Numerical Analyses of the Effectiveness of an Integrated Disc Based Piezoelectric Sensor-Actuator

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Abstract

This paper deals with numerical analyses of plates vibration reduction effectiveness of an integrated disc based piezoelectric sensor-actuator compared to standard type disc based piezoelectric actuator. For that purpose 400 x 400 x 2 mm plate clamped on all sides was modelled with 2 piezo elements attached to it. One was a standard square based piezoelectric actuator used to excite the plate. The second one is disc based and can be either a standard element or an integrated sensor-actuator and is used for vibration reduction.

The harmonic analyses were performed for the 1st, 2nd, 4th and 5th mode. Voltage used for plates excitation was always set to 100 V. The amplitude of voltage applied to the actuator was selected using internal ANSYS optimization procedures. The goal function for this was the minimum of the displacement vector sum of *n* nodes of the plate, with *n* having 3 possible values.

Keywords: AVC, FEM, ANSYS

1. Introduction

The concept of an active vibration reduction was introduced at the end of XIX century. Sometime later - around the 1930s - a concepts for an 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. Still the field of the active vibration control [2, 3] is constantly moving forward. Developments in material engineering, increase of technological potential and computing power allowed carrying advanced computer simulations [4] as well as to control processes leading to vibration and noise reduction.

Analytical field is also a subject of a continuous development. New theories and mathematical models are widely used for problems of objects vibrations [5] and sound radiation [6].

Other works deal with control type and algorithms [7, 8], combining active and passive methods [9].

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 as a simpler replacements for functionally graded actuators. The idea was first introduced with fairly simple models [10]. After some refining the improved models and certain analytical analyses were presented [11]. Another improvement was introducing the acoustic surrounding of analysed plate [12]. These works generally concluded that introduced change in material properties of piezo actuators didn't produce any substantial change in the reduction levels of plates vibration. Another work presented the attempts to verify numerical results with physical experiments [13]. Unfortunately small number of samples (they had to be custom made) and the differences between these samples made the results unsatisfactory.

However another idea was born from this. If the changes of 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 this idea are presented in the hereby work.

2. Numerical Models

To test if a concept of a sensor-actuator could actually be a feasible construct numerical models were created using ANSYS software. Models consisted of a steel plate clamped on all sides with 2 piezoelectric elements attached. One of them was square based and used to excite the plate. The other one was a disc based actuator which was either used to full capacity as a standard actuator or had a inner part “turned off” as to somewhat simulate the behaviour of a sensor-actuator. This piezoelectric element was used for vibration reduction. The modelled plate with piezo elements placement can be seen on Figure 1.

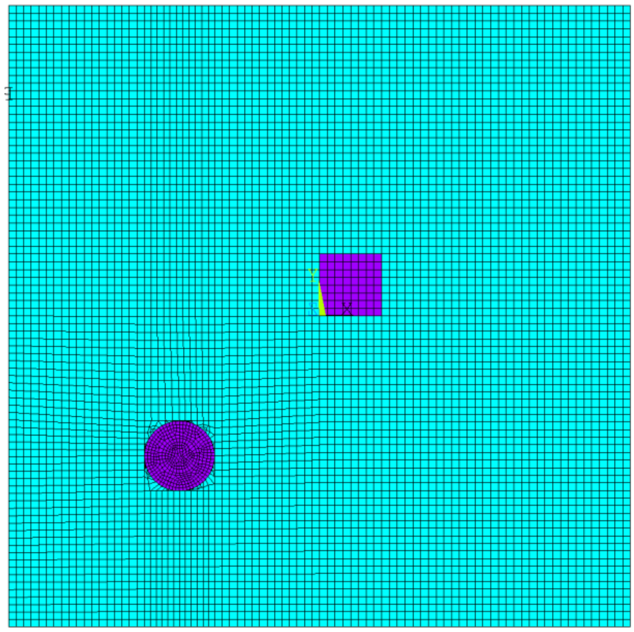

Figure 1. Modelled plate with piezoelectric actuators

Both piezo elements had a reference area of 400 mm^2 and thickness of 1 mm. Both were modelled using material properties of PZ 28. For the disc based actuator when used as an sensor-actuator the area of the part that was “turned off” was ¼ of the area of the whole actuator (Figure 2).

a) b)

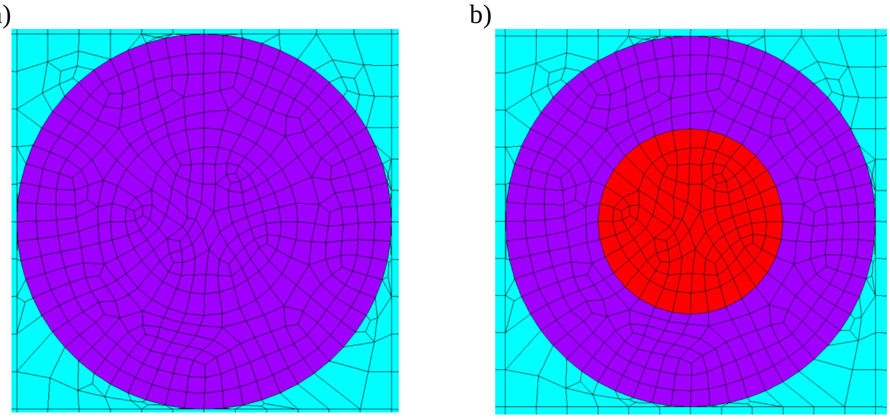

Figure 2. Disc based actuator a) when used as a standard actuator,
b) when simulating a sensor-actuator

Model parameters 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, v = 0.29, ρ = 7800 kg/m^3
Piezo elements	SOLID226	Properties of PZ 28
Air	FLUID30	ρ = 1.2 kg/m^3 c = 343 m/s

Harmonic analyses were performed for the 1st, 2nd, 4th and 5th mode. During each harmonic analysis voltage of 100 V was applied to the square based piezo actuator to excite the plate. Then an optimization procedure was performed to find the disc based actuator to find the amplitude of the voltage and reduce the exited vibrations. This was done using an internal ANSYS procedures. One cycle of optimization was set up to have no more than 30 steps. After the completion of a cycle the final value of voltage amplitude was taken as a starting value of the next cycle but with a narrower voltage range. The range of the first cycle was 0-500 V, the last was ±2.5 V of the last starting value.

The phase of the voltage applied to the disc based actuator was not a part of the optimization procedure as previous works shown that it would be 0° for the 1st and 4th and 180° for the 2nd and 5th mode.

The goal function used in the optimization procedure is given by equation 1:

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

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 are 3 possible values for n depending on the case:

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), that amounts to 7296 nodes and is considered a best case scenario;
b) n is equal to 81 nodes forming a "virtual" sensor the size of the disc 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 402 nodes forming a "virtual" sensor the size of the "turned off" part of sensor-actuator placed directly under the centre of the disc based actuator.

3. Results

The reduction of vibration was calculated as:

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

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

Table 2 presents the results of vibration reduction obtained for the case where the whole back area of the plate is used as a sensor. This will be treated as a base as it is a best case scenario for the global approach to the vibration reduction. It can be seen that there are no significant differences between the results for the standard actuator and the one simulating the sensor-actuator (the biggest difference being about 0.4 dB). These differences can be attributed to the optimization algorithm finding the optimal value, but the actual best value might differ a little (about 0.1-0.2 V).

It should be noted that although when using sensor-actuator we were able to obtain almost identical vibration reduction levels the voltage applied to it had to be significantly higher. This is of course the result of the working area of the actuator being smaller. It should be possible to somewhat mitigate this by making the sensor area of sensor-actuator smaller, but further test are needed to determine how would that affect it.

Table 2. Results obtained when n = 7296 nodes (whole back area 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

mode	type	U_a [V]	φ_a [°]	L_{red} [dB]
1	actuator	371.94	180.00	39.9
2		58.71	360.00	43.3
4		12.12	180.00	25.8
5		161.98	360.00	35.1
1	actuator-sensor	499.57	180.00	39.9
2		79.02	360.00	43.3
4		16.48	180.00	26.0
5		219.78	360.00	35.5

Table 3 presents the results of the vibration reduction when introducing a virtual sensor placed on the same diagonal as actuators, but in the upper right quarter of the plate. Apart from the results of vibration reduction from the virtual sensor the Table also presents what would be the reduction level from these voltage amplitudes calculated for every node making the back of the plate.

It can be seen that there are no significant differences between a standard actuator and simulated sensor-actuator (no more than 0.2 dB).

Table 3. Results obtained when n = 81 nodes ("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

mode	type	U_a [V]	φ_a [°]	L_{red} [dB]	L_{redf} [dB]
1	actuator	371.99	180.00	44.6	39.9
2		58.75	360.00	53.3	43.1
4		12.26	180.00	23.8	26.0
5		162.68	360.00	31.5	35.4
1	actuator-sensor	499.88	180.00	44.6	40.0
2		78.94	360.00	53.5	43.2
4		16.53	180.00	23.8	26.0
5		220.01	360.00	31.5	35.5

Table 4 presents the results of the vibration reduction when using the virtual sensor placed under the centre of the actuator used for reduction. It can be seen that for the sensor-actuator the obtained vibration reduction levels are slightly higher (up to 1.2 dB). This is actually a somewhat "false" reading. When we compare the reduction calculated by using all the nodes of the plate (L_{ref}) it can be seen that again there are almost no changes between different types of actuators used (less than 0.6 db). Possible reason for the difference in readings from the "virtual" sensor is the fact that for the standard actuator this area is working, whereas for sensor-actuator- it is simply "turned off", hence the lower reading when the voltage is applied to the actuator.

Table 4. Results obtained when n = 402 nodes ("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

mode	type	U_a [V]	φ_a [°]	L_{red} [dB]	L_{redf} [dB]
1	actuator	370.41	180.00	25.2	38.6
2		58.67	360.00	41.6	43.2
4		12.24	180.00	31.8	26.0
5		162.36	360.00	33.0	34.9
1	actuator-sensor	497.95	180.00	25.7	38.8
2		79.01	360.00	42.3	43.3
4		16.51	180.00	32.0	26.0
5		219.60	360.00	34.2	35.4

Figure 3. Comparison of vibration level reduction when recalculated to the L_{redf}; the FP stands for when using the whole plate as a sensor; OP then using sensor placed on the diagonal in the upper part of the plate; U when using sensor placed under the actuator; A is the "standard" actuator and S-A is the sensor-actuator

Figure 3 shows the comparison of vibration levels obtained when using different sensors which are recalculated for every node making the back area of the plate. This was done to show how a sensor-actuator will behave when compared to other cases. It can be seen that for the 1^{st} mode using the sensor placed directly under the actuator (simulating the sensor part of the sensor-actuator) results in slightly lower level of vibration reduction (1.1-1.3 dB). For the other modes there are basically no notable differences. The question remains whether this difference will become more significant as the sensor part of the sensor-actuator becomes smaller (which should bring down the amplitude of voltage required to obtain the results). If so it could limit the possible uses of such a hybrid.

3. Conclusions

This paper presents the results of preliminary simulations of a piezoelectric sensor-actuator hybrid. There were 2 questions to be answered. First, how will said hybrid behave when compared to a "standard" piezoelectric actuator in terms of vibration reduction levels. And the second question was how useful will the sensor part of such system be.

The results show that there are no significant differences between the sensor-actuator and the standard actuator in terms of vibration reduction levels. It did however required a significantly higher amplitude of voltage to obtain similar results as a "standard" actuator (this should be somewhat mitigated by reducing the size of the sensor part of the sensor-actuator).

As for the usefulness of the sensor part of sensor-actuator. It can be seen that depending on the mode of the plate using the sensor placed inside an actuator did result in slightly worse vibration reduction levels compared to other sensors.

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