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Piezoelectric disc based sensor-actuator hybrid in vibration reduction

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Abstract This paper presents the results of comparison of vibration reduction levels between standard disc based piezo actuators and piezoelectric sensor-actuator hybrids. Modelling was done using FEM method in ANSYS software. Model consisted of a steel plate with piezo elements attached. A square based element was used as an actuator to excite plate's vibrations. Disc based element which was either a standard homogeneous disc based actuator or a sensor actuator hybrid with 2 possible sizes of the sensor part of said hybrid. Harmonic analyses were performed for the 1st, 2nd, 4th and 5th mode shapes with the goal function being the minimalization of displacement vector sum of a number of nodes (there were 3 possible cases). Significant vibration reduction levels were obtained with no significant differences in said levels between standard actuators and sensor-actuator hybrids. Reducing the size of sensor part of sensor-actuator allowed for lower voltages needed to achieve vibration reduction levels.

Keywords: AVC, FEM, plates' vibration, sensors.

1. Introduction

The concept of application of piezoelectric material dates back to 1880-1881, when the Curie brothers first discovered the indirect and direct piezoelectric effect. Nowadays, piezoelectric elements made of composite materials have been used in a wide variety of applications including noise - vibration control. This is due to the fact that piezoelectric materials have the unique capability to be used effectively as both actuator and sensor elements. Much of the fundamental theoretical work was done by Fuller [1] as well as Hansen and Snyder [2].

The research on piezoelectric materials applications in vibration and sound pressure fields still continues. Be it beam [3-6] or plate structures [7-13], analytical calculations [3, 4, 6, 11-13], numerical models [5, 7, 9, 10], or physical experiments [8] new works are presented every year. Some deal with optimal placement of piezo elements [4, 6] and some with new concepts changing design and/or structure of the piezo elements themselves [6, 9-11, 14-17].

The author first started from an idea proposed by prof. Jerzy Wiciak from AGH University of Science and Technology that it might be possible to simplify a gradient piezo element to a 2-part element and it could still retain some of its properties. Results were presented in several publications [9, 16, 17] and culminated in a authors' PHD Thesis [18]. And from these results another idea was born – a piezo electric sensor-actuator. A sort of hybrid element consisting of 2 parts in which the inner part would be used as a sensor and the outer part as an actuator.

This paper is a continuation of [19] and presents the results for disc shaped piezo elements.

2. Materials and methods

Figure 1a presents a standard disc based piezo electric element, while Figure 1b presents a first iteration model of sensor-actuator hybrid based on an actuator with a step change in material properties.

(a) (b)

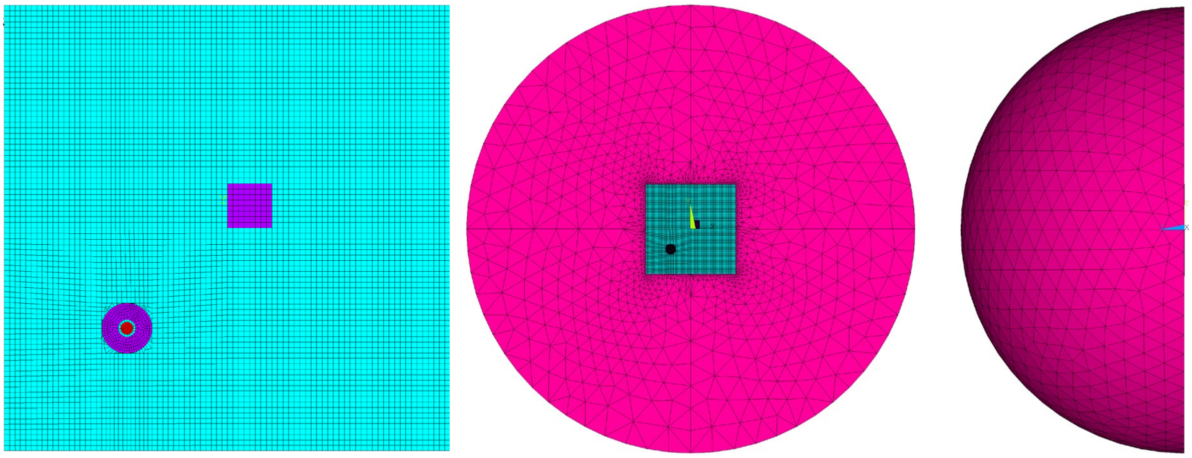
Figure 1. Idea of a sensor-actuator: a) standard disc based piezo-actuator; b) disc based sensor-actuator; colours: blue – plate, purple – piezo actuator, red – sensor part of the hybrid.

For the second generation models a space was added between 2 parts of piezoelement (Fig. 2). This should make it easier for the first iteration of physical prototypes, as the gap will allow for electrical separation between both parts. Also the disc based shape should be easier to work than square based.

(a) (b)

Figure 2. Second iteration of sensor-actuator a) disc based sensor-actuator with a larger sensor part; b) disc based sensor-actuator with a smaller sensor part; colours: blue – plate, purple – piezo actuator, red – sensor part of the hybrid.

As this is a continuation of previous work, the object sizes and materials used in models have the same parameters as in [19]. Therefore the base of the models is a steel plate 400 x 400 x 2mm with a square based piezoelectric actuator attached near the centre of the plate, used as an vibration source (Fig. 3a). A second piezo electric element placed on the plates' diagonal is either a standard actuator or a sensor-actuator hybrid and is used to reduce plates' vibrations. For continuity and consistency of results a half sphere of air (Fig. 3b, 3c) is also modelled (however air pressure results will not be shown in this work).



(a) (b) (c)

Figure 3. a) Modelled plate; b), c) modelled plate with surrounding air.

The total base area of modelled piezo elements is 1600 mm^2 (for the hybrid it includes the gap), which translates to around 12.732 mm radius for the disc elements and 20 mm side for the square actuator. Thickness of all piezo elements was 1 mm. There were 2 sizes of the inner (sensor) parts:

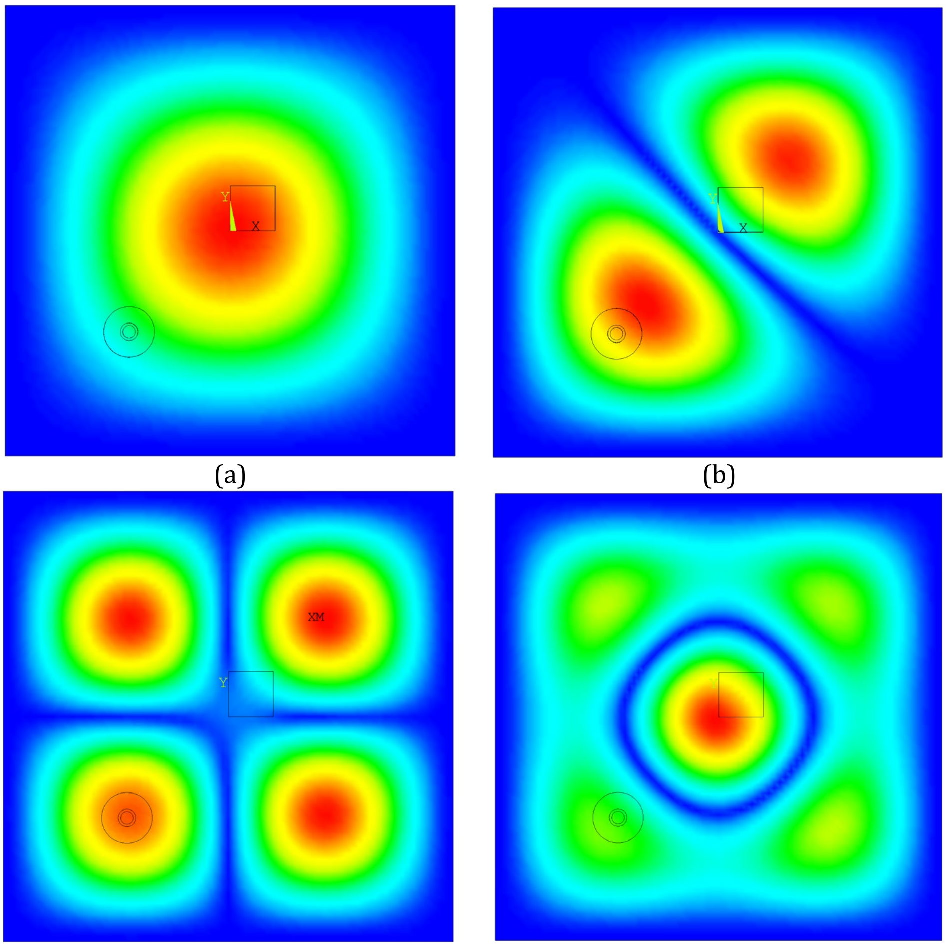
- for the hybrid with a larger sensor part the sensor part area was from 0 to 0.45 of the radius of whole element, while the actuator area was from 0.55 to the full radius of the whole element;
- for the hybrid with a smaller sensor part the sensor part area was from 0 to 0.25 of the radius of whole element, while the actuator area was from 0.35 to the full radius of the whole element.

Table 1 show what elements and materials were used in model.

Table 1. Parameters used in models.

Structural element	Element in ANSYS library	Properties
Plate	SOLSH190	$E = 1.93{\cdot}10^{11}$ Pa, $\nu = 0.29$, $\rho = 7800$ kg/m^3
Piezo elements	SOLID226	Properties of PZ28
Air	FLUID30	$\rho = 1.2$ kg/m^3 $c = 343$ m/s

Based on previous works a series of harmonic analyses was performed for the 1st, 2nd, 4th and 5th mode (Fig. 4). It can be seen that the actuator placed near the centre of the plate will work very well for the 1st and 5th mode. The placement for the 2nd and especially for the 4th mode isn't optimal, but will allow to check hybrid sensor-actuator in different scenarios. The placement of the disc based element was chosen for fairly optimal results with all of analysed modes.



(a) (b) (c) (d)

Figure 4. Analysed mode shapes a) 1st, b) 2nd, c) 4th, d) 5th.

For each of the analysed modes the plate was excited by applying a voltage with amplitude of 100 V and the phase angle 0° to the piezo actuator near the centre of the plate. Then an optimization procedure was performed using internal ANSYS functions to find the amplitude of the voltage to be applied to the second actuator to reduce plates' vibrations. The number of steps for a single run of the optimization procedure was capped at 30 steps. For each run range of voltages that could be applied to the disc based element was given, starting with 0-600 V for the first run. After completion of the first run of the procedure another run was started with the value from the previous run as a starting point the narrower range of voltages. This was repeated until the amplitude range of voltage was ±2.5 V of the staring value.

The phase angle of the voltage applied to the actuator was not a variable for the analyses as it was shown in previous works that depending on the mode it would be either 0° or 180° [20].

If any of obtained vibration reduction values differed from other results significantly manual check and tuning was performed.

The goal function used in the optimization procedure is given by equation:

$$J_1 = \min \sum_{i=1}^{n} |\mathbf{X}_{\text{sum}}(i)|, \tag{1}$$

where: min is the smallest value of sum; $\mathbf{X}_{\text{sum}}(i)$ is the displacement vector sum of the i-th node; n is the number of nodes used for calculations.

There were 3 cases for the sensor placement analysed, therefore possible values for n are given as:

a) n is equal to every node making the back of the plate (here the back of the plate is the side to which the piezoelectric elements are not attached). The actual number depends on the shape of hybrid element as well as the ratio of the inner and outer part (as these parameters influence the finite elements mesh) and for disc based piezo hybrid is at least 7074 nodes. This is considered a best case scenario;
b) n is equal to 25 nodes forming a "virtual" sensor with a quarter of the size of the square based actuator placed on the same diagonal as piezo actuators but in the upper level side of the plate (near ¼th of its length);
c) n is equal to at least 30 nodes forming a "virtual" sensor the size of the sensor part of sensor-actuator placed directly under it (the number changes depending on the size of the sensor part).

3. Results

This part presents the results of carried out numerical analyses. Equation 2 shows how the vibration reduction levels were calculated.

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

where: $\mathbf{X}_{1\text{sum}}(i)$ is the displacement vector sum in i-th node before the reduction, $\mathbf{X}_{2\text{sum}}(i)$ is the displacement vector in the i-th node after the reduction, n is the number of nodes used (as per 3 cases mentioned before).

Equation 3 presents how a parameter named voltage efficiency was calculated:

$$UL = \frac{U_{\text{a}}}{L_{\text{red}}}, \tag{3}$$

where: U_{a} is the amplitude of voltage applied to actuator, L_{red} is the level of vibration reduction.

This parameter was introduced as a simplified method of comparison between different shapes of used actuators. Since the area of the elements is the same and are modelled using the same material parameters this should help to compare the efficiency of piezo elements used in terms of voltages applied in relevance to obtained vibration reduction levels.

Table 2 presents the results for vibration reduction when using disc based actuators and sensor-actuators and using the whole back area of the plate as a sensor.

Obtained vibration reduction levels range from almost 26 dB to more than 43 dB depending on the mode of the plate. Interestingly for the 1st mode the values of vibration reduction levels obtained using sensor-actuators are higher than those obtained when using full actuator (up to 0.5 dB). The difference if small, but for square based elements [19] the situation was opposite (although the differences also weren't high). For the second mode there are no differences for any of modelled elements. For the 4th mode the results for the sensor-actuator with larger sensor part are 0.2 dB than for full actuator, but sensor-actuator with smaller sensor part is the same. For the 5th mode results for sensor-actuators are slightly higher than those for full actuator (up to 0.4 dB). Again a small change, but consistent for both shapes and sizes.

It can be seen that for the 1st mode the sensor-actuator results are about 0.3 dB lower than for the full actuator. There seem to be no differences for the 2nd mode. For the 4th and 5th mode it can be seen that results obtained when using sensor-actuators are slightly higher than for the full actuator (up to around 0.4 dB). All of the above mentioned differences are small (less than 0.5 dB), but they are consistent and at the same time there are almost no differences between sensor-actuators with different ratio of sensor to actuator part.

As for the voltages that were applied to the actuators and sensor-actuator it can be seen that when using sensor-actuator with a larger sensor part the overall voltage efficiency values are around 1.51 times higher than for the full actuator. This translates to about a 190 V higher voltage for the 1st mode. The values improve when using smaller sensor part as the actuator area is larger and are about 1.14 times higher than for full actuators (less than 60 V higher for the 1st mode).

Table 2. Results obtained for disc based actuators when using the whole back area of the plate as a sensor; mode - number of mode; type - full actuator, actuator-sensor; U_a - amplitude of voltage applied to actuator; φ_a - phase of the voltage applied to the actuator; L_{red} - vibration reduction; UL – voltage efficiency.

Mode	Type	U_a [V]	φ_a [°]	L_{red} [dB]	UL [V/dB]
1	actuator	371.94	180.00	39.9	9.3
2		58.71	360.00	43.3	1.4
4		12.12	180.00	25.8	0.5
5		161.98	360.00	35.1	4.6
1	actuator-sensor (larger)	561.43	180.00	40.1	14.0
2		88.37	360.00	43.3	2.0
4		18.18	180.00	25.6	0.7
5		247.29	360.00	35.4	7.0
1	actuator-sensor (smaller)	430.48	180.00	40.4	10.6
2		67.94	360.00	43.3	1.6
4		14.14	180.00	25.8	0.5
5		188.94	360.00	35.5	5.3

Table 3 presents the results of vibration levels reduction for disc based actuators and sensor-actuators for the scenario where a sensor would be placed on the same diagonal as actuator used for reduction but in the upper right quarter of the plate.

Vibration reduction levels obtained in this scenario range from almost 24 dB for the 4th mode to 54 dB for the 2nd mode. The vibration reduction levels obtained when using sensor-actuators are slightly higher (up to 0.7 dB) for the 2nd mode and slightly lower for the 4th and 5th (up to 1.2 dB) when compared to full actuators.

Similarly to previous table higher values of UL were obtained when using sensor-actuators than full actuators. This should be expected as voltages applied to actuators are almost the same and although obtained vibration reduction levels differ from the previous scenario they are similar for different actuators used, therefore the ratios of UL values for different actuators should also stay similar.

Table 3. Results obtained for disc based actuators when using a "virtual" sensor on the diagonal in the upper side of the plate; mode - number of mode; type - full actuator, actuator-sensor; U_a - amplitude of voltage applied to actuator; φ_a - phase of the voltage applied to the actuator; L_{red} - vibration reduction; L_{redf} - vibration reduction calculated for all nodes making the back of the plate; UL – voltage efficiency.

Mode	Type	U_a [V]	φ_a [°]	L_{red}[dB]	L_{redf} [dB]	UL [V/dB]
1	actuator	371.99	180.00	44.6	39.9	8.3
2		58.75	360.00	53.3	43.1	1.1
4		12.26	180.00	23.8	26.0	0.5
5		162.68	360.00	31.5	35.4	5.2
1	actuator-sensor (larger)	561.24	180.00	44.6	40.1	12.6
2		88.28	360.00	53.9	42.9	1.6
4		18.55	180.00	23.9	24.8	0.8
5		246.16	360.00	31.4	35.2	7.8
1	actuator-sensor (smaller)	430.52	180.00	44.6	40.4	9.6
2		67.94	360.00	54.0	43.3	1.3
4		14.16	180.00	23.8	25.7	0.6
5		188.85	360.00	31.4	35.5	6.0

Table 4 presents results for vibration reduction levels when using disc based actuators in a scenario where a sensor is placed under the centre of the actuator (or sensor-actuator) and is the size of the sensor part of sensor-actuator.

For this scenario obtained vibration reduction levels range from more than 25 dB for the 1st mode up to about 42.5 dB for the 2nd mode. It ca be seen that the differences in vibration reduction levels obtained for actuators and sensor actuators become more pronounced. For the 2nd mode values obtained when using sensor-actuator are up to 0.8 dB higher. Similar for the 4th (up to 0.3 dB) and 5th mode (up to 1.5 dB).

For UL values the situation is similar as before. The values are different because of the change in vibration reduction levels (which come from changing the sensor), but the ratios are similar.

Table 4. Results obtained for disc based actuators when using a "virtual" sensor placed under the centre of disc based actuator; mode - number of mode; type - full actuator, actuator-sensor; U_a - amplitude of voltage applied to actuator; φ_a - phase of the voltage applied to the actuator; L_{red} - vibration reduction; L_{redf} - vibration reduction calculated for all nodes making the back of the plate; UL – voltage efficiency.

Mode	Type	U_a [V]	φ_a [°]	L_{red} [dB]	L_{redf} [dB]	UL [V/dB]
1	actuator	370.41	180.00	25.2	38.6	14.7
2		58.67	360.00	41.6	43.2	1.4
4		12.24	180.00	31.8	26.0	0.4
5		162.36	360.00	33.0	34.9	4.9
1	actuator-sensor (larger)	559.49	180.00	25.8	39.3	21.7
2		88.56	360.00	42.5	42.7	2.1
4		18.25	180.00	32.1	25.5	0.6
5		247.31	360.00	34.5	35.4	7.2
1	actuator-sensor (smaller)	429.96	180.00	25.3	40.2	17.0
2		67.88	360.00	41.9	43.3	1.6
4		14.08	180.00	31.9	25.8	0.4
5		188.92	360.00	33.5	35.5	5.6

As for the differences in vibration reduction levels they look differently when we compare them after recalculating these values for best case scenario – that is using the whole back of the plate as sensor (L_{redf} column for tables 3 and 4, and L_{red} column for Table 2). These results are shown on Figure 5.

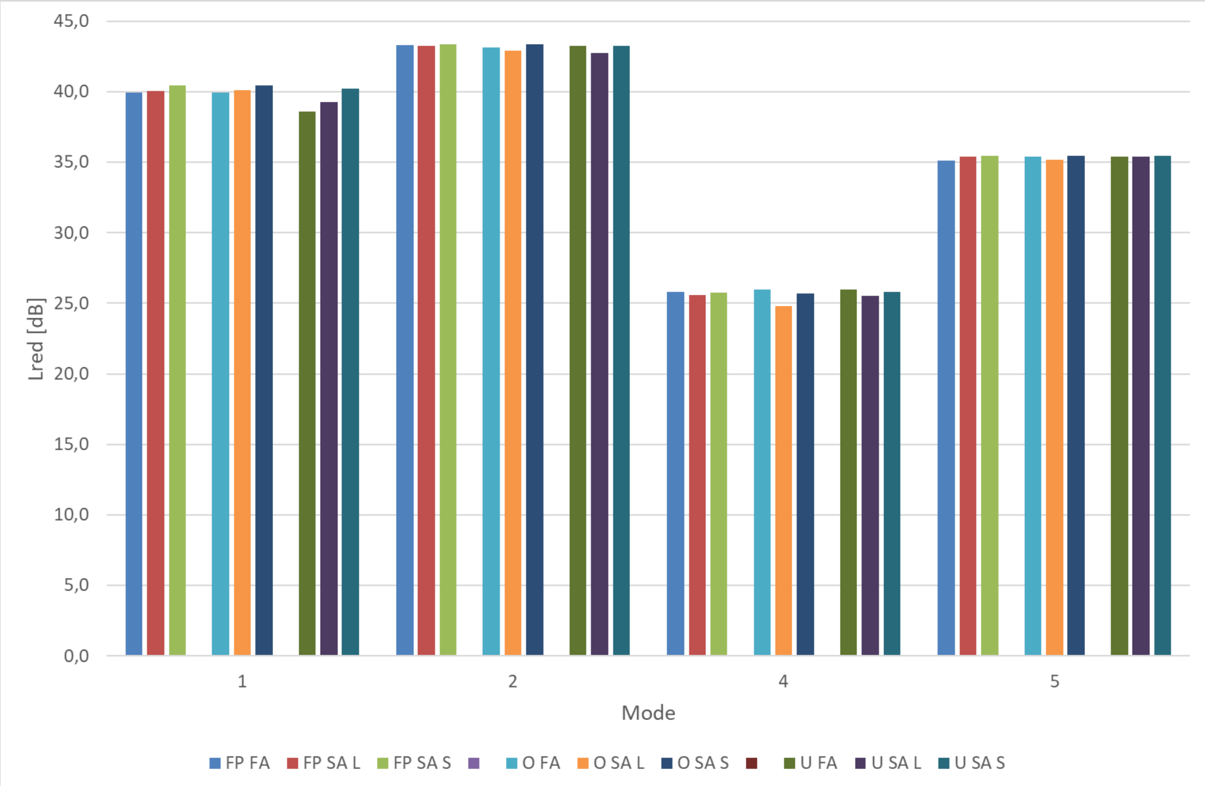


Figure 5. Comparison of vibration reduction levels obtained for disc based actuator recalculated for the full plate; FP – using scenario with a whole back of the plate as a sensor; O – using sensor placed on the diagonal in the upper right quadrant of the plate; U – using sensor placed under actuator (or sensor-actuator); FA – full actuator; SA L – sensor-actuator with larger sensor part; SA S – sensor actuator with smaller sensor part.

The first 3 bars for each mode are the results when using every node on the back of the plate for obtaining the vibration level reduction values. These were discussed above.

The next 3 bars show recalculated results for the scenario when sensor is placed on the diagonal in the upper right side of the plate. It can be seen that for the 1st 2nd and 5th modes the recalculated results are very similar to the results from the global scenario with the largest difference being about 0.4 dB. A much larger difference (about 0.8 dB) can be observed when using sensor-actuator with a larger sensor-part. This is interesting if we compare this with the results from the sensor, where sensor-actuator with a larger part has the highest vibration reduction level, although the difference to full actuator and the sensor-actuator with smaller sensor part is 0.1 dB so quite negligible.

The last 3 bars represent the third scenario – where the size and placement of the sensor corresponds to the sensor part of sensor-actuator. It can be seen that for the 1st mode the recalculated vibration reduction levels are lower than for other scenarios. The smallest difference can be observed for the sensor-actuator with smaller sensor part at about 0.2 dB and the largest for full actuator at 1.3 dB. The results for 2nd, 4th and 5th mode are fairly similar to other scenarios. So again it can be said that the sensor part of sensor actuator appears to be working fine and does not impair elements effectiveness. At least not in a significant way. What can be observed for the disc based actuators is that some of the recalculated results for the sensor-actuator with a larger sensor part are worse than those for the full actuator or sensor-actuator with a smaller sensor part while simultaneously being better for the sensor (table 3 and 4). These differences are for the most part small, below 0.5 dB (although the largest is at 0.9-1.2 dB), but can be observed on Figure 4. This with the recalculated vibration reduction levels for the sensor-actuator with smaller sensor part being almost always higher that for the one with bigger sensor part seem to indicate that changing the sensor part (and by that changing the actuator part size) might have some influence on the piezo element behaviour as actuator.

4. Conclusions

Similarly as for square based hybrid sensor-actuators [19] the proposed disc based hybrid appears to be capable of vibration reduction levels comparable to those of standard actuator. In some cases obtained results were slightly higher than those for full actuator. Although the differences were not really significant. The sensor part appears to be working correctly, the results are fairly comparable in every scenario.

It can be observed that for the disc based hybrid changing the size of the sensor part seem to have some influence on the recalculated results, something that wasn't observed for the square based sensor-actuators. And although the differences are not significant, they appear to be consistent.

The downside when using sensor-actuator are higher voltages that need to be applied to the hybrid to achieve vibration reduction levels comparable to standard actuators. This however was expected, after all the actuator part of sensor-actuator is smaller than the size of full actuator. Also this can be partially negated by using a smaller sensor part.

Next step of research would consist of creating a physical prototype of sensor-actuator on the basis of second iteration models and performing a physical experiment to confirm numerical results.

Next steps for numerical models would be finding optimal ratios between sensor and actuator parts, experimenting with different shapes of sensor parts (for example disc based sensor part with square based actuator part).

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Additional information

The author(s) declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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