TUNABLE TRANSDUCERS

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1. INTRODUCTION

This paper is concerned with two designs of tunable transducers : the two-plate high-frequency transducer and the low-frequency sandwich transducer.

Since 1983 there has been considerable interest in designing a wideband transducer by controlling or tailoring the frequency response by the application of active piezoelectric adjacent layers. The purpose of controlling or tailoring can be to obtain a multiple-resonance transducer [8] or to tune it [1,2,3,4,6,7]. A switchable transducer can resonate at two or more frequencies that are well separated whilst the tunable transducer can have a continuous range of resonant frequencies.

Various methods of achieving a variable or tunable transducer are summarised :-

2. SINGLE-PLATE TUNABLE TRANSDUCERS

(a) Single-plate transducer

The simplest method for realizing a tunable transducer is by series tuning [5]. Its resonant frequency can be varied between the series f_s and the parallel f_p resonant frequencies by varying a series inductance connected between the transducer and the driving voltage source.

(b) Fry's transducer

This is the first piezoelectric system with variable resonant frequency, demonstrated by Fry et. al [9] in 1951. His design employed a liquid column of variable length closely coupled to an electrically driven piezoelectric element so that a composite vibrating system was formed whose resonant frequency was capable of continous vibration depending on the length of the backing liquid. A frequency range of one octave between 40 kHz and 80 kHz was reported which are the $\lambda/2$-resonant frequency and $\lambda/4$-resonant frequency of the ceramic.

To increase the tunable frequency range, further additional active piezoceramic layers are needed as in the following designs.

3. MULTILAYER TUNABLE TRANSDUCERS

Generally a multilayer tunable transducer consists of two parts which are mechanically coupled; the '<u>driving element</u>' which provides the acoustic power; and the '<u>controlling</u> element' which controls the response characteristics of the driving element. The control function is obtained either by applying a passive electric load across the control ceramic or by applying an electrical voltage with an appropriate amplitude and phase

<u>(a) Low-frequency Tunable transducers</u>

The first publications on tunable acoustic transducers were made independently in 1983, by Chenghao [6] and Kasatkin [7]. In Chenghao's designs, shown in fig. 1(i), piezoceramic bars, resonant in length mode, were tunable over a frequency range of 1.5 octaves when radiating into air. The drive ceramics which provided the acoustic power were sandwiched between the control ceramics which were passively loaded with either inductive or capacitive electric loads.

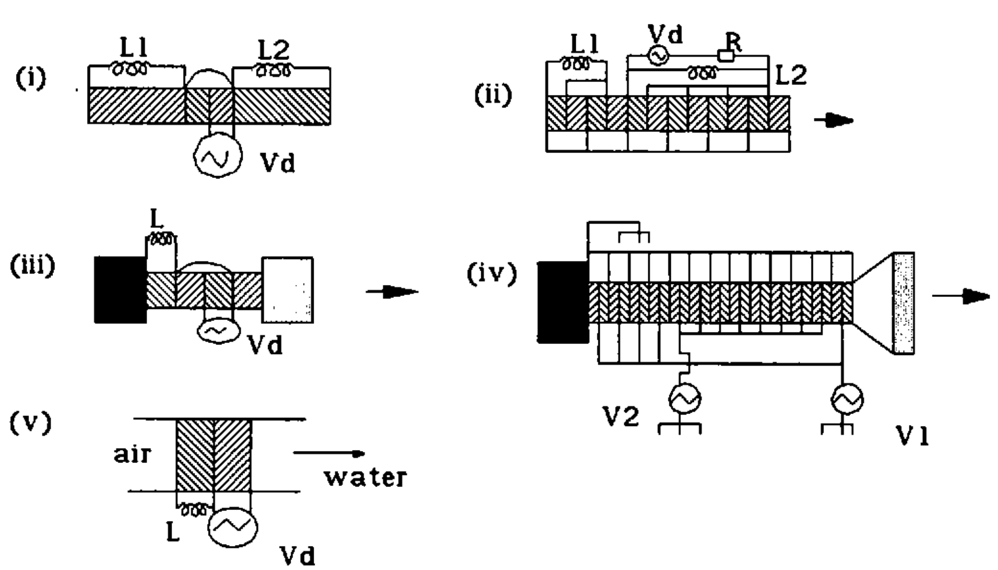

Fig. 1(i-iv) Low-frequency (v) High-frequency tunable transducer.

Kasatkin's tunable transducer is shown in fig. 1(ii). Effectively the transducer can be reduced to two bars connected mechanically in series with the driving bar in contact with the water. A resonant frequency variable over 1 octave, between 12 kHz and 23 kHz, could be obtained by passively terminating the electrical connection of the control bar with an inductance.

A sandwich transducer comprising a stack of piezoceramic rings sandwiched between a head and tail mass was reported by Jain and Smith [4], fig. 1(iii). The head is untapered to avoid flapping-head resonances. The transducer had a tunable frequency range between 25 to 75 kHz in water and employed passive inductive tuning on the tail-end control ceramic.

Lastly a switchable transducer was reported by Hamonic et. al [8] which is shown in fig. 1(iv). Rather than having resonances with high Q values, which can be shifted over a wide frequency range as in all the previously mentioned designs, it can be switched in three different bands of frequency. Voltage shading is applied to the control ceramic stacks which reinforces particular resonant modes. The three modes of operation are: the fundamental mode, the first overtone (the third harmonic) of the transducer and the flapping mode of the head mass. The fundamental mode is activated by standard excitation, which is obtained when the two voltage sources are equal in amplitude and phase ie: $\upsilon_1 = \upsilon_2$. The second mode is obtained when $\upsilon_1 = -\upsilon_2$, ie: both voltage sources are equal in amplitude but 180° out of phase and the third mode (the flapping head frequency) is reinforced with another appropriate ratio of amplitudes and phases.

The tunable ranges of the above methods of tuning are investigated [10] using a sandwich structure similar to that built by Jain [4] but with a slightly different ceramic dimensions, hence the difference in the fundamental and the third harmonic resonant frequencies.

The fundamental resonance at 30 kHz shown in fig. 2 is obtained by a conventional drive method. Its first overtone (third natural harmonic) is at 83 kHz. The resonance at 83 kHz is not prominent, but it was confirmed to be the third harmonic by driving as by Hamonic [8] such that the third harmonic is re-enforced and the fundamental is suppressed. The measured conductances obtained with these drive conditions are shown in fig. 3; the resonance around 83 kHz then becomes prominent. Finite-element analysis shows that the prominent resonance at around 109 kHz, in both figs. 2 and 3, and the spurious resonance at around 93 kHz are associated with flexural modes of the head and tail masses.

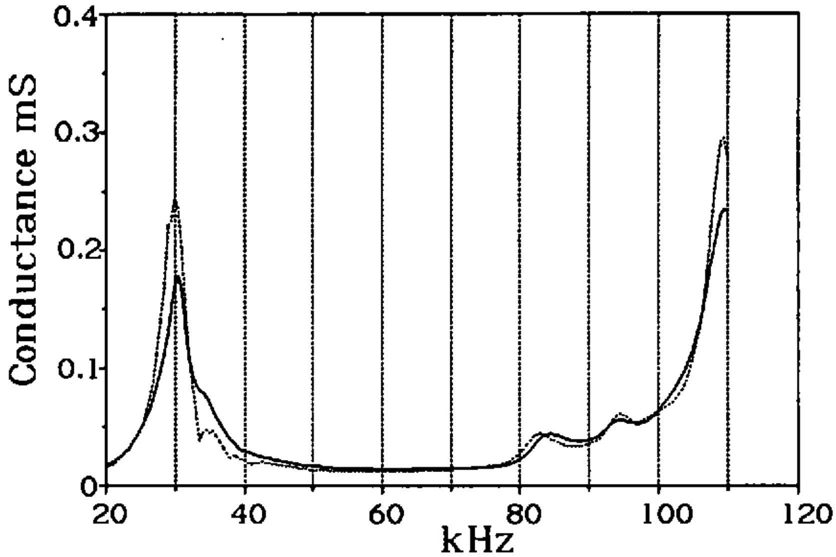

Fig. 2 Conductance in air and water of the fundamental harmonic at 30 kHz.

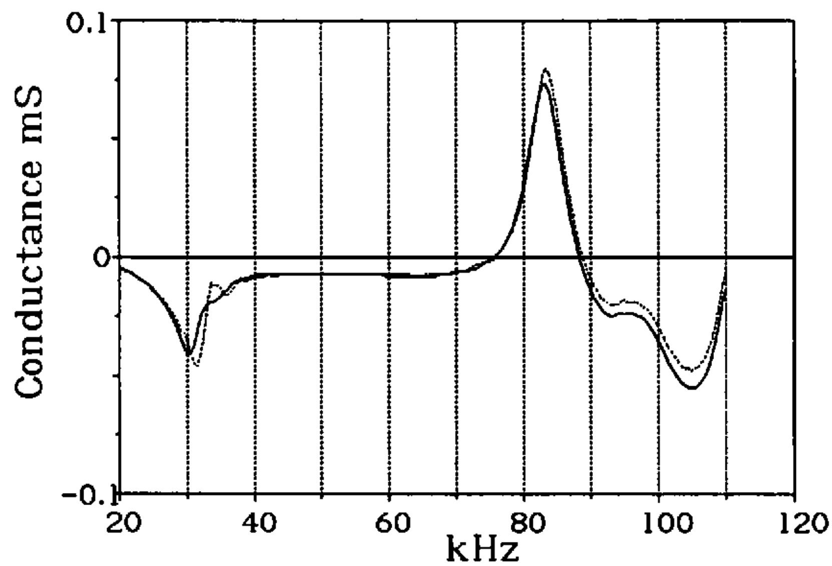

Fig. 3 Conductance in air and water of the third harmonic at 83 kHz.

The same structure can act as tunable transducers with various methods of tuning as reviewed above and these are shown in fig. 4. The fundamental and the third natural harmonics in figs. 2 and 3 respectively are obtained by short-circuiting the control ceramic. Resonances at other frequencies are obtained by loading the control ceramic with various values of inductances.

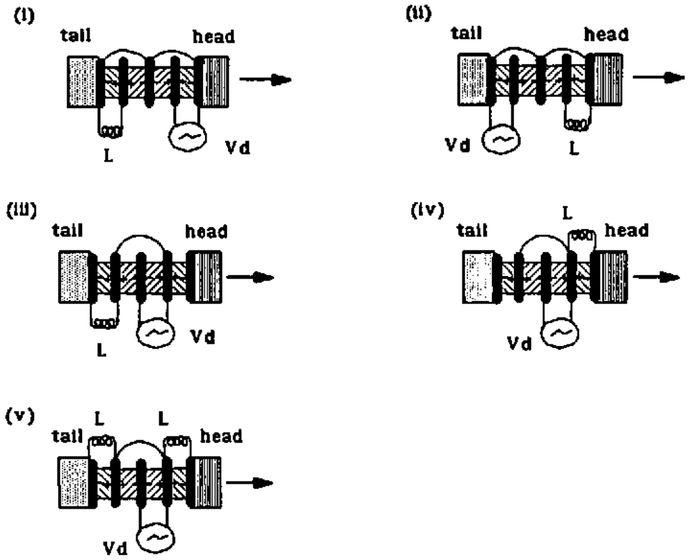

Fig. 4 Various methods of tuning.

From the conductance measurements the transducer with all those methods of tuning resonate continuously between the short-circuited resonant frequencies. Nevertheless from the radiation measurements resonances with the control ceramic at the front, in configurations (ii), (iv) and (v) are not radiating over the whole range. The tunable range with these configurations are not continuous between the first and the third natural harmonics because at some frequencies the contribution from the drive voltage source and the voltage developed across the control ceramic cancel each other.

In configurations (i) and (iii) the control stacks are at the back of the drive stacks and all the resonances from the conductance measurements are radiating. With these configurations the tunable range is continuous between the first and the third natural harmonics shown in figs. 5 and 6 with zero inductance. A tunable range of between 30 kHz and 83 kHz is shown by loading the control ceramic with an inductance with values between 0 to ∞. Initially with zero inductance two resonances are seen which correspond to the first and the third natural harmonics respectively. As the value of the inductance is increased the third natural harmonic shifts toward the first natural harmonic until the open-circuited resonant frequency is reached when the inductance value is ∞. By loading the control ceramic with a negative inductance i.e: a capacitance, the third harmonic can be shifted further towards the first natural harmonic. The operating frequency range can therefore be divided into two regions: the capacitive and the inductive tuning ranges. Since the capacitive range is very small only inductive loads were used in the experiment.

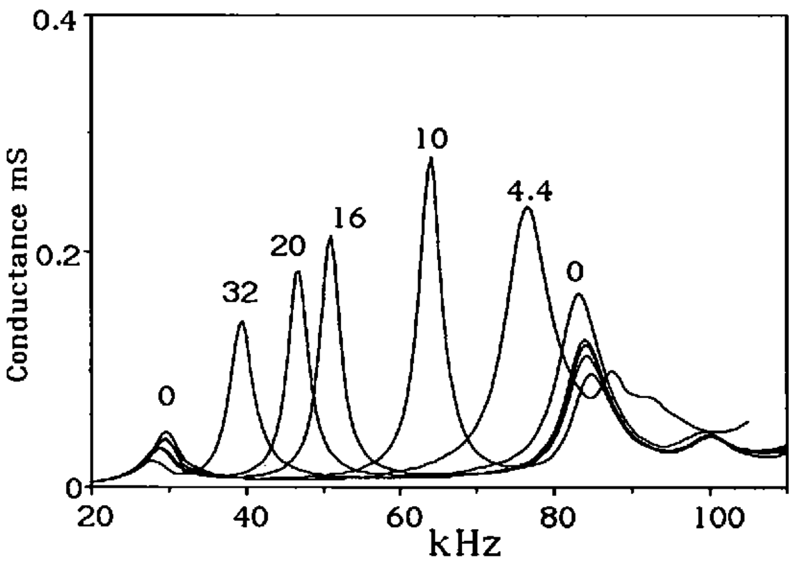

Fig. 5 The drive stack at the front for configuration in fig. 4(i). Tuning inductance values are in mH.

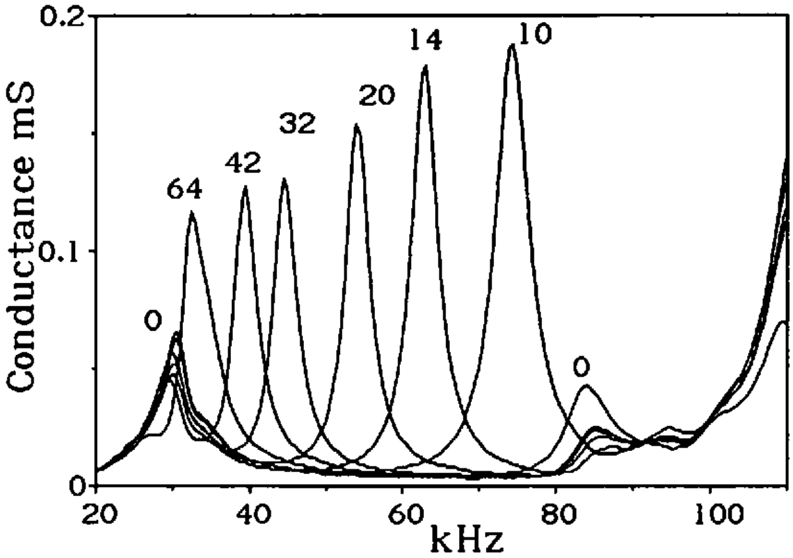

Fig. 6 The drive stack at the centre and the control stack at the tail-end for configuration in fig. 4(iii). Tuning inductance values are in mH.

There is no frequency shift of the first harmonic observed with various values of inductive and capacitive loads.

(b) High frequency tunable transducer

At frequencies higher than 100 kHz a thickness-mode tunable transducer is shown in fig. 1(v). Steel [1,2,3] used two identical ceramic discs, with the drive element in contact with the water load and backed by the control ceramic. The structure of a practical two-plate tunable transducer is represented by the diagram in fig. 7. The structure is more complicated than the simple ideal transducer depicted in fig. 1(v) in that there is a quarter-wavelength thick front layer, to provide matching at the second natural harmonic, and a rear layer to provide support.

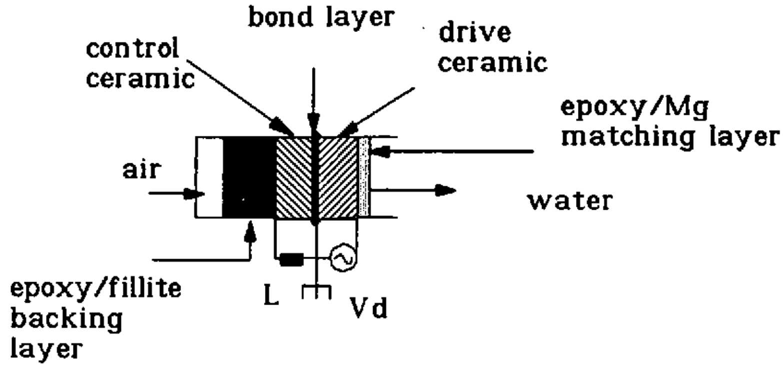

Fig. 7 The structure of a practical two-plate tunable tranducer [1].

The conductance measurements, fig. 8, show that a tunable frequency range of 1.7 octaves between 200 kHz and 760 kHz was achieved by loading with inductances ranging from 0 to 100 μH. These two limits are obtained by short-circuiting the control ceramic which represent the $\lambda/2$ and $3\lambda/2$-thick resonant frequencies of the whole structure.

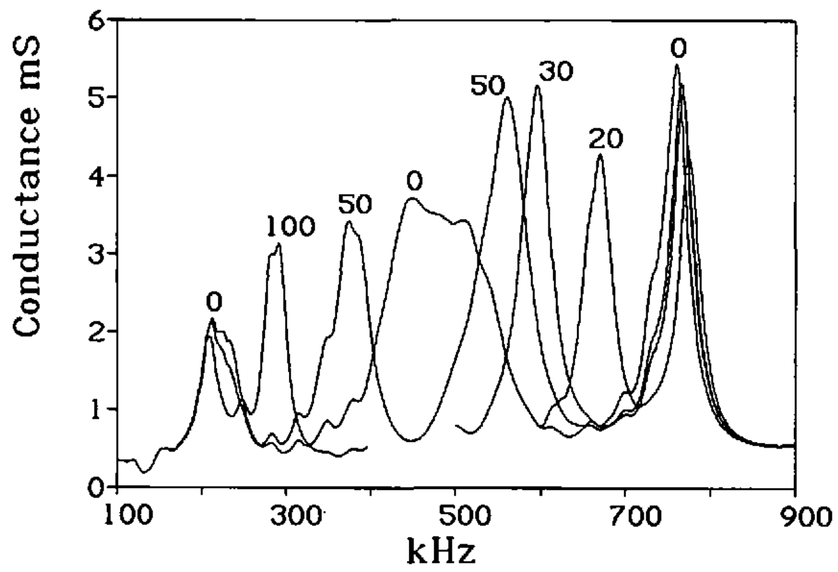

Fig. 8 A continous tunable range between the first and the third natural harmonics obtained by short-circuiting the control ceramic. Tuning inductance values are in μH.

In a similar manner to the sandwich design, the tunable range can be divided into two regions: the inductive and the capacitive ranges. Since the capacitive range is small only inductive loads were used in the experiment. All resonances were observed to be radiating.

Around the resonance of the drive plate the conductance frequency response is wider than would be obtained by a conventional water-loaded plate because of the $\lambda/4$ matching layer.

Conclusion

The fundamental tunable range is between the first natural harmonic and the third natural harmonic of the whole structure; these being defined with the control ceramic short-circuited.
For the high-frequency tunable transducer, the first and third natural harmonics are the $\lambda/2$ and $3\lambda/2$-thick resonant frequencies of the whole structure, which is a tunable range of 1.8 octave. If the two frequency limits are considered as the half-power points a wide-bandwidth transducer with an equivalent Q-factor of 0.64 was achieved.
The lower-frequency limit for a sandwich design has been identified as the fundamental mode and the upper frequency limit has been identified as the third harmonic [8] of the transducer. It has been shown that a tunable range of 1.5 octave can be obtained, irrespective of the excitation method provided the control ceramic is positioned at the tail-end of the stack.
A wide-bandwidth transducer with an equivalent Q-factor of 0.68 was achieved.

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