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Numerical analyses of a 2-part piezoelement sensor-actuator in vibration reduction

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ABSTRACT

This paper deals with numerical analyses of the usefulness of a 2-part piezo element sensor-actuator on the reduction of plate's vibration and the sound pressure generated by said plate. For that purpose numerical models of a square steel plate were created. The plate is 400 mm x 400 mm x 2 mm and is clamped on all sides. 2 piezo actuators are attached to it. One is a standard homogeneous piezo actuator placed near the centre and is used to excite the plate. The other one can be either a homogenous piezo actuator, or a 2-part element with the outer part used as an actuator and the inner part as a sensor. It's placed on the diagonal (near 1/4 of its length) and is used to reduce plate's vibration and sound pressure radiated by it. On one side the plate connected to a half sphere of air acting as a sound surroundings. Analyses were made for 4 chosen mode shapes. Results include the differences between vibration and sound pressure reduction obtained using standard piezo actuator and a sensor-actuator, how well the sensor part of the proposed element is acting compared to a local and global vibration readout from nodes as simulation of contactless sensors.

Keywords: ANC, AVC, FEM
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

The concept of active vibration reduction was introduced at the end of XIX century. Sometime later - around the 1930s a concepts for active noise reduction were formulated. One of the first work dealing with the problem of reduction of structural sounds transmitted to acoustic surrounding was the article of C.R. Fuller and J.D. Jones published in 1987 [1]. Authors used a single electrodynamic actuator and were able to reduce the acoustics pressure levels emitted by an external monopole source inside a cylindrical shell by about 10-20 dB. Developments in material engineering, increase in technological potential, computing power allowed carrying advanced

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computer simulations [2] as well as to control processes leading to vibration and noise reduction.

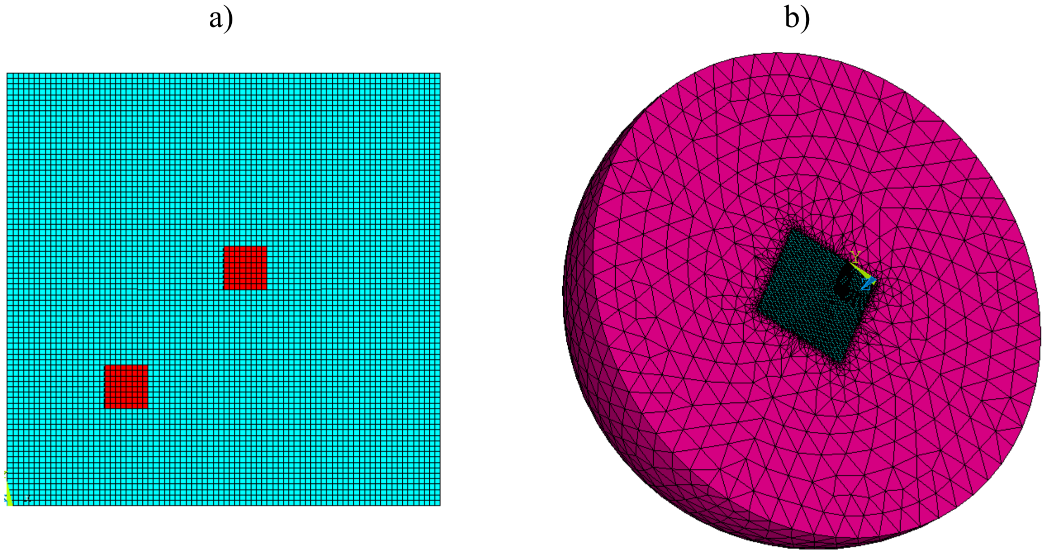
Of course analytical approach is also a subject of continuous development. New theories and mathematical models are widely used for problems of objects vibrations [3] and sound radiation [4].

In their previous works authors concentrated on piezo actuators with a step change in materials properties. The idea behind them was that perhaps they could serve a simpler replacements for functionally graded actuators. The idea was first introduced with fairly simple models [5]. After some refining improved models and some analytical analyses were presented [6]. Another improvement was introducing the acoustic surrounding of analysed plate [7]. These works generally concluded that introduced change in material properties of piezo actuators didn't produce any substantial change in the levels of reduction of plates vibration. Another work presented the attempts to verify numerical results with physical experiment [8]. Unfortunately small number of samples (they had to be custom made) and the differences between said samples made the results unsatisfactory.

But from this another idea was born. If the changes to the inner part of a piezo element have a negligible influence on its effectiveness in obtained reduction levels perhaps it could be used as a sensor. The numerical results of said idea are presented in this work

2. NUMERICAL MODELS

To test the feasibility of an idea of piezo sensor-actuator numerical models were created using ANSYS software. The models consisted of a steel plate (400 x 400 x 2 mm) clamped on all sides with 2 attached piezo elements and volume of air contained by a half sphere (fig. 1).


a)

b)

Fig. 1. a) plate with piezo elements; b) plate with the surrounding air

Both piezo elements have their base in the form of a square with a side having 20 mm of length, both have thickness of 1 mm and both are simulated using the material properties of a PZ 28. One of them is used to excite the plates vibration (the one near the middle of the plate), the other one is used either fully as an actuator or as an sensor-actuator. To use it as an sensor-actuator the element was divided into the outer and inner part (fig. 2).

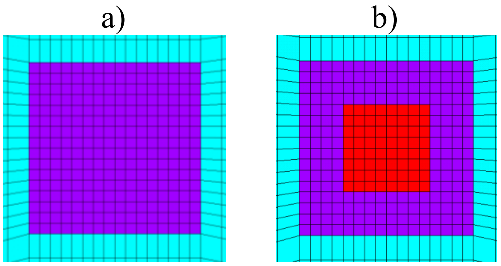


Figure 2 Modelled piezo element: a) homogeneous; b) 2-part

The outer part has the length of its base sides is half of that what was for the outer part (10 mm). Or in terms of area size of the base - its 1/4 of the outer part base area. When used fully as an actuator the element is treated as a homogeneous one (there is no distinction to the outer and inner parts). When used as sensor-actuator the inner part is "switched off" (as in these models the vibration will be taken directly from the nodes as a displacement).

The radius of the half sphere containing simulated air is 1 m.

The elements and material properties used in the models can be found in Table 1.

Table 1. Models parameters

Structural element	**Element used for modeling**	**Properties**
Plate	SOLSH190	$E = 1.93*10^{11}$ Pa, $\nu = 0.29$, $\rho = 7800$ kg/m^3
Piezo elements	SOLID226	Properties of PZ 28
Air	FLUID30	$\rho = 1.2$ kg/m^3 c = 343 m/s

Based on previous works the following modes were chosen for harmonic analyses: 1st, 2nd, 4th and 5th. For illustration and comparison purposes figure 3 shows the displacement vector sums of excited plate for each analyzed mode. Similar figure 4 shows the acoustical pressure levels emitted by excited plate for each of the analyzed modes. As scales are included these can easily be used as a reference for the images with reduced values that will be shown in the results part later.

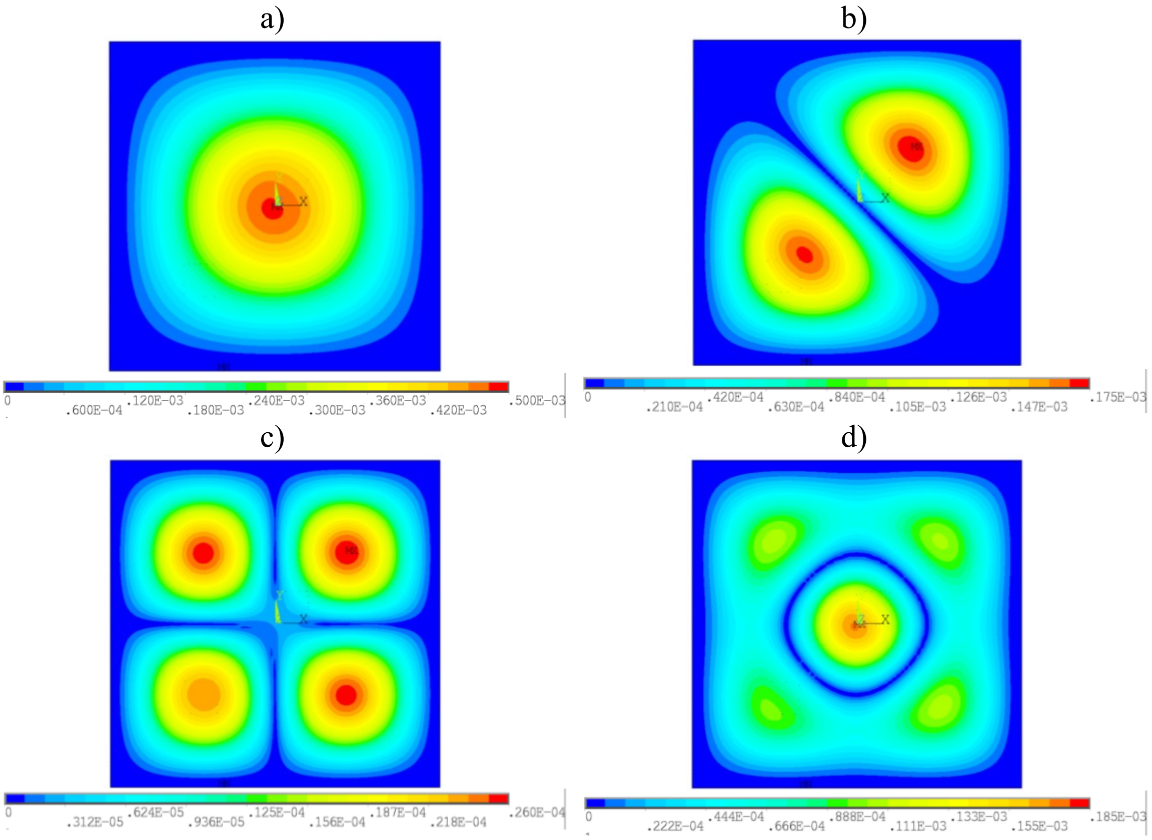


Figure 3. Displacement sum vector for analyzed modes a) first, b) second, c) fourth, d) fifth

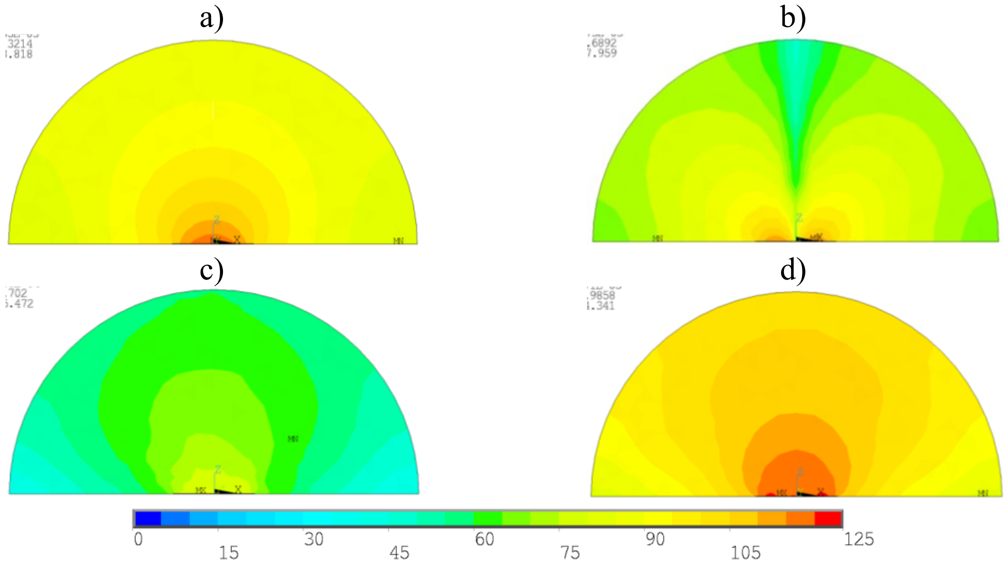


Figure 4. Sound pressure levels emitted by the plate for analyzed modes a) first, b) second, c) fourth, d) fifth

During each harmonic analysis the voltage applied to the actuator responsible for the excitation of the plate was 100 V. The amplitude of voltage required for the second piezo element to reduce these vibrations were selected using internal ANSYS optimization procedures according to the goal function (Equation 1).

$$J_1 = \min \sum_{i=1}^{n} \left|\mathbf{X}_{sum}(i)\right| \qquad (1)$$

where: min is the smallest value of sum; $\mathbf{x}_{sum}(i)$ is the displacement vector of the i-th node, n is the number of nodes used. There are 3 possible cases for n:

a) where n is equal to every node of the back of the plate (for our purpose the back of the plate is the side opposite to the one where piezo elements are attached) - 7654 nodes. This scenario is considered a case of global vibration reduction.

b) where n is equal to 81 nodes that form a "virtual" sensor attached to the plate. Its size is the same as the base of piezo elements and its placed on the same diagonal as the sensor-actuator near 1/4 th of its length from the upper right side (Fig. 1 a). This scenario is considered as the one closest to usual working conditions for sensors and actuators (different placements of sensors and actuators). It should be considered as a case for local vibration reduction, but because of its placement and the form of the object (square plate clamped on all sides) it should be pretty similar to the global vibration reduction.

c) where n is equal to 81 nodes that form a "virtual" sensor under the sensor-actuator. Its size is the same as for the inner part of the sensor-actuator and its placed under the inner part of the second piezo element so that reading the displacements of those nodes had direct translation to voltage readings from the sensor part of piezo element.

The phase of the voltage applied to actuators was not part of the optimization procedure, as from the previous studies it was found that depending on the mode it was always either 0° or 180°.

One cycle of optimization procedure was set to have 30 steps. After the completion of said cycle a new was started, again with 30 cycles, but with the range of voltage amplitudes narrowed according to values found in the last cycle. The final cycle had voltage ranges ± 2,5 V from the last optimal value.

3. RESULTS AND ANALYSES

The reduction of vibration (L_{red}) was calculated as (Equation 2):

$$L_{red} = 20log\frac{\sum_{i=1}^{n}|\boldsymbol{X}_{1sum}(i)|}{\sum_{i=1}^{n}|\boldsymbol{X}_{2sum}(i)|} \tag{2}$$

where $\mathbf{X}_{1sum}(i)$ is the displacement vector in i-th node before reduction and $\mathbf{X}_{2sum}(i)$ is the displacement vector in the i-th node after the reduction and n is the number of nodes used.

Similarly the reduction of the acoustic pressure emitted by the plate was calculated as (Equation 3):

$$L_{red} = 20log\frac{\sum_{j=1}^{m}|p_{1sum}(j)|}{\sum_{j=1}^{m}|p_{2sum}(j)|} \tag{2}$$

where $p_{1sum}(j)$ is the pressure in j-th node before reduction and $p_{2sum}(j)$ is the pressure in the j-th node after the reduction and m is the number of nodes used. The nodes used for this calculation were part of the volume of air, basically each node that was between the radius of 0,45 and 0,55 m (384 in total).

Obtained results are shown in tables 2-4.

Table 2. Results obtained using every node on the back of the plate; mode - number of mode; type - full actuator, actuator-sensor; U_a - amplitude of voltage applied to actuator; φ_a - pahse of the votage applied to the actuatorl; L_{red} - vibration reduction; SPL_{red} - acoustical pressure level reduction

mode	type	U_a [V]	φ_a [°]	L_{red} [dB]	SPL_{red} [dB]
1	actuator	365,29	180,00	41,3	55,5
2		57,77	360,00	43,1	32,1
4		12,05	180,00	25,8	8,4
5		159,95	360,00	34,7	48,9
1	actuator-sensor	487,43	180,00	41,3	55,4
2		77,27	360,00	43,1	32,1
4		16,24	180,00	26,0	8,4
5		215,37	360,00	35,0	47,4

When using the whole area of the plate for the purpose of vibration reduction it can be seen that there aren't any significant differences in the values obtained using sensor-actuator compared to full actuator. The biggest difference can be found when reducing the fifth mode, but that's barely 0,3 dB.

Results for the corresponding sound pressure level reduction are similar. For the 1st, 2nd and 4th mode there difference is negligible (below 0,1 dB). For the 5th mode it rises to about 1,5 dB which is higher than corresponding vibration reduction, but still acceptable.

Of course the obvious downside when using a sensor-actuator is the need to supply higher voltage to achieve the same level of reduction. The amount needed is about 1,33-1,34 of the voltage applied to the actuator. This does not necessarily directly translate to the same change in the amount of power that needs to be delivered, as actuators used have different base areas and shapes, but it can limit the maximum reduction that can be obtained when using a sensor-actuator. Still that was expected from the beginning.

Table 3. Results obtained using simulated sensor placed in different place than actuator; mode - number of mode; type - full actuator, actuator-sensor; U_a - amplitude of voltage applied to actuator; φ_a - pahse of the votage applied to the actuatorl; L_{red} - vibration reduction; SPL_{red} - acoustical pressure level reduction; L_{redf} - vibration reduction calculated when using all nodes forming the back area of the plate

mode	type	U_a [V]	φ_a [°]	L_{red} [dB]	SPL_{red} [dB]	L_{redf} [dB]
1	actuator	365,42	180,00	44,6	54,8	41,3
2		57,80	360,00	53,6	32,1	43,0
4		12,20	180,00	23,9	8,4	25,9
5		158,66	360,00	31,6	41,8	33,7
1	actuator-sensor	487,79	180,00	44,6	55,4	41,4
2		77,29	360,00	53,8	32,1	43,1
4		16,31	180,00	23,9	8,4	26,4
5		213,26	360,00	31,6	41,9	33,7

When using a simulated sensor placed elsewhere than the actuator again the obtained values of vibration reduction are very similar. Almost identical actually, with the exception of the 4th mode, where the sensor-actuator was able to achieve a better reduction. Of course the difference is negligible (about 0,2 dB) and might be the result of the optimization procedure of not actually finding the best possible value of voltage amplitude.

When calculating the vibration reduction using all nodes of the back area of the plate (as a reference to the best case scenario) it can be seen that the reduction obtained when using a local sensor are in this case very similar for the first three modes analyzed. For the last one we can observe that the results are slightly worse (1 and 1,3 dB respectively).

Corresponding reduction of sound pressure levels are very similar. The biggest difference is for the 1st mode and is about 0,6 dB. It can also be seen that for the 5th mode the obtained reduction levels were lower than for the previous case (which corresponds to lower values of L_{redf}).

Table 4. Results obtained using simulated sensor placed under the actuator; mode - number of mode; type - full actuator, actuator-sensor; U_a - amplitude of voltage applied to actuator; φ_a - pahse of the votage applied to the actuatorl; L_{red} - vibration reduction; SPL_{red} - acoustical pressure level reduction; L_{redf} - vibration reduction calculated when using all nodes forming the back area of the plate

mode	**type**	**U_a [V]**	**φ_a [°]**	**L_{red} [dB]**	**SPL_{red} [dB]**	**L_{redf} [dB]**
1	actuator	363,40	180,00	25,4	45,4	39,2
2		57,76	360,00	41,9	32,1	43,1
4		12,27	180,00	31,4	8,4	25,7
5		161,03	360,00	33,4	42,2	34,4
1	actuator-sensor	485,30	180,00	25,9	45,6	39,2
2		77,30	360,00	42,6	32,1	43,1
4		16,38	180,00	32,1	8,4	25,9
5		216,19	360,00	34,5	43,3	34,6

The results obtained when using a "virtual" sensor placed directly under piezo element show higher obtained vibration level reduction when using a sensor-actuator. This is consisted for each of the analyzed modes and ranges from 0,4 to 1,1 dB. This is most likely because the part of the piezo element that has direct contact with the sensor is not active (so it doesn't actively apply force to it). This is further confirmed when looking at our reference (reduction calculated from all the nodes forming the back of the plate). In this case the reduction for both actuators are again almost the same, and again lower than for the best case scenario for the 1st and 5th modes.

Results of sound pressure levels reduction are also similar between both actuators used. And again obtained reduction levels are lower for the 1st and 5th mode (when compared to the best case scenario).

Figure 5 shows the displacement vector sums of the plate after the reduction for the best case scenario (the ones before the reduction can be seen on figure 3).

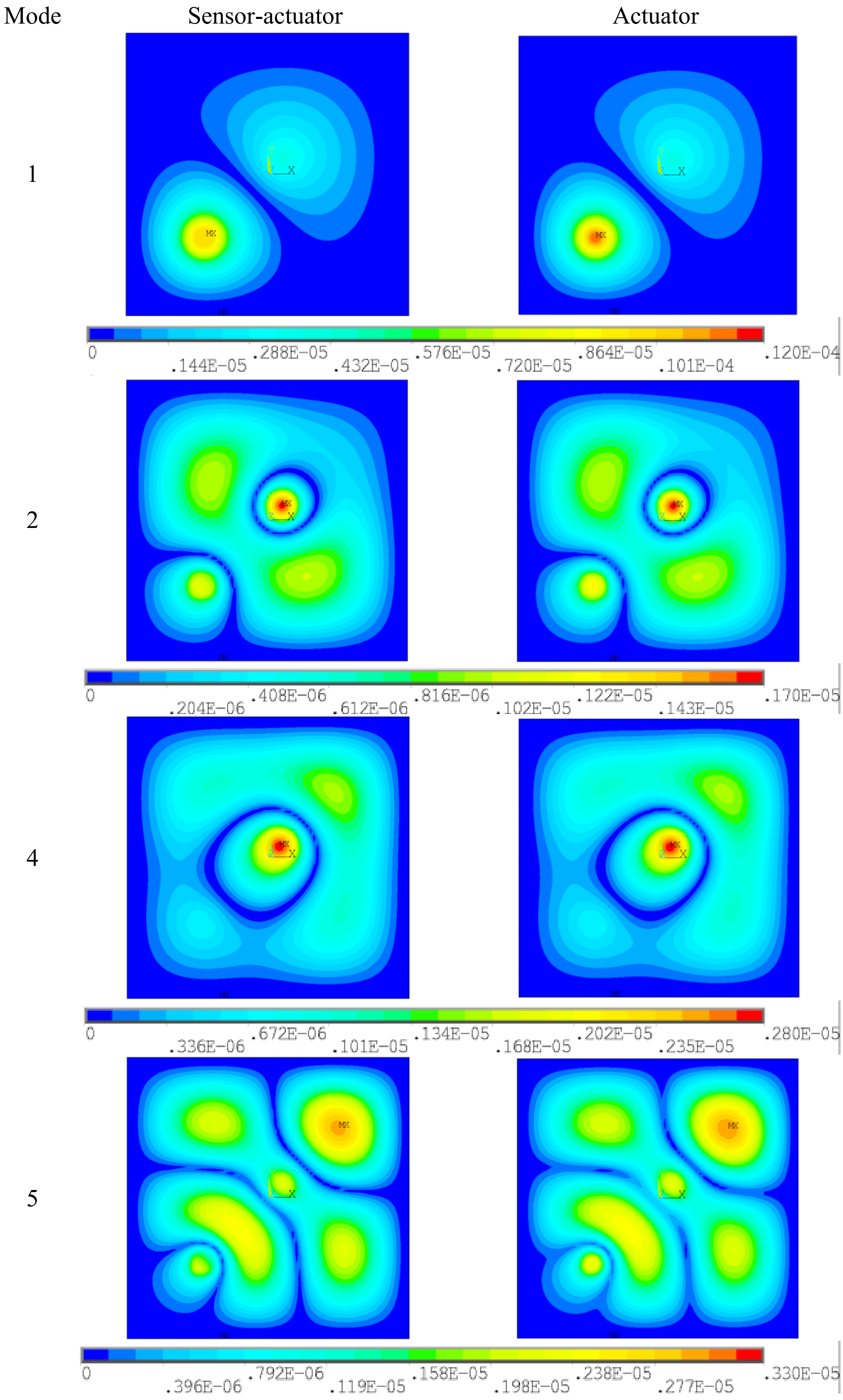


Figure 5. Displacement vector sums of the plate after the reduction when using best case scenario

It can be seen that for the most part the figures of displacement vector sums are very similar. The most noticeable (perhaps the only noticeable) difference is for the 1st and 5th mode where the values of said vectors are slightly lower for the sensor-actuator under the sensor, which corresponds to the inner part of the element not being active.

For other cases only the modes for which some discernible changes either from the best case scenario or between the actuators can be seen will be shown.

When using a "virtual" sensor placed in different place than actuator we have a similar situation. There aren't many differences between different actuators, there is however a large differences in the image of displacement vector sums for the 5th nodes between this and the best case scenario. Amplitudes a higher and the "image" of the reduced mode itself changes (figure 6).

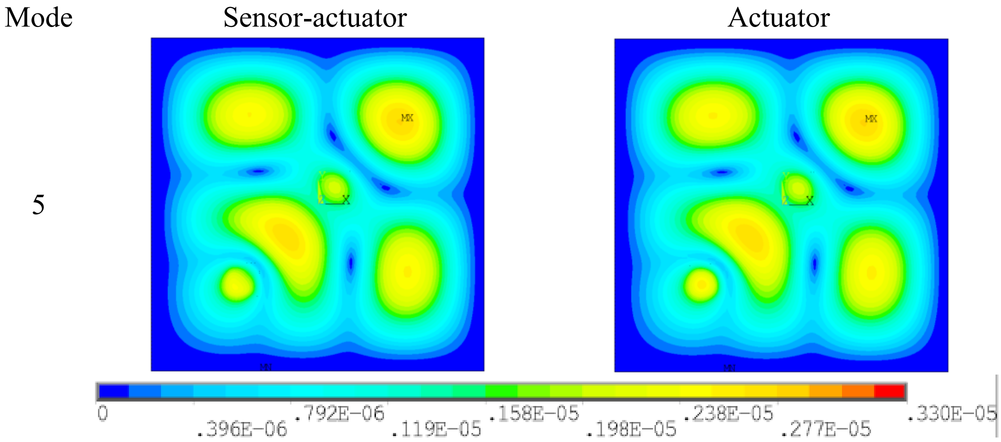


Figure 6. Displacement vector sums of the plate after the reduction when using second scenario

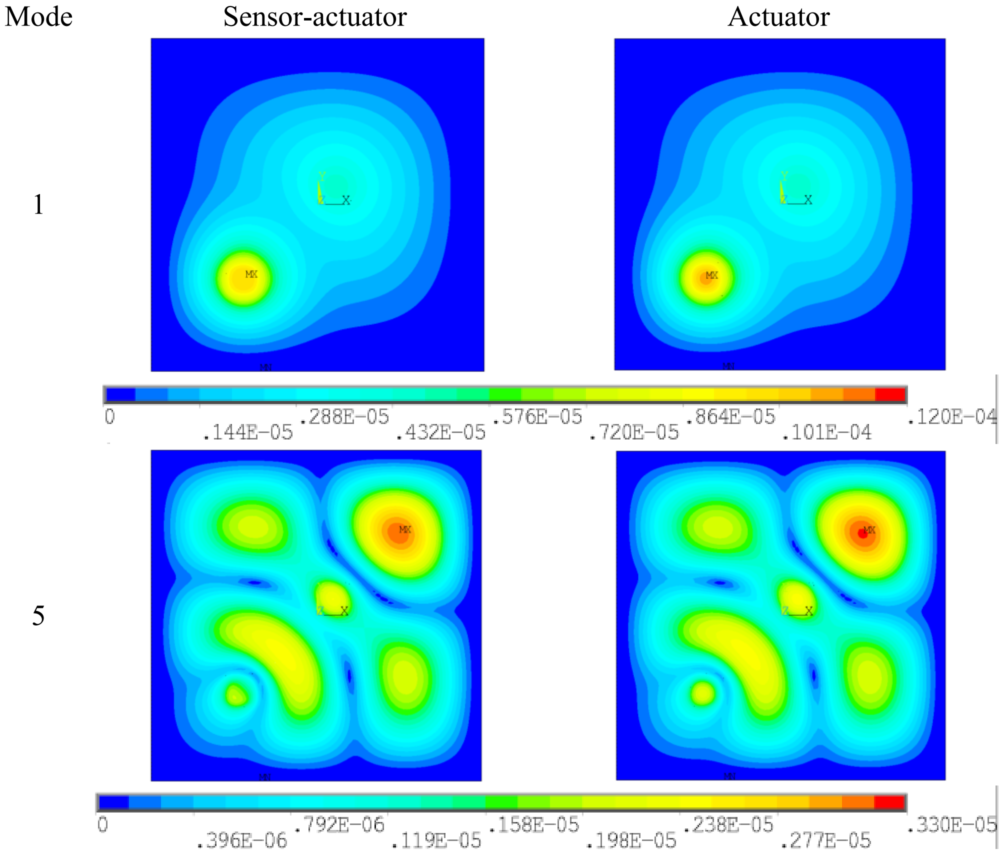


Figure 7. Displacement vector sums of the plate after the reduction when using third scenario

For the third scenario, where the sensor is placed underneath the inner part of the actuator (or sensor-actuator) again there are no significant changes between different types of actuators. We can however observe changes in the 1st and 5th mode values when compared to the best case scenario. Again the amplitudes rise and the images of the reduced modes change (fig. 7).

Figure 8 shows the acoustic pressure levels in the air surrounding the plate for the best case scenario (a cut in the half of the hemisphere).

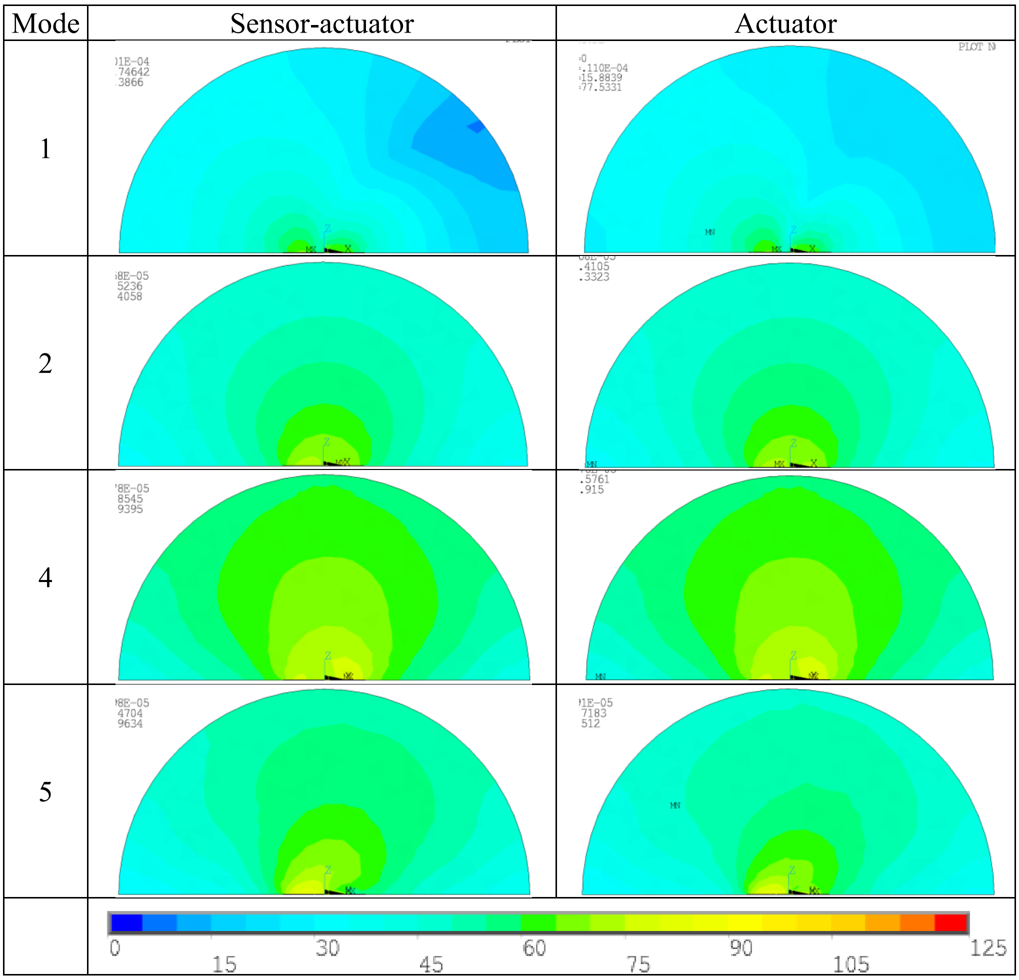


Figure 8. Sound pressure levels emitted by the plate after the reduction when using best case scenario

When using all the nodes making the back area of the plate it can be seen that the most noticeable differences can be seen for the 1st and 5th modes. The differences for the 5th mode can be easily explained with the difference in acoustic pressure levels reduction. it was about 1,5 dB higher when using a full actuator, so the levels observed on figure 8 are slightly higher for the sensor-actuator. But when looking at the 1st mode there is a very noticeable difference in sound pressure levels emitted by the plate, but almost no difference in observed reduction (was about 0,1 dB). Since the placement of some of the nodes that were taken to calculate SPL_{red} should correspond with observed differences, perhaps its specific of the plane in which the cut was made.

For the other 2 scenarios (when using a "virtual" sensor) are pretty similar. The differences between the actuators are rather small. Whereas when comparing to the best case scenario we can observe that for the 1st mode the acoustical pressures are higher and the images becoming more "symmetrical". For the 5th mode we can also see higher sound pressure levels and also a change in the image of the emitted sound. It looks similar to the one for the 4th mode. But here the changes mostly correspond to the changes in SPL_{red}. The 2nd and 4th modes remain unchanged.

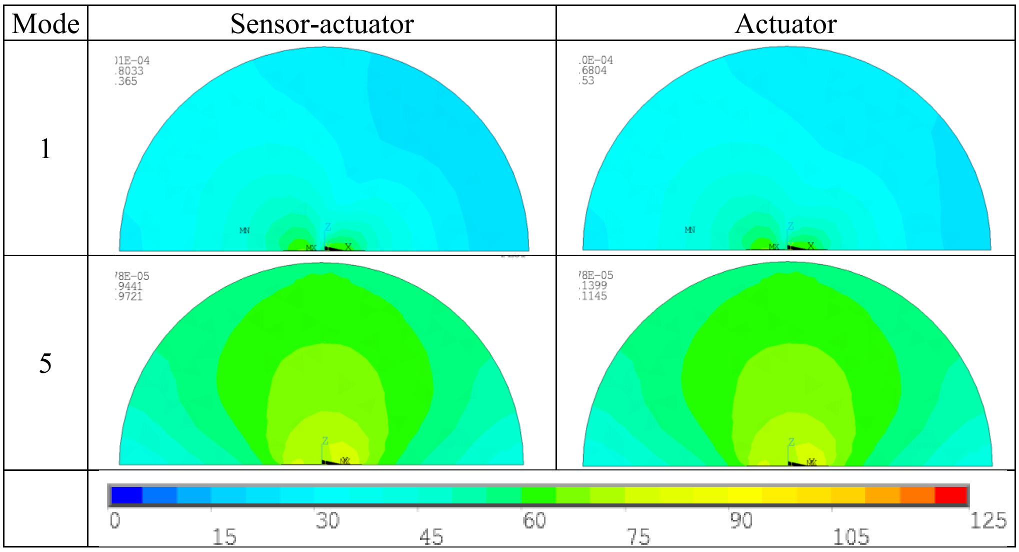


Figure 9. Sound pressure levels emitted by the plate after the reduction when using second scenario

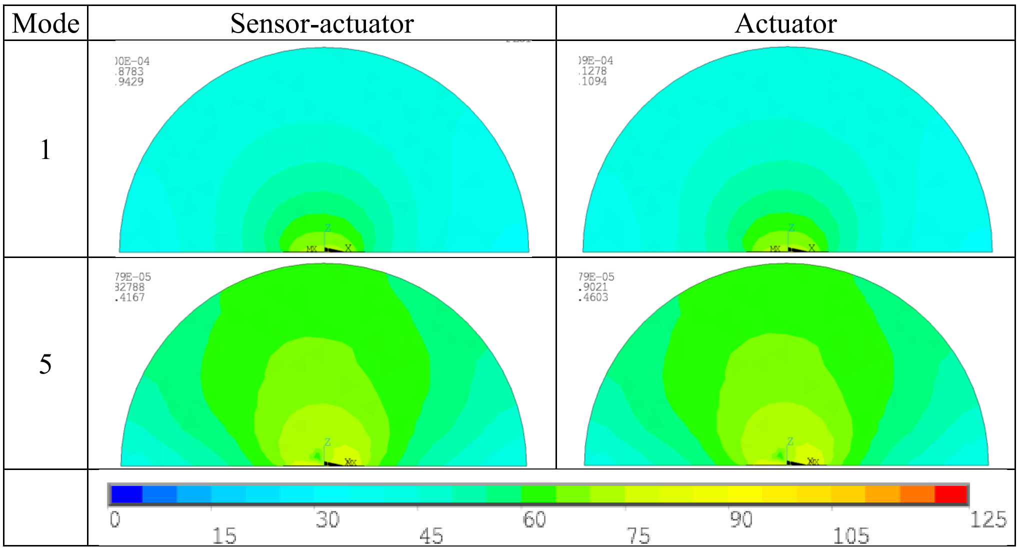


Figure 10. Sound pressure levels emitted by the plate after the reduction when using third scenario

4. CONCLUSIONS

"Turning off" part of the piezo actuator did not influence obtained levels of vibration and sound pressure levels reduction in any significant manner.

As expected the sensor-actuator required higher voltage amplitude compared regular actuator to achieve the same level o reduction. How that relates to possible changes in power draw of such piezo elements remains an open question.

Higher voltage needed for sensor-actuator can limit its effectiveness in some cases.

5. ACKNOWLEDGEMENTS

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