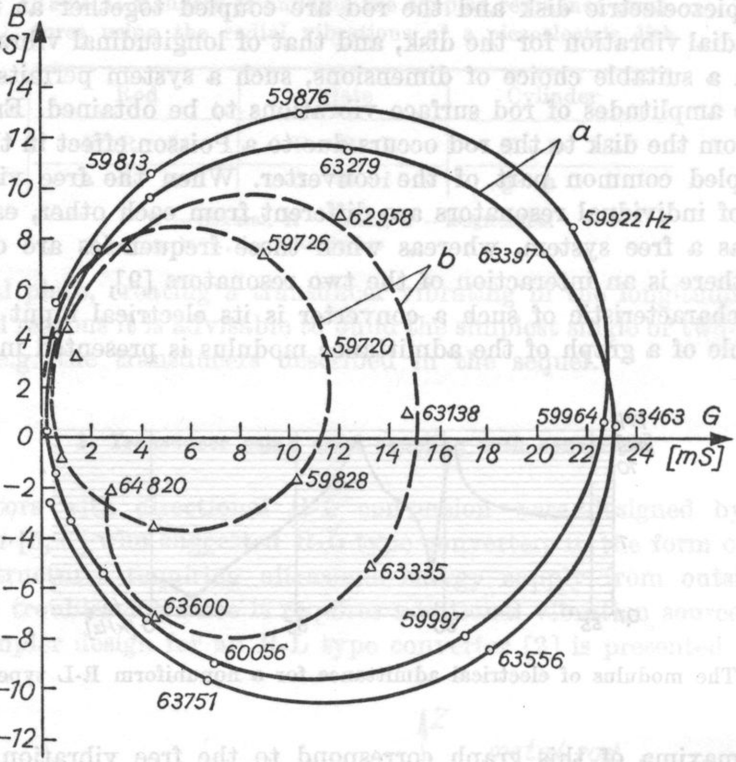

Fig. 3. The amplitude and phase characteristics of the electrical admittance of an R-L type converter

(a) unloaded converter, (b) unilaterally water loaded converter

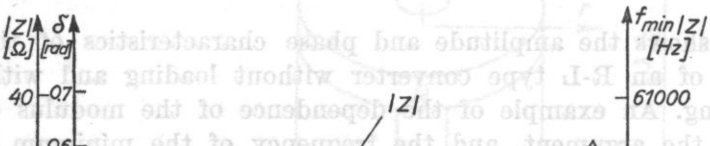

Fig. 4. The temperature characteristics of the impedance of an R-L type converter

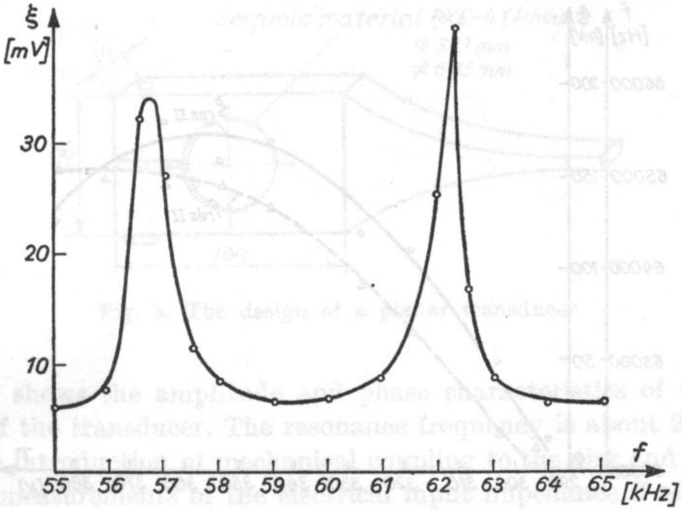

Fig. 5. The resonance curve for an R-L type converter in air

Fig. 6 shows the temperature characteristics of the resonance frequency and the surface displacement amplitude of the rod resonator for f_{resI}, and Fig. 7 shows similar characteristics for f_{resII}.

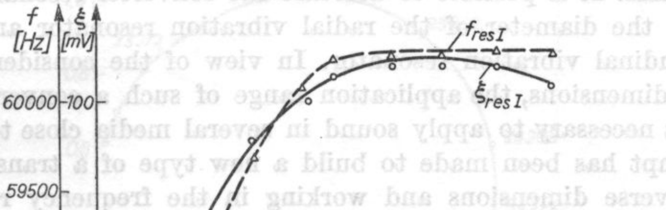

Fig. 6. The temperature characteristics of the resonance frequency and the surface displacement amplitude in the rod resonator for f_{resI}

It can be concluded from the characteristics shown that the displacement amplitude maxima occur at temperatures of 330-350 K, i.e. the optimal working temperature for the converter investigated occurs in this range.

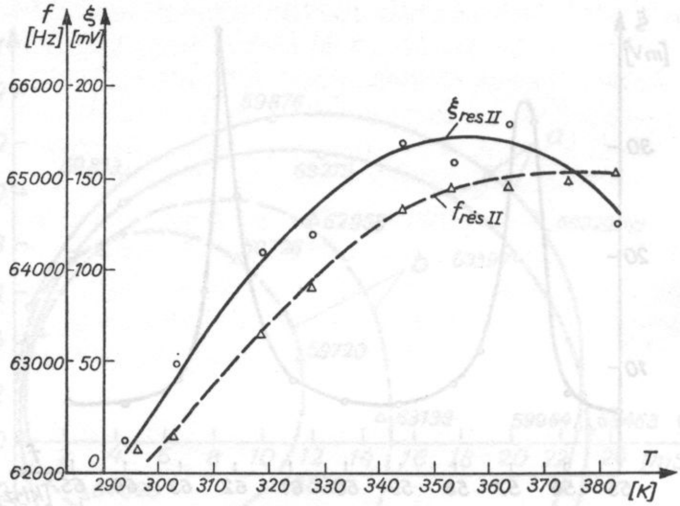

Fig. 7. The characteristics, as in Fig. 6, for f_{resII}

3. Transducer using circumferential coupling without conversion

The R-L converter described above operates in the range of frequencies at about 60 kHz. It is possible to decrease the converter resonance frequency by increasing the diameter of the radial vibration resonator and the length of the longitudinal vibration resonator. In view of the considerable increase of transverse dimensions, the application range of such a converter is limited, e.g. when it is necessary to apply sound in several media close to one another [1]. An attempt has been made to build a new type of a transducer having smaller transverse dimensions and working in the frequency range near to 20 kHz [4]. This transducer involves radial vibration of a piezoelectric disk circumferentially coupled to a metal plate, which reduces its resonance frequency. The plate and the disk together constitute the longitudinal vibration transducer. In view of its flat design this transducer has been called *planar*.

Mechanical coupling of the disk and the plate was achieved by: 1. gluing, 2. coupling with a screw, and 3. thermal setting of the piezoelectric disk in the metal plate.

During the investigation it was found that a good mechanical coupling over a wide temperature range could be achieved using the last two methods.

3.1. A planar transducer mechanically coupled with a screw. An example of a transducer design mechanically coupled with a screw is shown in Fig. 8.

It is composed of a piezoelectric disk of Philips PXE-4 ceramic material and a duraluminium plate. A slot in the plate permits a screw-adjusted mechanical coupling of the disk and the plate.

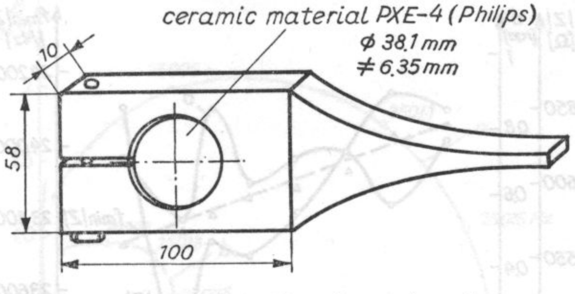

Fig. 8. The design of a planar transducer

Figure 9 shows the amplitude and phase characteristics of the electrical admittance of the transducer. The resonance frequency is about 23 kHz. With a view to the introduction of mechanical coupling to the disk and the plate [7] temperature measurements of the electrical input impedance Z at a frequency corresponding to the minimum of the modulus of impedance were made. The measurement results for a specimen transducer are shown in Fig. 10.

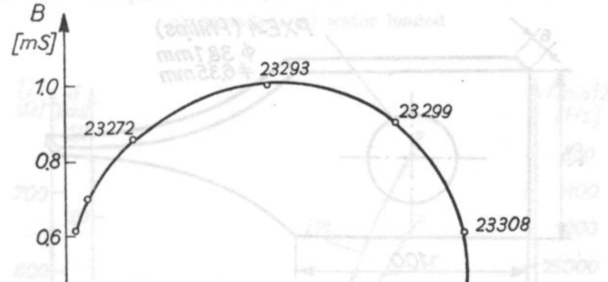

Fig. 9. The amplitude and phase characteristics of the admittance of a planar transducer in air

In the temperature range of 290-370 K the frequency $f_{\min|Z|}$ diminishes by about 300 Hz, whereas the modulus and the argument of the impedance change by about 500-750 and 0.5-0.9 radians, respectively.

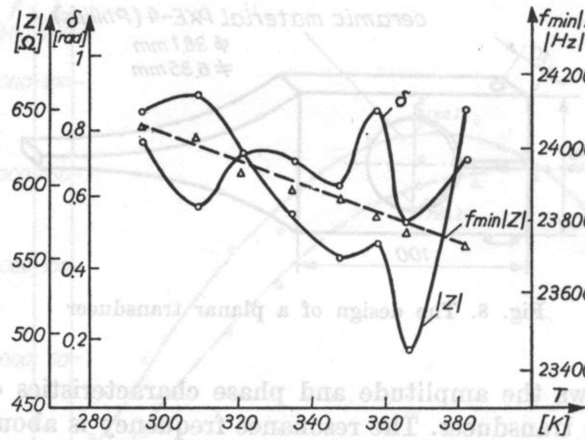

Fig. 10. The temperature characteristics of the impedance of planar transducer

3.2. A planar transducer mechanically coupled by the thermal method. Figure 11 shows the design of a planar transducer with a concentrator of resonant frequency of about 25 kHz, in which mechanical coupling was achieved by thermal setting of the piezoelectric disk in a metal plate. The piezoelectric disk at a temperature of about 290 K was set in a duraluminium plate at a temperature of about 420 K, and the whole was subsequently cooled. The amplitude and phase charactеrictics of admittance for such a design of transducer are shown in Fig. 12, while Fig. 13 presents the temperature dependencies of the frequency and impedance corresponding to the minimum of the modulus of impedance.

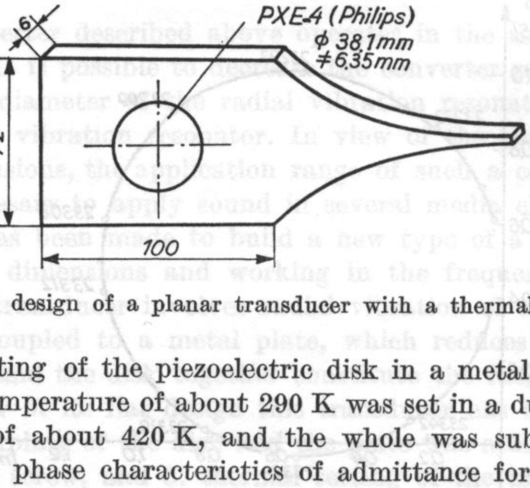

Fig. 11. The design of a planar transducer with a thermally set disk

Both the graphs of the modulus of impedance and the argument of impedance are almost flat in the temperature range of 290 - 340 K, which implies a good mechanical coupling of the disk and the plate in this temperature range.

Figure 14 shows the curve for the dependence of the concentrator surface displacement amplitude on frequency. The measurement was made using an electrostatic MM-004 type Brüel and Kjaer sensor. Figure 15 shows the de-

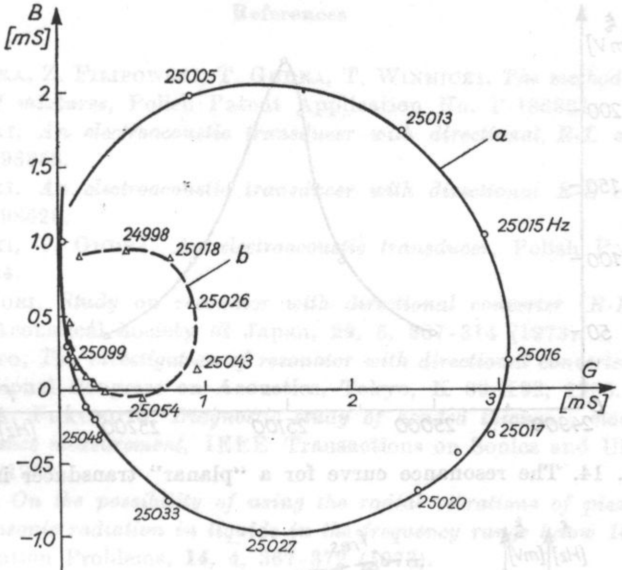

Fig. 12. The amplitude and phase characteristics of the admittance of planar transducer (*a*) unloaded, (*b*) water loaded

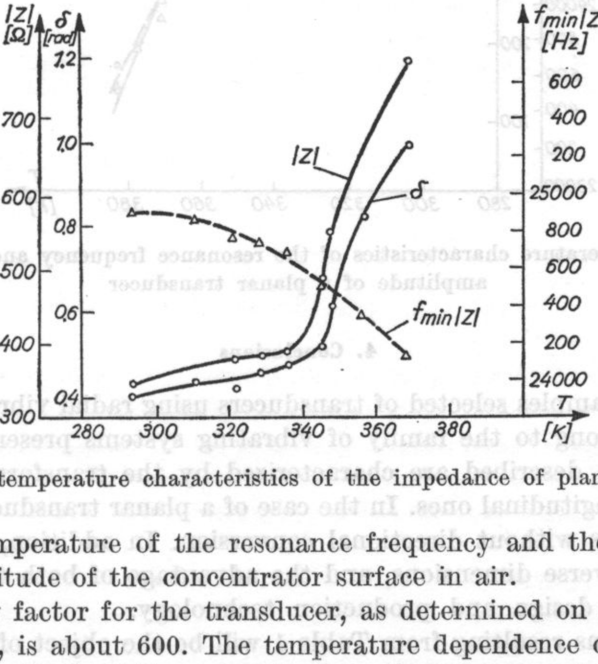

Fig. 13. The temperature characteristics of the impedance of planar transducer

pendence on temperature of the resonance frequency and the resonance displacement amplitude of the concentrator surface in air.

The quality factor for the transducer, as determined on the basis of the resonance curve, is about 600. The temperature dependence of the resonance displacement amplitude of the concentrator surface corresponds to the temperature dependence of impedance shown in Fig. 13.

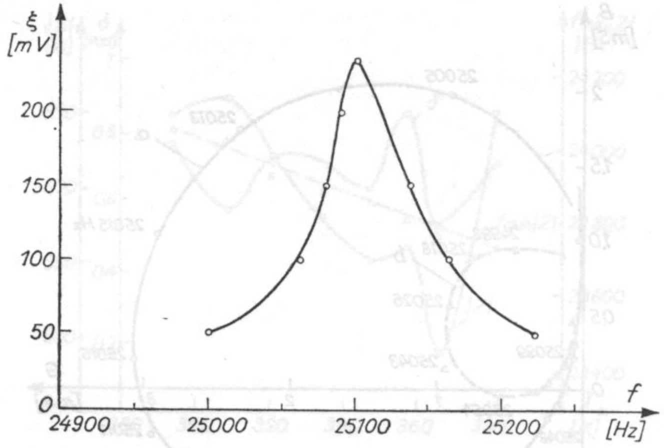

Fig. 14. The resonance curve for a "planar" transducer in air

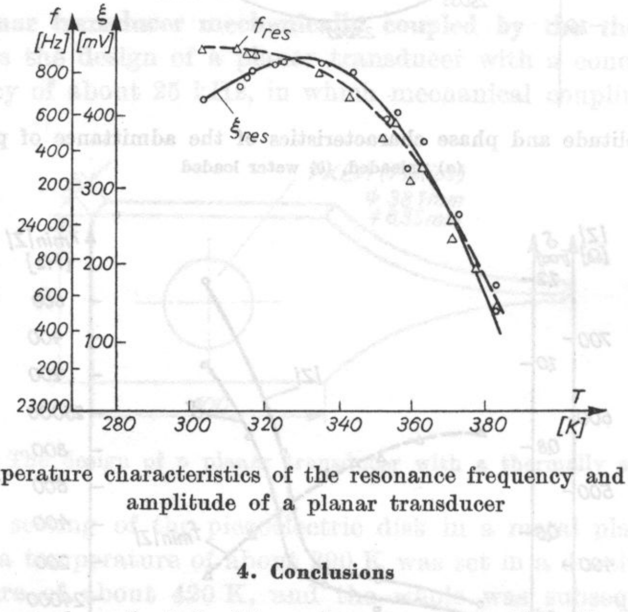

Fig. 15. The temperature characteristics of the resonance frequency and the displacement amplitude of a planar transducer

4. Conclusions

The two examples selected of transducers using radial vibration of a piezoelectric disk belong to the family of vibrating systems presented in Table 1. The transducers described are characterized by the transformation of radial vibrations to longitudinal ones. In the case of a planar transducer such a transformation occurs without directional conversion. In addition, this transducer has small transverse dimensions, and the advantage of both transducer types is their simple design and production technology.

Other designs resulting from Table 1 will be the object of further investigations, e.g. a transducer with directional R-L conversion where the longitudinal vibration resonator is a cylinder [3].

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