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# The Construction of a Piezoelectric Transducer for Sound Application in Liquid Steel

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**Abstract** This paper concerns structural assumptions for a piezoceramic head for sound amplification of liquid steel in industrial conditions. The head in question is to replace magnetostrictive heads used in laboratory conditions exclusively. Sound amplification is assumed to improve the internal structure of steel. The head consists of a three-layer transducer, a stepping concentrator with an exponential notch, and a wave-guide finished with a replaceable bit submerged in liquid steel. In order to optimally insulate the piezoceramics in the transducer, being sensitive to temperature, a new method of calculating the passive layers was required to be developed so that the radiant layer was the thickest one (on maintenance of the preset frequency of resonant vibrations). This paper contains a description of the method of selecting thicknesses of the individual transducer layers which were experimentally verified by constructing a head prototype and its application for sound amplification of steel ingots of 130 kg of mass.

**Keywords** High temperature · Piezoelectric head · Steel · Thermal conductivity · Ultrasound

## 1 Introduction

Tests of sound amplification of liquid steel [1–3] conducted so far have been based on the application of magnetostrictive transducers, the efficiency of which is ca. 80 %, which is lower than that of piezoceramic transducers operating in identical

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conditions (90 %) [4]. The magnetostrictive transducers are hardly available, whereas structures for sound amplification based on such heads must be very large. Furthermore, they are stationary structures and their wave-guide bits, when submerged in liquid steel, are destroyed [1]. Therefore, the studies [1–3] implying the positive influence of ultrasonic waves causing cavitation on the structure of steel were limited to laboratory examinations based on samples of a mass of several kilograms. These studies were assumed to determine the optimum frequency of vibrations and the intensity of the ultrasonic wave.

In order that, based on the results obtained, one could develop a technology capable of being used in industrial conditions, in which it is very difficult to maintain repeatability of all parameters and factors such as strong infrared radiation, dustiness, electronic smog, etc., that occur, it was necessary to build a power generator of small dimensions, mobile extension arms changing the head's position as well as small piezoceramic heads. These enable the use of ceramic disks with a very high Curie point (for ceramics, PZT $- T_C = 773$ K [5]) mechanically combined in stacks enabling a high surface density of energy to be obtained which is particularly important due to the limited surface of access to liquid steel in the ingot mold.

The fact of having prepared the radiant section of the three-layer transducer, i.e., the stepping concentrator with an exponential notch [1] and the cylindrical wave-guide of 0.7 m of length using a single roll of heat-resisting steel, enabled avoidance of the acoustic wave reflection on boundaries of the head's components.

After a few attempts, the mobile extension arm of the lift enabled selection of the optimum length of the ferrule to avoid its degradation during sound amplification lasting for several hundred seconds. The sound amplification time was limited by the time of the liquid steel solidification in the ingot mold.

The tests were conducted in liquid steel poured into an ingot mold. The mass of the steel was ca. 130 kg. The tests were preceded by determination of the temperature drift of the phase velocity $c_\varphi(T)$. The drift examined in the temperature range from 293 K to 1,173 K came to 6,000 $\text{m} \cdot \text{s}^{-1}$ to 5,115 $\text{m} \cdot \text{s}^{-1}$ [6], which enabled projection of the change of the resonance frequency during the sound amplification of liquid steel. Having analyzed the dependence of the $|Y|$ admittance module (in relative units) in liquid steel as a function of frequency $f$ enabled determination of the difference between the resonance frequency of the head's vibrations at room temperature (293 K) in water and the resonance frequency in liquid steel. The difference in question for the basic mode was 900 Hz (Fig. 1).

## 2 Design

In order to build an optimum three-layer transducer, being the most important component of the sound amplification head for liquid steel, due to the aforementioned reasons, it was required that the traditional method of selecting the thickness of the $l_b$ ballast layer on the known thickness of four PZT-46 ceramic disks (relative permeability of $\varepsilon_r = 120$, $c_c = 5,500\,\text{m} \cdot \text{s}^{-1}$, $\rho_c = 6.7 \times 10^3\,\text{kg} \cdot \text{m}^{-3}$ [5]) was to be abandoned (Fig. 2). This method is based on the assumption that the thickness of the radiant part is $l_r = \lambda_r/4(\lambda_r = c_r/f$, where $c_r$ is the phase velocity of the sound wave

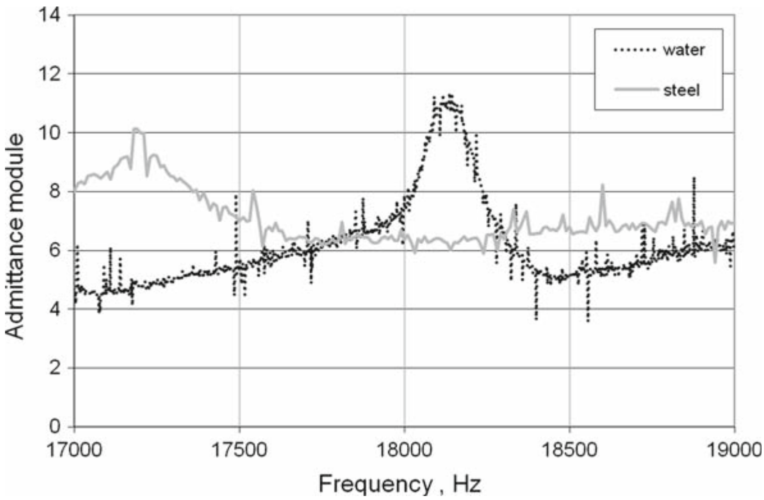



**Fig. 1** Admittance module $|Y|$ (in relative units) in water and in liquid steel as a function of frequency $f$

in the radiant part, in $\mathrm{m} \cdot \mathrm{s}^{-1}$) and the material the radiant part is made of should be characterized by as low acoustic impedance as possible (e.g., duralumin), whereas the rear-part material—by as high acoustic impedance as possible (e.g., steel), and the thickness of the ceramic components should be considerably smaller than that of the passive components. The dependence between $l_\mathrm{b}$ and $l_\mathrm{c}$, referred to as the Langevin formula [7], is as follows:

$$tg\,(k_\mathrm{b} l_\mathrm{b}) \cdot tg\,(k_\mathrm{c} l_\mathrm{c}) = z_\mathrm{bc} \tag{1}$$

where

$$z_\mathrm{bc} = \frac{\rho_\mathrm{b} c_\mathrm{b}}{\rho_\mathrm{c} c_\mathrm{c}}; \tag{2}$$

$$k_\mathrm{b} = \frac{2\pi f}{c_\mathrm{b}} \cdot l_\mathrm{b}; \tag{3}$$

$$k_\mathrm{c} = \frac{2\pi f}{c_\mathrm{c}} \cdot l_\mathrm{c}; \tag{4}$$

$k_\mathrm{b}$ and $k_\mathrm{c}$ are wave numbers for the individual transducer layers, $z_\mathrm{bc}$ is the relative impedance, $\rho_\mathrm{b}$ and $\rho_\mathrm{c}$ are the material densities of the individual layers, $c_\mathrm{b}$ and $c_\mathrm{c}$ are the phase velocities of the sound wave in the layers, and $f$ is the resonance frequency.

The classical design of the transducer was to be replaced by a model based on the generalized Langevin formula [7] which, in the confounded form, links the thicknesses of the individual three layers:

$$tg\,(k_\mathrm{c} l_\mathrm{c}) - z_\mathrm{bc} \cdot z_\mathrm{rc} \cdot tg\,(k_\mathrm{b} l_\mathrm{b}) \cdot tg\,(k_\mathrm{c} l_\mathrm{c}) + z_\mathrm{bc} \cdot tg\,(k_\mathrm{b} l_\mathrm{b}) + z_\mathrm{rc} \cdot tg\,(k_\mathrm{r} l_\mathrm{r}) = 0 \tag{5}$$

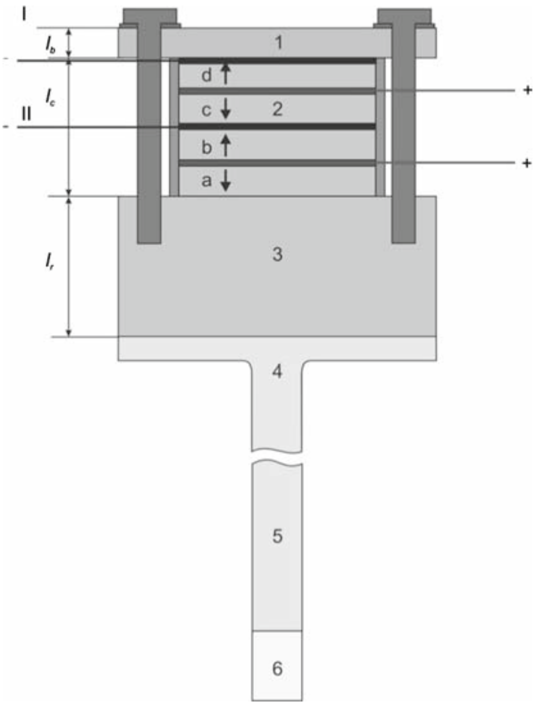



**Fig. 2** Longitudinal section of the piezoelectric head designed for liquid steel sonication: *1* back passive part, *2* piezoceramics, *3* passive radiating part, *4* stepping concentrator with an exponential notch, *5* cylindrical wave-guide, *6* ferrule

where

$$z_{\mathrm{rc}} = \frac{\rho_{\mathrm{r}} c_{\mathrm{r}}}{\rho_{\mathrm{c}} c_{\mathrm{c}}} \tag{6}$$

and

$$k_{\mathrm{r}} = \frac{2\pi f}{c_{\mathrm{r}}} \cdot l_{\mathrm{r}} \tag{7}$$

In order to simplify this relation, two new variables were introduced:

$$x_{\mathrm{r}} = z_{\mathrm{rc}} \cdot tg\,(k_{\mathrm{r}} l_{\mathrm{r}}) \tag{8}$$

indirectly representing the thickness of the radiant section $l_{\mathrm{r}}$,

$$y_{\mathrm{b}} = z_{\mathrm{bc}} \cdot tg\,(k_{\mathrm{b}} l_{\mathrm{b}}) \tag{9}$$

related to the thickness of the rear part $l_{\mathrm{b}}$ and the $\alpha(f) = \alpha$ parameter,

$$\alpha = (tg\,(k_{\mathrm{c}} l_{\mathrm{c}}))^{-1} \tag{10}$$

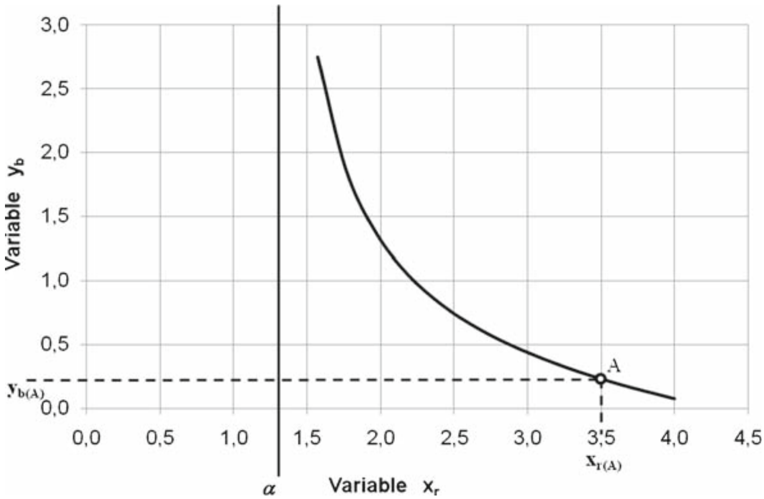
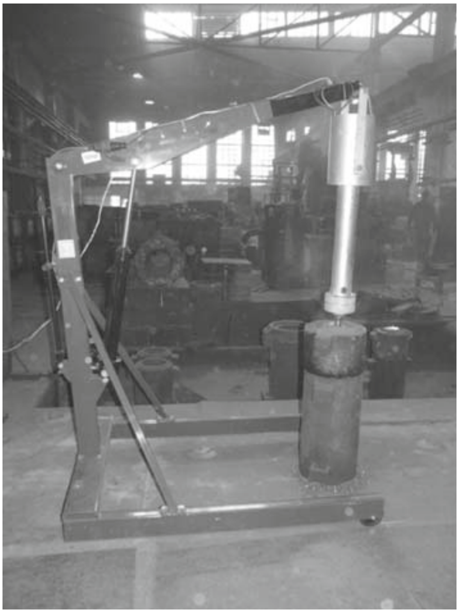



**Fig. 3** Relationship between the variables $x_\mathrm{r}$ and $y_\mathrm{b}$ characterizing the thickness of the passive parts for the variable parameter $\alpha$ characterizing the piezoceramic layer

**Fig. 4** View of encased piezoelectric head at the testing station



depending on the type of the ceramics used and the number and thickness of the piezoceramic disks. It enabled obtaining the $y_\mathrm{b} = f(x_\mathrm{r})$ function in a simplified form,

$$y_\mathrm{b} - \alpha = \frac{\alpha^2 + 1}{x_\mathrm{r} - \alpha} \tag{11}$$

The above relation is a first-degree hyperbola shifted by the $\alpha$ parameter against the $x_r$, $y_b$ co-ordinate system.

It was assumed that the transducer's resonance frequency is $f = 20\,\text{kHz}$, and both passive layers are made of heat-resisting steel ($c_r = c_b = 5,950\,\text{m} \cdot \text{s}^{-1}$ at 293 K), whereas the overall thickness of the piezoceramic stack composed of four disks is $l_c = 0.036\,\text{m}$. For the above data, the graph of Eq. 11 has been provided in Fig. 3.

The transducer of such a design including the concentrator, the wave-guide, and the ferrule was used in ten tests of sound amplification of liquid steel. The layout of the test stand used has been provided in Fig. 4.

## 3 Conclusions

1. It is possible to use a piezoceramic head designed in accordance with the principles discussed in the paper for sound amplification of liquid steel.
2. The head's temperature measurements conducted during the tests imply that it is possible to perform further modernization of the head by decreasing the length of the waveguide and replacing the heat-resisting steel in the radiant part with duralumin of smaller absorption coefficient.
3. Due to the decrease of the cavitation threshold occurring on sound amplification with a simultaneous decrease of the head's resonance frequency, this frequency is to be maintained within the range from 10 kHz to 20 kHz.

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