Numerical modeling of a flexural displacement-converter mechanism to excite a flat acoustic source driven by piezoelectric stack actuators

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Abstract

This paper studies an acoustic source with a relatively small thickness and high bending stiffness. The acoustic source operates in the low frequency, quasi-static regime. The focus of the current study is on the actuation part in order to design an appropriate excitation mechanism. A flexural mechanism is modeled in combination with piezoelectric actuators to convert an in-plane displacement of the actuators to a perpendicular out-of-plane direction. First, an optimization simulation is used to determine the size of the required piezoelectric actuator. Then an equivalent electrical circuit of the lumped acoustic source is developed. This equivalent circuit can directly be connected to the electrical model of a switching amplifier. Finally, a coupled numerical finite element analysis is carried out by using COMSOL Multiphysics software package to model the combination of both flexural mechanism and piezoelectric device. The suggested flexural mechanism is sufficiently narrow to overcome the space limitation challenge in the design.

1 Introduction

Thin acoustic sources operating at low frequencies can be useful in active noise control as sources with severe space constraints. In the current research, a thin acoustic source is studied. This acoustic source is introduced in Refs. [1] and [2]. In this acoustic source, a high bending stiffness is obtained by attaching the source to a sandwich structure. In another research [3], a lumped model is used to investigate the possibility of using piezoelectric stack actuators as the excitation parts of this acoustic source.

In the present work, the same acoustic source that is introduced in Ref. [1], is studied. The main focus in the current research is on the design of an excitation mechanism for the acoustic source. Due to the limited available space in the thin acoustic source, piezoelectric stack actuators cannot directly be used. Therefore, the design of a displacement-converter mechanism is crucial. With the aid of a displacement-converter mechanism, piezoelectric stack actuators can be used while their displacement in one direction is converted to a displacement in a desired direction.

Commercial amplified actuators are widely used in industry [4, 5]. Thanks to compact size, straightforward design, manufacturability, and wide range of output motion and output force, these integrated amplified piezoelectric actuators offer a larger stroke than single piezoelectric multilayer actuators. However, they are only manufactured in specific dimensions and in limited aspect ratios. Among all the commercial designs, on the one hand, there is no suitable amplified actuator available that has the small dimensions compatible with the dimensions of our acoustic source. On the other hand, the available small commercial designs are not capable of delivering the required stroke and force to our acoustic source.

Integrated mechanisms are investigated in several studies to amplify the displacement of stacked piezoelectric elements. Some suggested integrated designs that use piezoelectric devices are shown in Fig. 1. Reference [6] studies a design named bridge-type amplifier shown in Fig. 1(a), in which the input and the output displacements are in the same direction. In another model called flexure hinge [7], four similar piezoelectric stack actuators are located in a symmetric in-plane configuration and are connected through a central flexural hinge. According to Fig. 1(b), the resulting displacement is, however, in-plane. A honey-comb flexural design in Fig. 1(c) is proposed in Ref. [8]. This design can translate an input displacement into an out-of-plane displacement. The suggested oval-shaped design in Ref. [9] can generate an out-of-plane output displacement according to Fig. 1(d). However, these two out-of-plane designs only perform at high frequencies and require high applied voltages. Therefore, the suggested designs deliver either an in-plane output displacement or in the case of an out-of-plane displacement, the operating frequency range is not applicable to our acoustic source.

This motivated the authors to investigate a new design for the actuators. In the current research, a flexural mechanism is proposed and is numerically studied. Due to the lack of sufficient space for the actuators in the structure of the thin acoustic source, the input and output displacements are not in the same plane. In the suggested configuration, an output displacement of the flexural mechanism is obtained by using piezoelectric stack actuators in the horizontal plane. The suggested mechanism is able to convert the displacement of the actuators to a perpendicular out-of-plane displacement to drive our acoustic source.

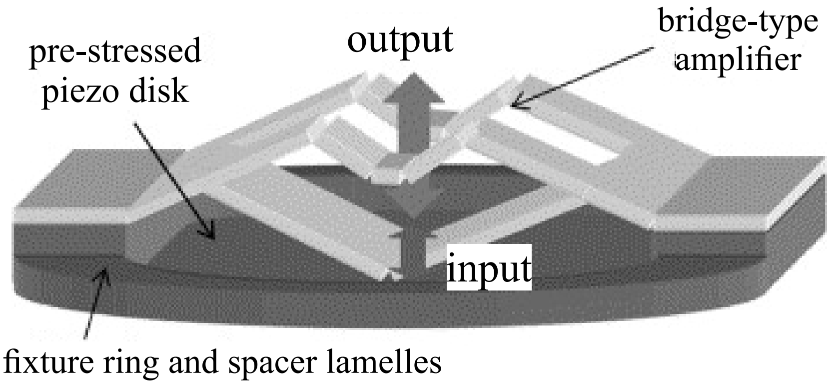
2 Methodology

2.1 Acoustic source

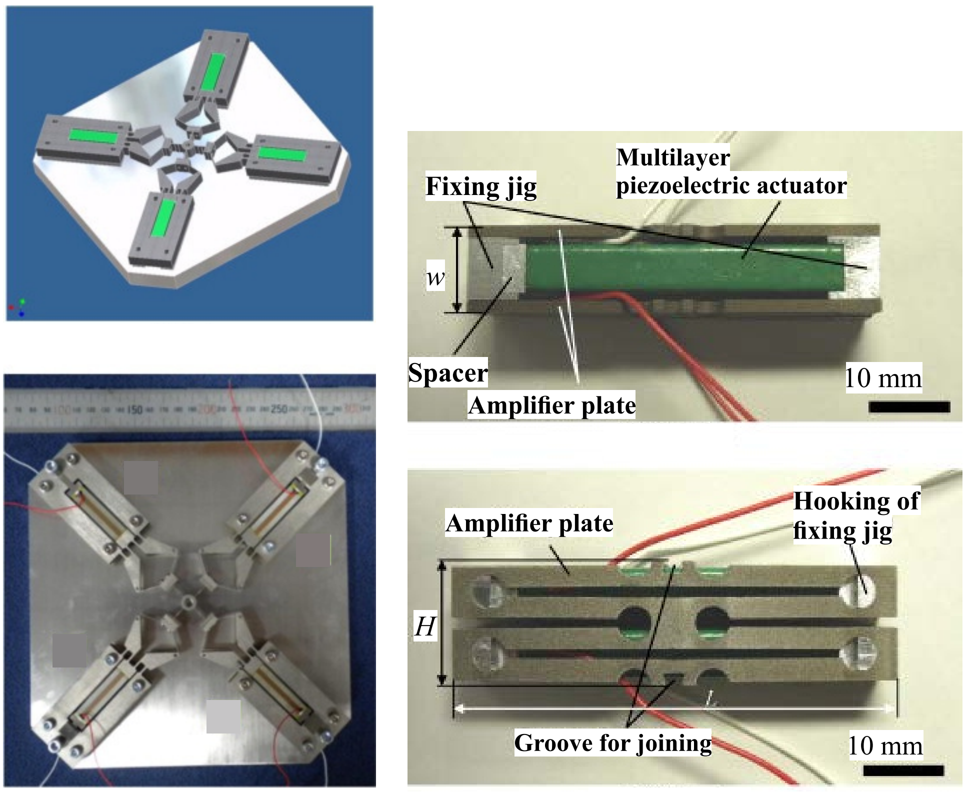
In our acoustic source, a high bending stiffness is obtained by attaching the source to a sandwich structure. The structure of the acoustic source is shown in Fig. 2. It consists of a radiating surface, a honey-comb structure, a perforated surface, an air cavity, and piezoelectric actuators. The face of the sandwich structure internal to the source is perforated to increase the acoustic compliance. The details of this acoustic source are described in Ref. [3].

2.2 Equivalent electrical circuit

A fully-lumped model of the flat acoustic source is considered in this study. To simplify the computation, an equivalent electrical circuit of the lumped acoustic source is used in combination with the equivalent electrical circuit of piezoelectric stack actuators. The resulting circuit is represented in Fig. 3, where i_t and V_t are the total current and voltage, respectively, that are supplied to the electrical connected amplifier (*Amp.*). The current along and voltage across the piezoelectric element are respectively shown by i_{piezo} and V_{piezo}. Parameters i and e represent the output current and voltage of the electrical domain, respectively. Correspondingly, u and F_{in} show the input velocity and force to the mechanical domain, while F_{out} is the output force of the mechanical domain. In the acoustical domain, the input volume velocity and pressure are represented by U_d and P_{in}. In the electrical domain, C_0 shows the capacitance of the piezoelectric device. In the mechanical domain, Z_T and Z_S are the compliance and effective mass of the piezoelectric actuator, respectively. M_s, C_s and R_s are correspondingly the mass, compliance and mechanical damping of the acoustic source. Parameters Z_{cavity}, Z_{hollow}, Z_{screen} and Z_{rad} represent the equivalent acoustical impedances of air in the cavity, air in the hollows of the honeycomb structure, the perforated plate, and the radiation impedance of the acoustic source. U_1 and U_2 are the volume velocity along the cavity and hollows of the honeycomb panel, respectively. The parameters α and A are the conversion coefficients between domains, where the later is the surface area of the acoustic source. All the parameters in this fully-lumped model are described in detail in Ref. [3].

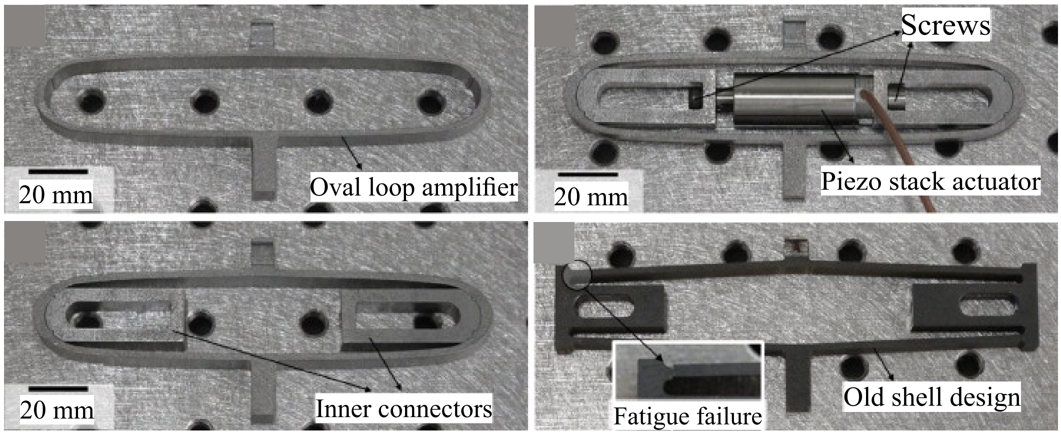


(a) Bridge-type model [6]



(b) Flexure hinge model [7]

(c) Honey-comb model [8]



(d) Ovel-shape model [9]

Figure 1: Available designs of the piezoelectric actuator amplified displacement models in the literature.

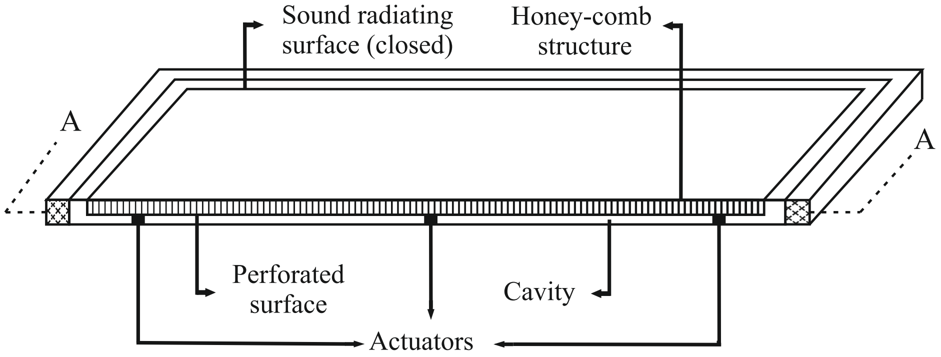


Figure 2: Cross section of the thin acoustic source.

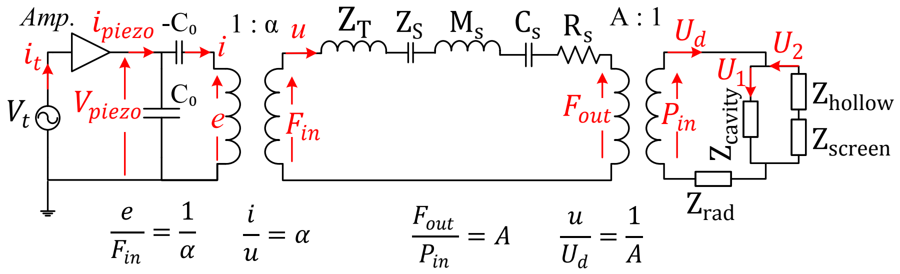


Figure 3: Complete equivalent electrical circuit of the acoustic source and piezoelectric actuators that can be connected to a switching amplifier.

According to the electrical analogy in Fig. 3, the radiation power of the lumped acoustic source is defined as the dissipated power in element Z_{rad}. This power dissipation occurs when U_d passes through the radiation impedance, Z_{rad}, in the circuit. One can evaluate P_{rad} by using the following equation:

$$P_{rad} = 0.5\Re(U_d^2 \cdot Z_{rad}^*) \tag{1}$$

Since the current in the acoustical domain, U_d, is a function of all the electrical elements in the circuit, the resulting radiation power is also a function of those elements. Therefore, P_{rad} is a function of i_{piezo} and V_{piezo}. That implies that P_{rad} is a function of the characteristics of the piezoelectric device, i.e. the dimensions of the piezoelectric element.

2.3 Optimization

The equivalent lumped electrical circuit, which is introduced in Ref. [3], is used in combination with MATLAB R2015b optimization toolbox to obtain optimum dimensions of the piezoelectric stack actuator. The following optimization problem is defined:

$$\begin{aligned} \underset{r_p, l_p}{\text{maximize}} \quad & P_{rad}(r_p, l_p) \\ \text{subject to} \quad & m_{piezo} = constant \end{aligned} \tag{2}$$

where r_p and l_p are the radius and length of the piezoelectric stack actuator, respectively. According to Eq. (2), the only constraint is the mass of the piezoelectric stack actuator (m_{piezo}). The objective is maximizing the radiation power (P_{rad}) of the acoustic source at a low frequency below $1000\mathrm{Hz}$ (for instance, at $200\mathrm{Hz}$) when it is excited by a piezoelectric stack actuator. The radiation power in Eq. (2) is calculated according to Eq. (1).

The result of optimization is shown in Fig. 4. According to the figure, the maximum radiation power for the acoustic source corresponds to the optimum radius and length of $4\mathrm{mm}$ and $100\mathrm{mm}$, respectively, for the piezoelectric stack actuator.

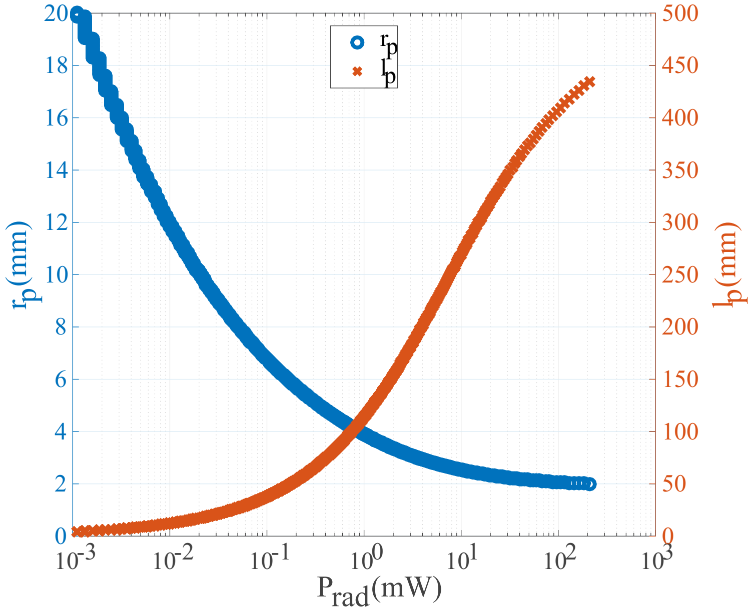


Figure 4: Optimization result showing the optimum radius and length of the piezoelectric actuator that results in a maximum radiation power of the acoustic source.

2.4 Requirements and limitations

According to the outcome of the optimization, a piezoelectric stack actuator with the length of $100\mathrm{mm}$ is needed. However, the available space for the actuator in the structure of the acoustic source is limited to the cavity gap with the thickness of $10\mathrm{mm}$. Since the defined piezoelectric element is not fitted in the available gap, the existence of a displacement-translator mechanism is crucial. With the aid of a displacement-converter mechanism, displacement of a piezoelectric device in a direction without any space constraint can be converted to the desired vertical displacement.

3 Numerical modeling

Flexures are elastically deforming parts that provide a precise range of motion in the desired degrees of freedom. The produced motion is predictable and repeatable [10]. These compliant mechanisms have a relatively high stiffness in the constrained directions [11]. Due to the fact that flexures are both frictionless and maintenance-free [11], they can be used in the design of the required converter mechanism in the current research.

Using a flexural displacement-converter, it is possible to use piezoelectric devices in a horizontal plane and obtain the converted displacement in a vertical out-of-plane direction. In the present paper, a 3D numerical finite element simulation in COMSOL Multiphysics software package is performed. The designed mechanism has only one degree of freedom for the displacement in the vertical direction.

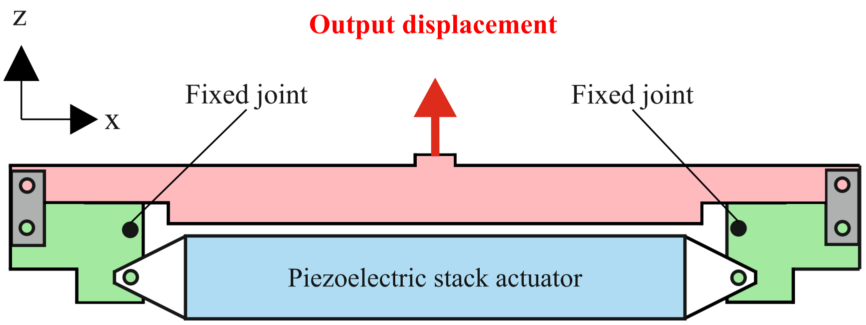
To design the flexural mechanism, first, a rigid multibody dynamics model is studied that fulfills the following requirements:

- The suggested structure has to be very small in order to be fitted in a ten-millimeter air cavity gap,
- Since a smooth vertical displacement is desired that has no parasitic motion in other directions, a symmetric design is crucial to ensure bending modes are not transmitted to the output.

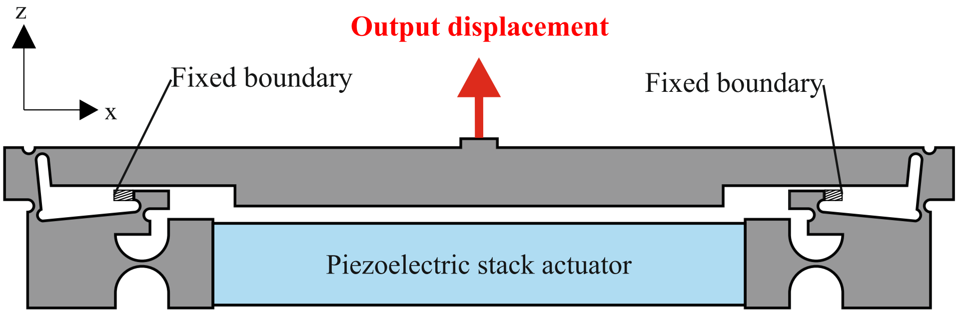
In the next step, the rigid multibody dynamics model is converted to an equivalent flexure-based mechanism. Therefore, all hinge joints used in the multibody dynamics model are replaced by flexural notch hinges.

4 Results and discussion

The suggested 3D design is schematically shown in Fig. 5. First, a rigid multibody model is designed that is shown in Fig. 5(a). Then, the joints and hinges in the rigid multibody design is converted to the equivalent flexural notch hinges. According to Fig. 5(b), by using flexural notch hinges, the entire mechanism becomes a single piece. As it can be seen in the figure, both ends of the flexural mechanism are fixed to resemble the fixed joints in the multibody counterpart model. Therefore, the horizontal deformation of the piezoelectric stack actuator is translated to the output. Due to the symmetric design, the central part of the mechanism only experiences a vertical displacement. The thickness of the designed mechanism in the direction of z-axis is only $10\mathrm{mm}$ similar to the thickness of the air cavity. The out-of-plane thickness of the flexural mechanism in the direction of y-axis is $20\mathrm{mm}$ to ensure that the mechanism is stiff enough in the out-of-plane direction.



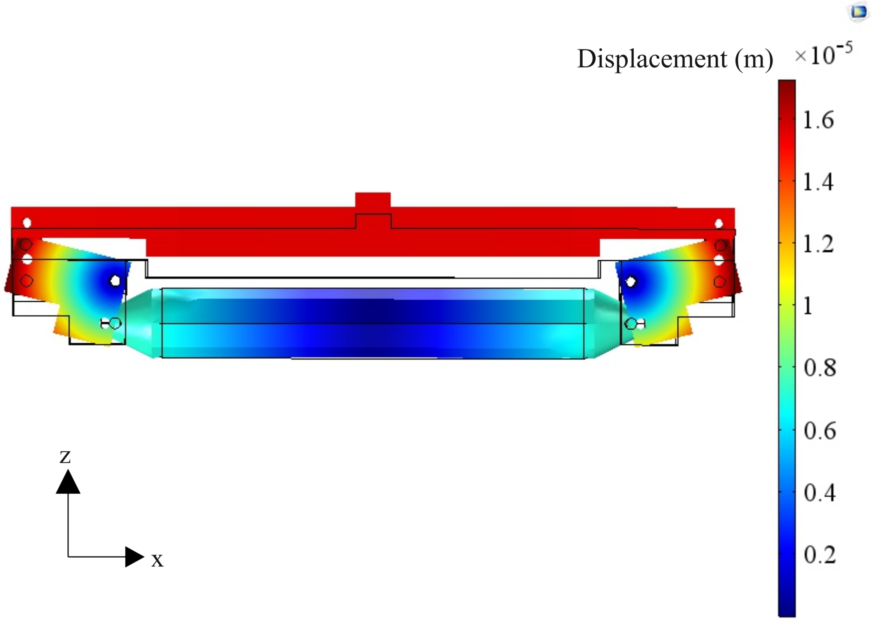
(a) Rigid multibody model.



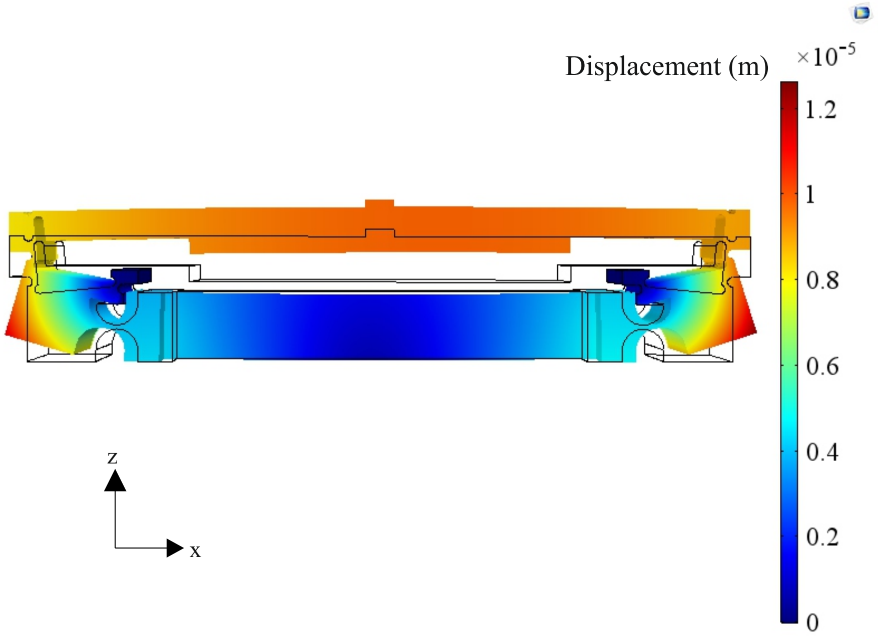
(b) Flexural design.

Figure 5: The suggested displacement-converter mechanism.

The results of a numerical simulation of the suggested mechanism in COMSOL Multiphysics is shown in Fig. 6. According to the figure, a vertical output displacement with the order of magnitude 1.5×10^{-5}m and



(a) Rigid multibody model.



(b) Flexural design.

Figure 6: Displacement of the suggested displacement-converter mechanism simulated in COMSOL.

1.2×10^{-5}m is obtained using the rigid multibody model and the flexural design, respectively. The input displacement to both mechanisms is supplied by a piezoelectric stack actuator that is located in the horizontal plane (see Fig. 5) and deforms in the direction of x-axis. The deformation of the piezoelectric element is approximately 4.5×10^{-6}m.

Thanks to the proposed flexural mechanism in the structure of our acoustic source, it is possible to use a piezoelectric stack actuator larger than the available cavity gap. The numerical results reveal that the proposed design is able to achieve the required force and displacement for the acoustic source, while the small thickness of the thin acoustic source is preserved. The combination of the flexural mechanism and a horizontal piezoelectric element is an alternative for a vertical single piezoelectric multilayer actuator.

5 Summary

In the present research, the optimization study shows that the required length for the piezoelectric multilayer element as the excitation part of our acoustic source is approximately $100\mathrm{mm}$. However, due to space limitation in our thin acoustic source, it is not possible to use a piezoelectric stack actuator with a length larger than $10\mathrm{mm}$. Therefore, a flexural mechanism is designed to be used as a displacement-converter mechanism. The flexural mechanism is simulated numerically using COMSOL Multiphysics software package. The mechanism aims to translate an in-plane input displacement to an out-of-plane vertical output displacement. With the aid of the suggested displacement-converter mechanism, deformation of a piezoelectric stack actuator, which is located in the horizontal plane, is translated into a vertical direction. The configuration of the suggested flexural mechanism and the piezoelectric device can be used as the actuation part of the thin acoustic source. The thickness of the suggested flexural mechanism is small enough to be fitted in the air gap of the thin acoustic source.

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