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The Influence of Alarm Siren Structure Parameters on Output Sound Pressure Level

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The paper is a discussion of the construction of an alarm siren based on the active piezoelectric element. The influence of various parameters on the loudness of the siren was investigated. Efforts to increase the efficiency of selected design were made. The simulations carried out based on an ANSYS. Individual dimensions of a piezoelectric transducer were selected as well as a collaborate diaphragm. The possibility of using different piezoelectric materials was also analyzed. All tasks and computer simulations were aimed at receiving a siren structure able to obtain the highest sound pressure level at selected frequency.

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1. Introduction

The basic functions of the alarm sirens are warning and information. A siren signal usually means unfavorable phenomena such as theft, burglary, fire or state of emergency. A very desirable feature of an alarm siren is its ability to produce a very loud noise, audible even at large distances from the source [1]. A siren with an active element as a piezoelectric transducer, is appropriate for this role [2–4]. In several aspects the sirens, using the phenomenon of piezoelectricity, are unbeaten against their dynamic and mechanical counterparts. The criteria used are: the low weight and dimensions of the siren and power efficiency [2, 3]. Therefore, the rest of this article takes into consideration this type of signaling and alarm devices. The starting points of this study are the numerical analyses which use field emission microscopy (FEM) to investigate the acoustic field [5–8]. The final phase, in turn, constitutes an attempt to optimize the parameters and shape of the model [7, 8].

2. Description

The aim of this study was to analyze the influence of specific parameters of the acoustic siren transducer on the distribution of sound pressure level in space. The article describes the numerical calculations carried out in the ANSYS program, aimed at increasing the efficiency of the alarm siren.

The study involved a siren component corresponding to the excitation of sound waves, that is a piezoelectric acoustic transducer. A drawing of the transducer and the way it has been fixed is shown in Fig. 1. FEM model without the surrounding transducer air is shown in Fig. 2a, and with views of the surrounding air (Fig. 2b).

This is not the only part corresponding to the output sound pressure level of the siren. This level represents the sum of operation of several components of the device, including an electronic circuit of a generator and its housing, which also acts as a sound reinforcement horn. However, the previously mentioned acoustic transducer is the most important part of the device and the starting point for deliberations on the optimization of the structure of the piezoelectric siren. The subject of optimization is the sound pressure level measured at a distance of one meter from the unit. This is the most important siren parameter given by each manufacturer.

For the analysis of the physical phenomena occurring in the tested model, the finite element method was used, and the calculations were performed in ANSYS. Numerical solution of the problem consists of the discretization of the structure, calculating the generalized coordinates in mesh nodes, solving equations, and then using the shape function to calculate selected values inside ele-

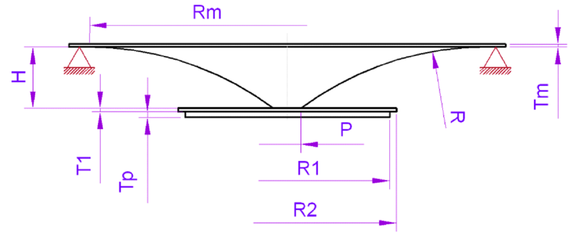

Fig. 1. Driver unit siren — the parameters considered.

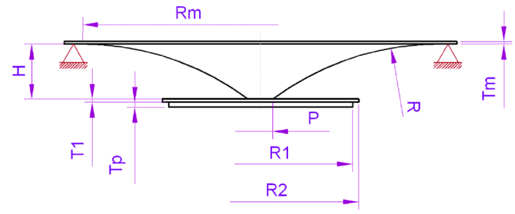

Fig. 2. (a) FEM model of a piezoelectric acoustic transducer, (b) transducer with surrounding air.

ments. In the case of interaction of structural and acoustic fields we obtain a system of Eqs. (1) consisting of the wave equation and the dynamic equation for the structural element [9].

$$\begin{bmatrix} [M_e] & [0] & [0] \\ [M^{fs}] & [M_e^p] & [0] \\ [0] & [0] & [0] \end{bmatrix} \begin{Bmatrix} \{\ddot{w}_e\} \\ \{\ddot{p}_e\} \\ \{\ddot{V}\} \end{Bmatrix} + \begin{bmatrix} [C_e] & [0] & [0] \\ [0] & [C_e^p] & [0] \\ [0] & [0] & [0] \end{bmatrix} \begin{Bmatrix} \{\dot{w}_e\} \\ \{\dot{p}_e\} \\ \{\dot{V}\} \end{Bmatrix} + \begin{bmatrix} [K_e] & [K^{fs}] & [K^z] \\ [0] & [K_e^p] & [0] \\ [K^z]^{\mathrm{T}} & [0] & [K^d] \end{bmatrix} \begin{Bmatrix} \{w_e\} \\ \{p_e\} \\ \{V\} \end{Bmatrix} = \begin{Bmatrix} \{F_e\} \\ \{0\} \\ \{L\} \end{Bmatrix}, \tag{1}$$

where $[M_e^p]$, $[M_e]$ — liquid and structural mass matrix, $[K_e^p]$, $[K_e]$ — liquid and structural stiffness matrix, $[C_e^p]$, $[C_e]$ — liquid and structural damping matrix, $[M^{fs}] = \rho_0[R_e]$ — coupling mass matrix, ρ_0 — mean liquid density, $[K^{fs}] = -[R_e]$, $[K^d]$ — dielectric conductivity matrix, $[K^Z]$ — piezoelectric coupling matrix, $[F_e]$ — applied load vector, $\{L\}$ — electrical load vector (nodal, surface, and body charge), $\{u_e\}$ — nodal displacement component vectors, $\{p_e\}$ — nodal pressure vectors, V — vector of nodal electrical potential.

The ANSYS model was built using several different types of finite elements: Solid 45 for the diaphragm and a brass plate, Solid 5 for the introduction of ceramic piezoelectric material properties and Fluid 30 to simulate air against the diaphragm. Also used, was the fluid–structure interaction module to trigger an effect by the moving diaphragm on the surrounding air. Since the structure is symmetrical, only half of the model was built. This reduced the number of finite elements used to build the model and shortened the time needed for calculations.

In order to increase the sound pressure level, a closer examination was carried out to see how individual parameters of an acoustic transducer impact the obtained value. Piezoelectric transducer used in acoustic alarm sirens consists of a piezoelectric transducer bonded to the diaphragm. The diaphragm is made of plastic (usually mylar) or aluminum and generates an acoustic wave using piezo transducer vibration motion. Piezo transducer, in turn, consists of a thin, piezoelectric ceramic disc and two claddings. Usually one of the claddings is made of brass plate which protects the fragile ceramics from mechanical damage. On the opposite side of the ceramics a thin layer of metal is sprayed to act as the second cladding. Acoustic transducer parameters taken into account during the simulations are shown in Fig. 1.

The parameters in Fig. 1: R_{m} — diaphragm diameter, H — height of the diaphragm, T_{m} — diaphragm thickness, R — radius of the transition of the diaphragm, P — the radius of fixing, T_1 — thickness of the protective plate, T_{p} — thickness of the piezoelectric plate, R_1 — radius of the piezo plate, R_2 — radius of the guard plate.

A characteristic feature of piezoelectric transducers (Fig. 3) is that they operate efficiently while working near its resonant frequency. This is not a big disadvantage in the case of the sirens because the bandwidth for these devices is relatively narrow and is usually in the range from 2 to 4 kHz. This is due to the high sensitivity of the human ear that picks up these frequencies [1, 10, 11].

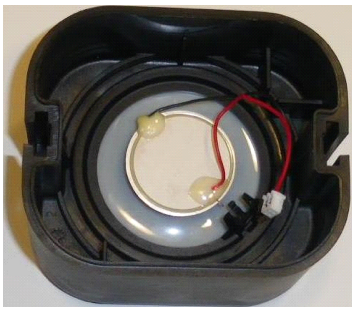

Fig. 3. Transducer mounted in the housing.

TABLE I

Parameter values and ranges in which their change was examined.

Parameter	Initial value	Lower range of changes	Upper range of changes
U	60	30	90
piezoceramic material	PZT4	–	–
R_{m}	29	15	38
H	9	4	20
T_{m}	0.3	0.1	0.5
R	45	30	100
P	0.8	0.5	3.5
T_1	0.1	0.1	0.3
T_{p}	0.33	0.1	0.4
R_1	15	5	18
R_2	16	10	25

For this reason, most sirens have their own resonant frequency at about 3 kHz, as the siren sound is modulated and changes near this value. Therefore, simulation studies were carried out for a particular frequency. On the basis of Robinson and Dadson equal loudness chart, optimal frequency was set at 3.6 kHz [11]. The study should begin by assuming starting values of model parameters, later, these values will be changed to get the best effect, that is a louder siren. The initial parameter values had been inspired by the alarm siren used in Delphi security systems (Table I).

3. The results of numerical calculations

3.1. Material

The study started from selecting the most suitable material for the piezoelectric ceramics. For this purpose eleven types of ceramics were compared. As might have been expected, the best results were obtained for ceramics with the highest piezoelectric d_{33} module. Ceramics PZ21 and PZT5H increased the sound pressure level by 5 dB (C) compared to PZT4 with no intervention in the geometry model. Results for the compared ceramics are given in Table II and Fig. 4.

Analyzing Fig. 4, the effect of proper ceramics selection on obtained sound pressure level is clearly visible. The difference in sound pressure level between ceramics with extremely different properties reached 28 dB (C). Therefore, it is one of the most important parameters. Selecting this parameter ought to be the start to acoustic transducer design.

TABLE II

Sound pressure level for given structural parameters.

Parameter	Initial value	Lower range of changes	Upper range changes	Maximum SPL at the least favorable parameter values in the range (1)	Maximum SPL at the most favorable parameter values in the range (2)	The difference between (2) and (1)
U	60	30	90	87.11	96.65	9.54
piezoceramic material	PZT4	PZ46	PZ21	70.05	98.20	28.15
R_{m}	29	15	38	41.4	99.8	58.4
H	9	4	20	67.27	101.6	34.33
T_{m}	0.3	0.1	0.5	65.74	100	34.26
R	45	30	100	74	107	33
P	0.8	0.5	3.5	87.74	93.79	6.05
T_1	0.1	0.1	0.3	78.30	93.14	14.84
T_{p}	0.33	0.1	0.4	82.68	95.91	13.23
R_1	15	5	18	78.66	93.23	14.57
R_2	16	10	25	90.9	93.20	2.3

3.2. Voltage amplitude

The next parameter, which is not directly related to the geometry of the model but also affects the acquisition of satisfactory results, is the voltage amplitude. The mentioned amplitude marked further as U, is the voltage applied to the electrical conductor of the piezoelectric transducer. In various structures U between 30 to 100 V_{pp} was used. For industrial applications the voltage is closer to the lower value of this range [12]. As it turned out, it has less impact than the previously discussed parameter. The increase in voltage from 60 to 90 V causes an increase by 3 dB SPL, but one must remember that the increase in amplitude also results in increased power consumption by a siren. Voltage reduction from 60 to 30 V results in loss of sound pressure level by 6 dB. Seeking the highest possible sound pressure cannot afford such a loss.

In Fig. 5, we observe the trend of parameter optimization, depending on supply of voltage. For easier interpretation, the affixed above plot line are values of maximum sound pressure levels on the extreme points of the graph. This procedure will be repeated in subsequent graphs in the article. It should also be explained what is the optimization parameter appearing in the following charts. The numerical value of optimization parameter is not important for the interpretation of graphs. The main component of the parameter is the arithmetic sum of the

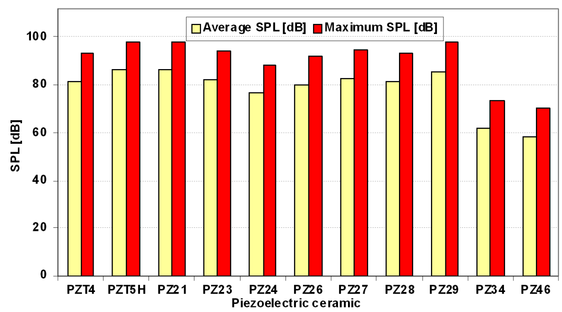

Fig. 4. Influence of the selected ceramics on the sound pressure level.

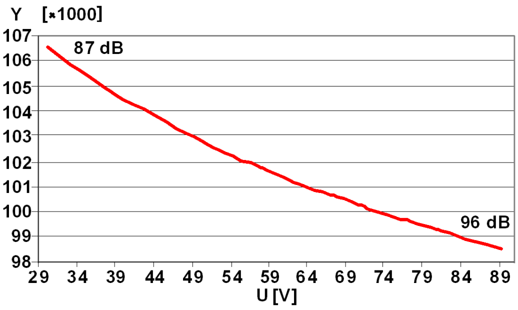

Fig. 5. Effect of voltage amplitude on the change of optimization parameter.

value of sound pressure levels in the nodes which are one meter away from the surface with the sound source. This parameter was additionally transformed in such a way so that its lowest value would point to the best result from the perspective of optimization

$$Y = X - \sum_{i=1}^{n} L_{Ci}. \tag{2}$$

In formula (2) Y is the goal function, L_C is sound level C, n is number of certain levels sound and X is constant dependent on the FEM mesh density but always greater than the sum of the levels of SPL.

Taken into account was the sum of many nodes,instead of only the nodes near the main axis of the siren. This was done to avoid a situation in which optimization would result in a very loud model but with strong directional properties. As previously mentioned, the numerical value of this parameter is only an auxiliary value defined in the program for optimization and does not contain valuable information for the reader.

3.3 Parameters associated with the geometry

Further calculations examined the influence of parameters associated with the geometry of the model. In the initial phase, only their influence has been examined, ignoring the interactions between them. Assuming lack of dependence between the effects of these parameters would obviously be wrong.

The starting step is examining the impact of brass plate thickness; the plate is one of piezoelectric transducer covers. The results showed a regularity: the thinner protective plate is, the higher sound pressure level received. The $T_1 = 0.1$ mm — assumed at the beginning — turned out to be the best value. Increasing thickness causes quite a significant decrease in SPL, in turn further thickness reduction is dangerous from the viewpoint of the fatigued strength of the bent plate.

The impact of piezoelectric plate thickness, T_{P}, was also examined. Simulations can easily help to deduce that an increase in thickness increases the sound pressure level. Numerical calculations were carried out to a maximum thickness of 0.4 mm T_{P}, thicker piezoelectric layers are not found in commercially available transducers. The initial value of the parameter amounted to 0.3 mm and the increase in SPL value after the change of T_{P} to 0.4 mm was 3 dB, while at the parameter value of 0.1 mm, there was a decline of 10 dB in SPL.

In order to examine all the geometrical parameters related to the piezo transducer the impact of diameters of both the plate brass and the piezoceramic disk were investigated. It has been proven that the optimal dimensions are with both diameters being similar to each other. However, given the protective function of the plate, the value of radius R_2 should be 1 mm larger than the ceramics radius R_1. Based on the results acquired from the graph it was concluded that the minimum value of R_1 which enables to obtain satisfactory results is $R_1 = 13$ mm. Anywhere below this value, we get a very rapid decline in SPL, increasing this value slightly increases this level. However, taking into account the restrictions of the overall dimensions of the piezo siren, the best value of $R_1 = 22$ mm and $R_2 = 23$ mm.

The parameter related to both the converter and the diaphragm was a fixing radius P. Fixing radius is radius at which the diaphragm is fixed to the transducer with an adhesive layer. Decreasing the value of this parameter causes a decrease of SPL. The assumed initial value of $P = 0.8$ mm was considered as sufficient. Further reduction of this value results in an increased probability of failure, i.e. converter detachment due to inertial forces, and the SPL gain of 1 dB for $P = 0.5$ is not satisfactory.

Factors associated with the diaphragm have greatest impact on the resulting levels. Factors such as the diaphragm radius R_{m}, the diaphragm height H and the transition radius R (indicated parameters — see Fig. 1) have a decisive influence on the sound pressure level achieved in the simulation. These parameters are strictly interrelated and have a significant impact on each other. But because of previously approved line of proceedings, they are considered individually, in order to find the one with the greatest impact on the system. The model built in ANSYS program was created in such a way that the parameters interact with each other, for example, a change in the radius R_{m} or the diaphragm height H changes the position of the transition radius R and the shape of the diaphragm.

The height of the diaphragm has a significant influence on the sound pressure level achieved. Based on the simulations it can be concluded that with the height increase of the diaphragm H, the SPL generated by the system decreased. On the other hand, a decrease in the value of H increased the level (see Fig. 6). However, these changes were to some extent due to the way the geometric model was constructed. A change in diaphragm height changed the angle of the created diaphragm line when in conjunction with the piezo transducer.

The transition radius R also shows a similar relationship. When the value of the radius decreases, which at an unchanged value of the height, causes a "sharpening" effect of the diaphragm section cooperating with the transducer, the value of SPL increases (see Fig. 7). The great-

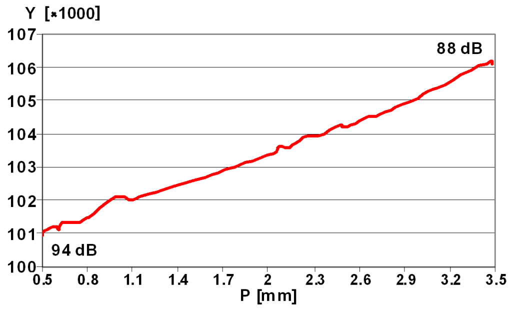

Fig. 6. Influence of fixing radius P on SPL.

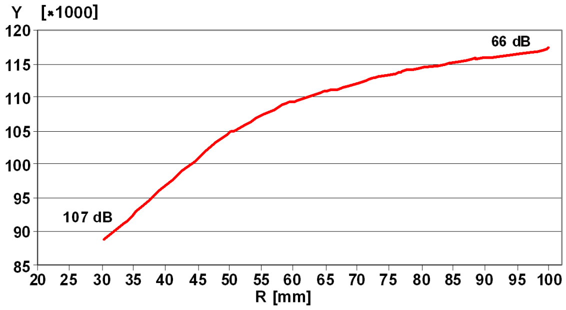

Fig. 7. Impact of the transition radius R on SPL.

est improvement in the acoustic properties of the transducer, in relation to the initial model, were achieved by changing this parameter. The increase in SPL amounted to as much as 14 dB. Increasing the radius R brings the opposite effect. The shape of diaphragm, with an increase of this value, becomes similar to a cone, and the SPL falls.

The impact of the radius R_{m} on the sound pressure level should also be taken into account. The acoustic transducer shows a dependence: the larger the diaphragm diameter, the greater the sound pressure level possible to achieve. The diaphragm shape, which changes with modifications to the diameter and a constant value of transition radius R, also has an effect.

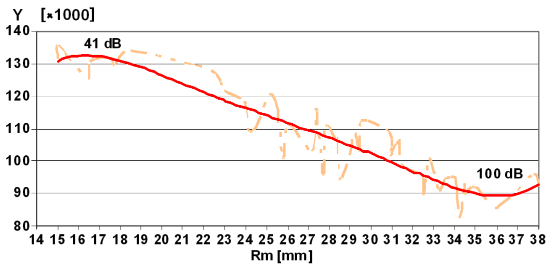

Fig. 8. Effect of the radius R_{m} on the level of SPL.

The solid line in Fig. 8, indicates the trend line. This was done to better identify the change in the parameter which is subject to optimization, also dependent on the tested radius R_{m}. A large value of the radius is not possible due to an increase in siren's outer dimensions.

By analyzing the parameters associated with the geometry of the diaphragm it can be concluded that they are closely interrelated. It is not enough to analyze individual parameters during the optimization process, but the influence of individual parameters on one another should also be taken into account. Slanting line of the diaphragm according to the radius is not optimal. A better solution would be the expansion of the diaphragm in an exponential manner [13]. The parameters H, R_{m}, and R have the greatest impact on the obtained output sound pressure level.

4. Analysis of results

All studied parameters and their influences are listed in Table II. the last column displays the difference between the maximum SPL values when compared using the least and most favorable parameter values in range (Fig. 9).

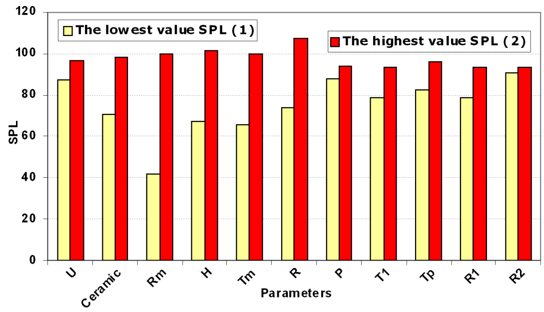

Fig. 9. Results on a graph.

The article presents the results of preliminary model studies made on the basis of computer simulations in ANSYS. Results expressed as minimal and maximal values of sound pressure level for given structural parameters are presented in Table II and Fig. 9 displays the data from this Table in a bar chart.

5. Conclusions

Based on the obtained results and analysis the following conclusions can be drawn:

- The suitability of use of piezoceramic in the construction of the siren is determined by the piezoelectric strain coefficient d33, the higher the coefficient, the greater the sound pressure level which can be achieved.
- Brass plate and piezo plates diameter dimensions should be quite similar, and the thickness of the ceramic should be several times higher than the thickness of the plate.
- Diameter of the piezoelectric transducer should be large. In the analyzed model it should be about

40 mm. An additional increase above this dimension, results in a very small increase in sound pressure.

- Diameter of the diaphragm should be in the range of 50 to 75 mm, depending on the intended siren dimensions.
- The diaphragm should have a more complex shape than in the analyzed model.
- The highest sound pressure level obtained for the model was 111 dB (average level at a distance of meter — 101 dB) and was about 18 dB higher than the initial state.

Based on the conclusions of the article and Table II, there is the possibility of increasing the value of SPL by a few dB for the structural solutions currently used sirens. These results provide the basis and foundation for a further and more thorough analysis of the model. The results obtained can be used in experiments investigating the influence of several parameters simultaneously. The computational model also requires experimental verification. The experiment should confirm the conclusions stated above, deliver additional knowledge about the model and be useful for a possible correction of the computational model.

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