INVESTIGATION OF THE DYNAMIC BEHAVIOR OF A DOUBLE-PADDLE SCANNER

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Abstract. *Dynamic characterization is a key factor in the design, fabrication and optimization of microsystems. Micro-scanners are currently subjected to a wide research work. In this paper, the dynamic behavior of a monolithic single-crystal silicon microstructure is investigated. The microstructure used is a double-paddle scanning mirror for laser applications. It consists of two similar plates (wings) connected to other plate (mirror) and is suspended by one torsion bar. The dynamic characterization is conducted numerically, using Finite Element Analysis (FEA). The numerical modeling is described. Due to the tiny size of the scanner, the effect of the acoustic pressure in the surrounding air may become critical and is subsequently investigated. Through numerical simulations, the influence of variations in other parameters, such as Young's modulus and mass density, which mainly suffer some changes due to fabrication processes, are also reported.*

Keywords*. Double-Paddle Scaner, dynamic analysis, modal analysis, fluid-structure interaction.*

1. Introduction

In order to design microsystems from a mechanical point of view, it is necessary to characterize their dynamic properties. The microsystem investigated in this work is a double-paddle scanning laser mirror structure (DPS). One particular mode of this oscillator is a torsion mode in which the mirror and the paddles are twisted. Most of the work presented here is concentrated on this mode as the desired operation mode. The other modes are also shown for design purposes. The prupose of this paper is to analyze the torsional mode and explore its suitability for the design of a DPS with sufficient quality factor. The dynamic characterization becomes a key factor in the design process, where it is conducted via finite element analysis, as described in the sections below. Different microfabrication techniques can be used to produce microsytems [Madou, 1997]. Among them, the microfabrication by micromachining a single crystal [1,0,0] Si wafer (bulk silicon micromachining) using KOH as a selective etchant, and which was the first to be used on a large scale production of microsystems such as pressure sensors, accelerometers, and ink jet heads. It takes advantage of the exceptional mechanical properties of silicon. Due to this fabrication processes, the mechanical properties of the Si may suffer some changes, which could have an effect on the operation of the DPS. For this purpose, the effect of material changes on the dynamic behavior of the DPS is investigated. On the other hand, after the mountaing of the DPS in the operating box, the influence of the fluid/structure interaction could also have a great effect on the operation of the DPS, and for this reason the effect of the acoustic cavity on the structure is also preliminarily investigated. The work presented here is part of the design process for developing an acoustically-excited double-paddle scanner using microelectromechanical systems (MEMS).

2. Definition of the DPS structure

The micromechanical double-paddle scanner investigated in this work is made of monolithic, single-crystal silicon. It consists of a mirror plate (5 x 3 mm) connected to a double rectangular plates each of 3.5mm x 3.5mm and the structure is suspended to a frame by a 3mm torsion bar. They are to be used as mechanical oscillators for, among other applications, the deflection of laser beams on laser printers and bar code readers (Ferreira et al., 1998, Ferreira and Moehlecke, 1999). Figure 1 shows the DPS structure used in this investigation. This DPS is designed to be excited by an acoustical device, thus no rotor circuits are build on its surface. When acoustic waves, generated by small loud speakers, are directed to the double paddles at a certain frequency, the DPS will vibrate in a certain mode in which the mirror will start to twist around its axis. The manufacturing of the DPS is based on a one-sided, polished, 0.280mm thick [1,0,0] wafers. First, a SiO2 is grown on one side, and a thick layer of photoresist is spun onto its surface. Then the wafer is cleaved, exposing a [1,0,0] edge. The mask is then aligned to this edge. Using a [1,0,0] wafers and aligning to the([1,0,0] axis results in a non-rectangular corners in the anisitropic etch process. The KOH when used as an etching agent does not etch perpendicular to the [1,0,0] surface, but in an angle of 54.7º with respect to the [1,0,0]. The etching effect on the wafer is taken into account in the FEA modeling of the DPS structure.

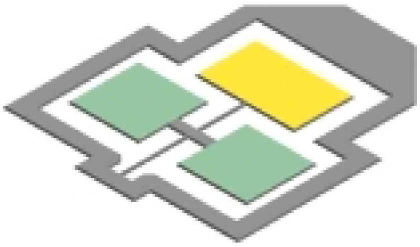
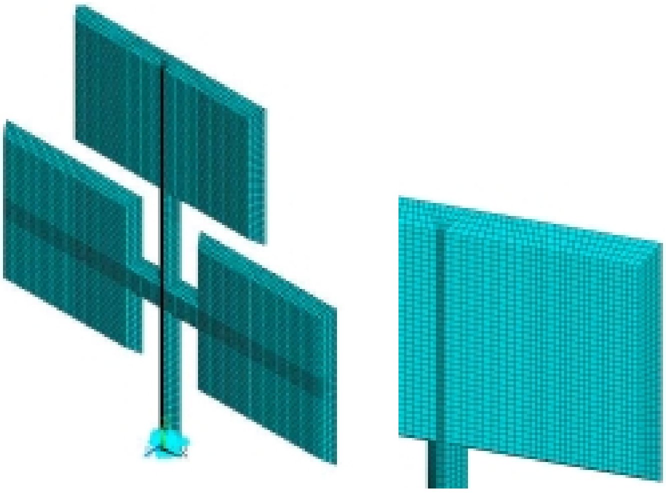


Figure 1. Double-Paddle Scanner with its supporting edge.

3. DPS modal analysis via FEA

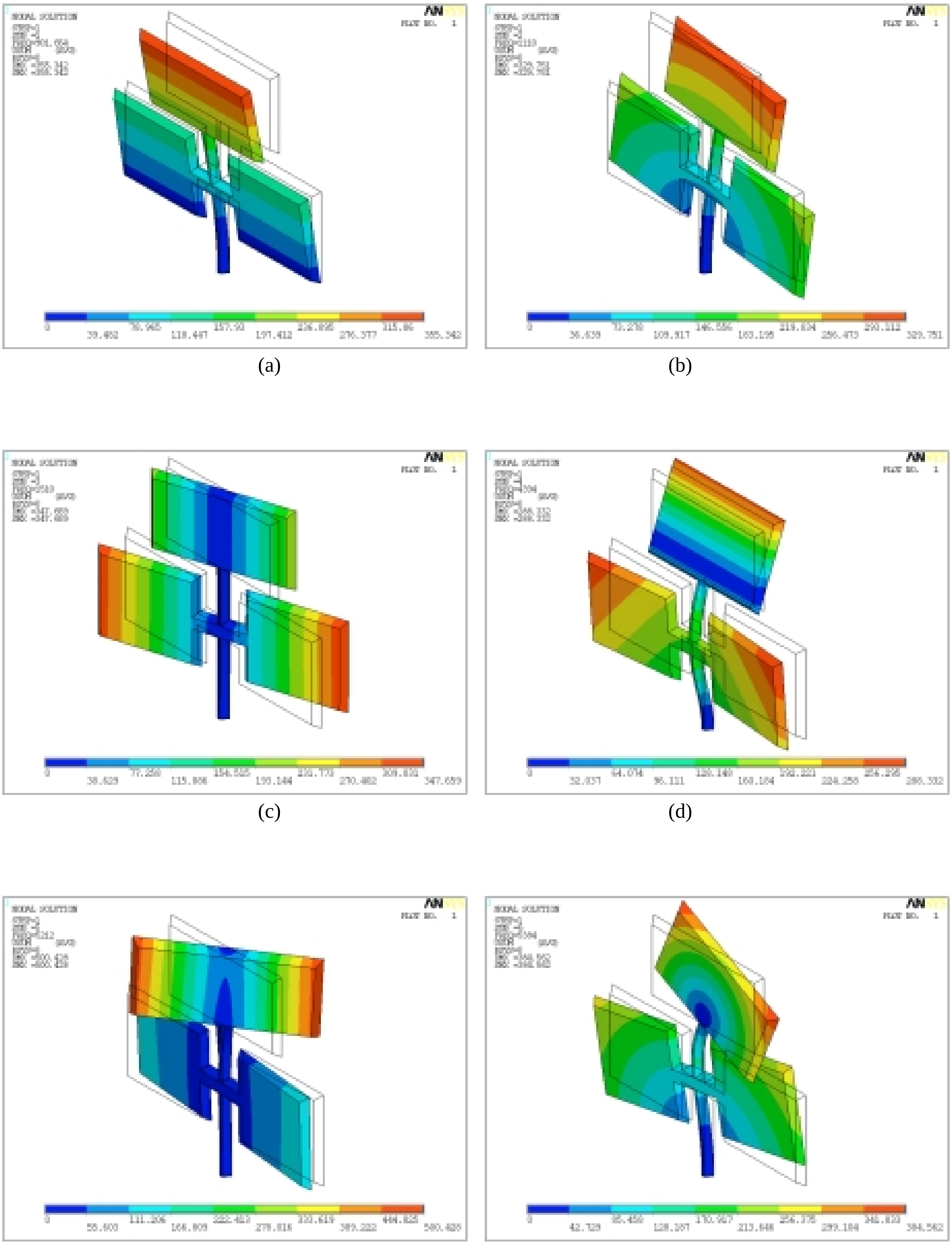
The DPS described in Figure 1 was modeled via FEA. The purpose of this work is to analyze the vibration modes of the DPS and explore their suitability for certain applications. A very specific application is the design of an acoustical excitation device for the excitation of the scanner in a certain torsional mode. These analysis is based on the form of the operation mode and the displacement magnitudes of the laser scanner (mirror). For the identification of the first modes, a finite element model was developed using ANSYS® Automatic Parametric Design Language, APDL. The FEA model of the DPS was created, taking into account the etching effect of 54.7º, which results in cross-sections with a trapezoidal form. For this kind of geometry it was not possible to use shell element, which are relatively easier to model, but instead a tridimensional solid elements were used. SOLID45 is used for the three-dimensional modeling of solid structures. This kind of element is defined by eight nodes having three degrees of freedom at each node. The use of this kind of element would eventually result in larger DOFs system to solve. A total of 23560 elements were used in the mesh, resulting in 31090 nodes each with 3 DOFs and 4 element to represent the DPS thickness, see Figure 2(a,b). The elastic stiffness constants used are: mass density ρ=2330Kg/m^3, Young's modulus E=150GPa, Poisson ration ν=0.09 and a thickness of 280μm.



(a) (b)

Figure 2. The DPS mesh (a) with the trapezoidal cross-section characteristics (b).

The calculated mode shapes of the lowest 6 natural frequencies are shown in Figure 3(a-f). It should be noted that the displacements shown in the figure are normalized for each mode separately. The DPS is to be designed to operate by reflecting laser beams at the top mirror and thus, the 3rd mode of 1510 Hz, shown in Figure 3(c), is the selected operation mode for the scanner.



(a) (b)

(c) (d)

(e) (f)

Figure 3. The lowest 6 mode shapes of the DPS.

Table 1 First 6 natural frequencies of the DPS.

mode Nº	Figure index	Value in Hz element size=300x10^{-6}	Value in Hz element size=100x10^{-6}
1	3 (a)	901.65	919.16
2	3 (b)	1124.2	1110
3	3 (c)	1706.3	1510
4	3 (d)	4538.1	4394
5	3 (e)	5521.4	5212
6	3 (f)	5914.1	5384

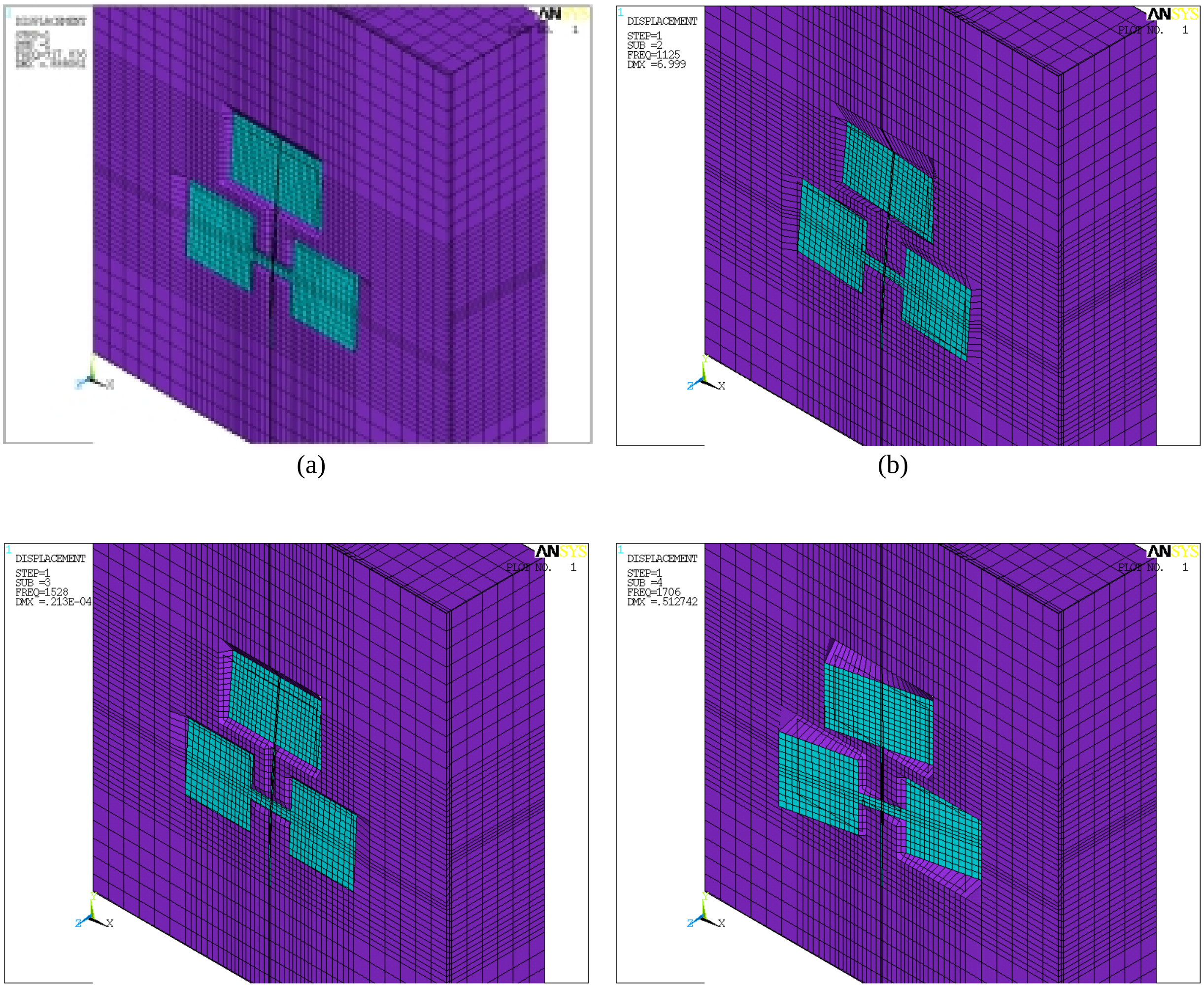
Table 1 shows the values of the natural frequencies identified through the FEA model for two different meshes, with different element sizes. The solution was observed to converge to an element size of 100x10^{-6}. The other element size is used for the sake of comparison with the fluid-structure interaction problem where this element size was used for fluid-structure analysis due to element number limitations of the used version of ANSYS®. Observe that the 5th mode of 5212.4 Hz has a similar behavior as the 3rd mode but with larger relative displacement. The 3rd mode is adopted as the operation mode, nevertheless, the 5th mode also has to be investigated for operational suitability.

4. Fluid-structure interaction

The suggested DPS microsystems is packed onto a plexiglas mount with a circular hole that gives access to the double-paddle plates. An acoustic excitation device is currently being built, consisting of two mini loudspeakers mounted in such a way that the acoustic waves are guided to both sides of the double-paddle plates. Gaps of 5mm below and around the DPS and of 2mm above the DPS are left for the free vibration of the system. These gaps were modeled with fluid domain elements, which will have an effect of the dynamic behavior of the DPS, by changing its modal characteristics. These effects are investigated by analyzing the air-structure interaction behavior. For this, the acoustic/structure domain is modeled via FEA. Initially, an element size of 300x10^{-6} was used for the meshing of the DPS structure and a size of 900x10^{-6} was used for the meshing of the fluid domain. Therefore, the natural frequencies obtained should be compared to those of the DPS given in the third column of Table 1. It should be mentioned here that no boundary condition was applied at the boundaries of the fluid domain, thus, resulting in the consideration of the natural condition of rigid wall (Neuman boundary condition). The obtained natural frequencies are given in Table 2. The first structural mode shapes of air-DPS interaction are shown in Figure 4 describing the displacements of the DPS. Note that the fluid elements above the DPS of thickness 2mm were cutout in the figures in order to observe the DPS mode shapes.

Table 2 First 4 natural frequencies of the air-DPS interaction model.

Mode Nº	Figure index	Type	Characteristic	Value in Hz
1	4 (a)	deflection in x-z plane	structure-dominated	917.84
2	4 (b)	rotation about z-axis	structure-dominated	1124.8
3	4 (c)	deflection in x-z plane	acoustic-dominated	1528.3
4	4 (d)	rotation about y-axis	structure-dominated	1705.8



(a) (b)

(c) (d)

Figure 4. The first four structural mode shapes of the air-DPS interaction model. Nodal solution is displacement.

It was noted that the same natural frequencies of the DPS-only are maintained, except that the 3rd structure-only mode is now shifted to be the 4th mode. In contrast to the other three modes, the 3rd mode in this case (of 1528.3Hz) is an acoustically dominated mode caused by the acoustic cavity in which the acoustic pressure generated in the cavity causes the DPS structure to vibrate in a form similar to that of the 1st mode. This characteristic can be observed in Figure 5 in which the acoustic pressure is observed to have higher values in contrast to the other 3 modes where the acoustic pressure was almost zero. The acoustic mode shapes described by the pressure DOF are given in Figure 6(a-d).

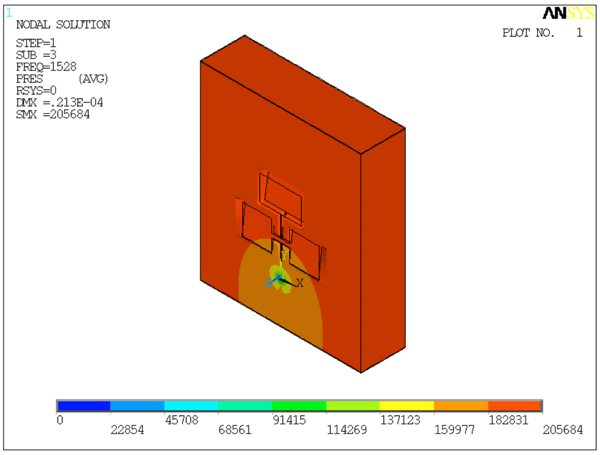
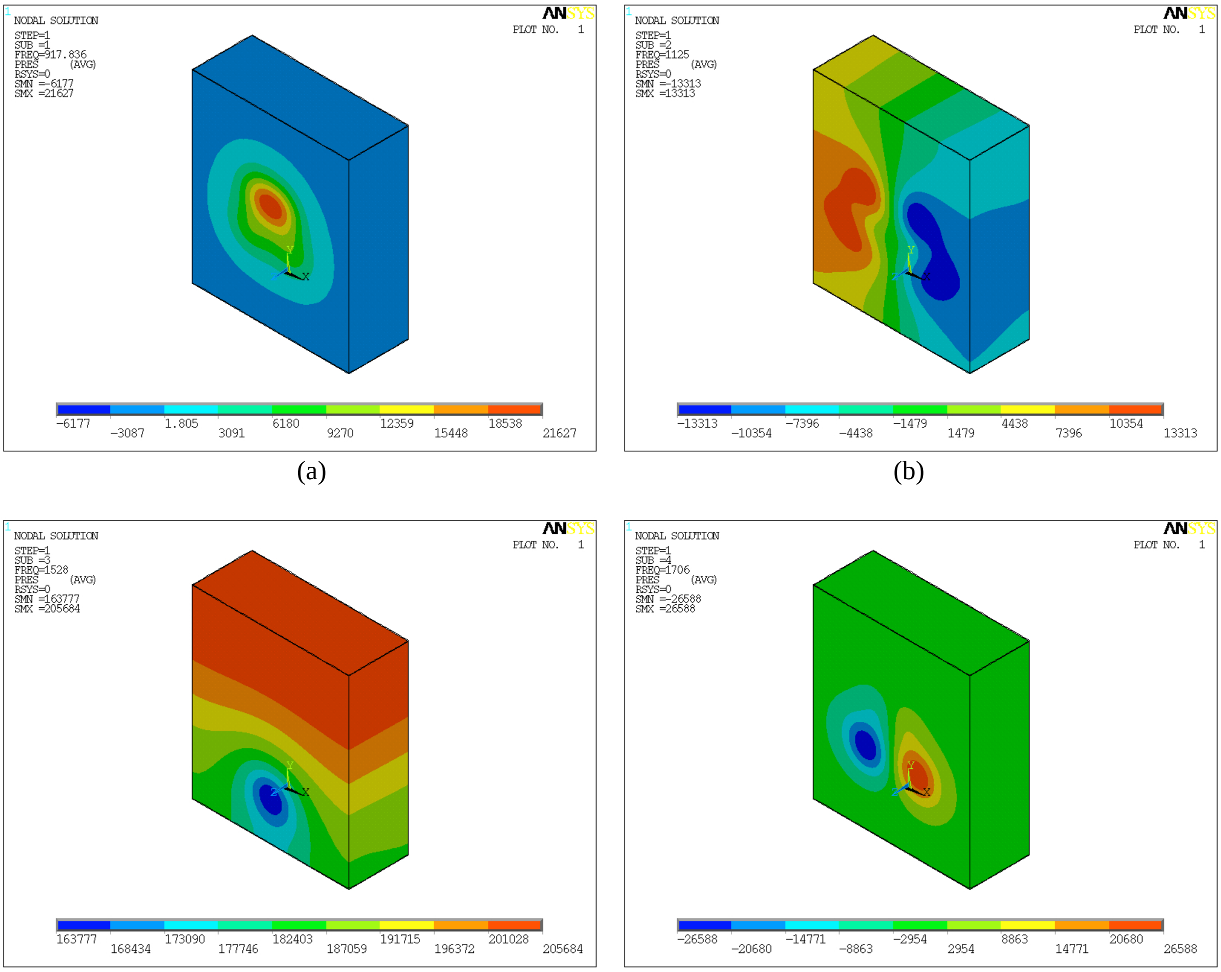


Figure 5. The acoustically dominated mode causing a new vibrating mode of the DPS.

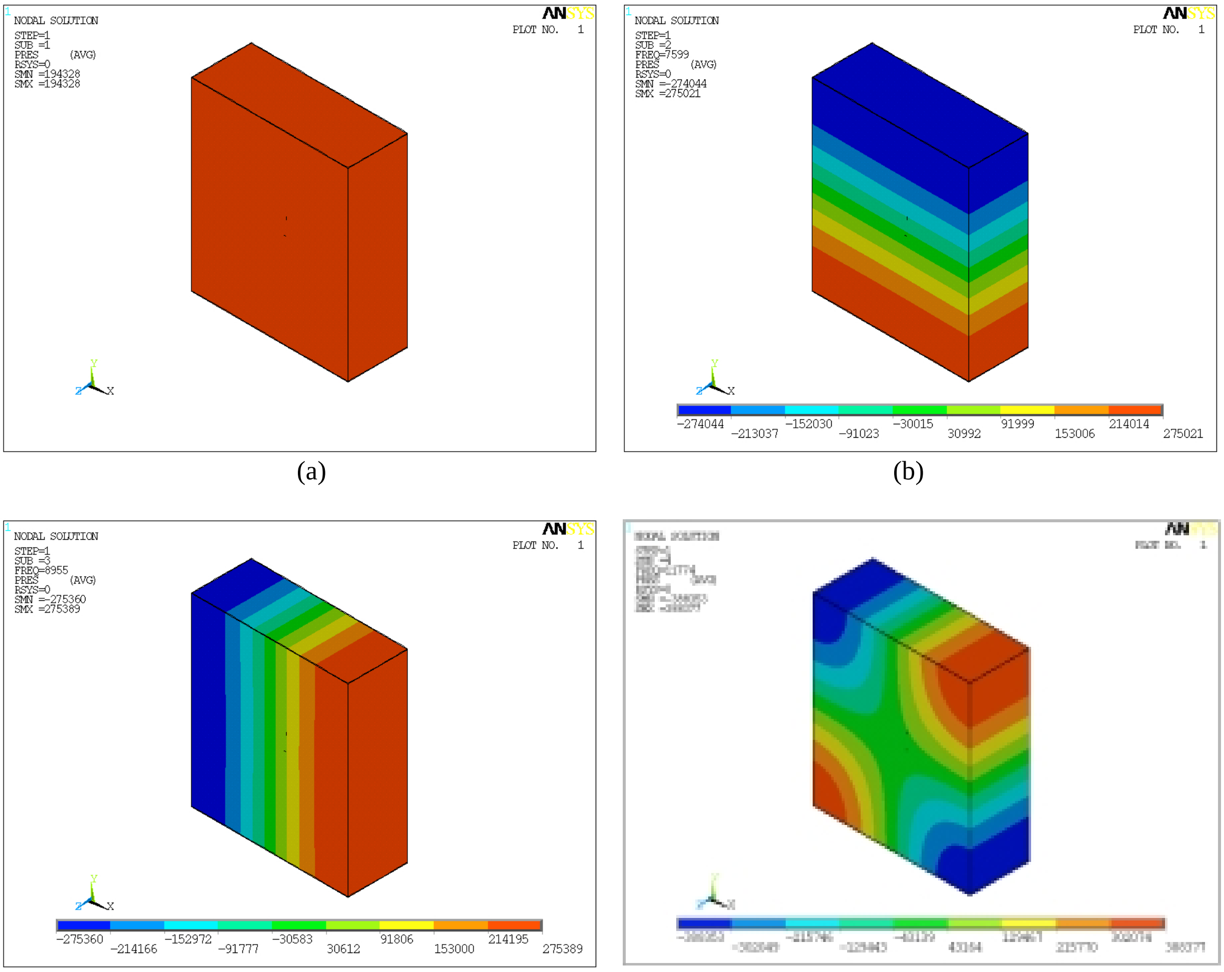


(a) (b)

(c) (d)

Figure 6. The first acoustic mode shapes of the air-DPS model. Nodal solution is pressure.

For the sake of clarity, the fluid-only model is also analyzed, disconsidering the existance of the DPS structure. The resulted acoustic-only mode shapes, with their respective natural frequencies are shown in Figure 7 (a,b,c and d). Observe that the 1st mode is the rigid-body mode. All modes are similar to those usually obtained for closed acoustic cavities.



(a) (b)

(c) (d)

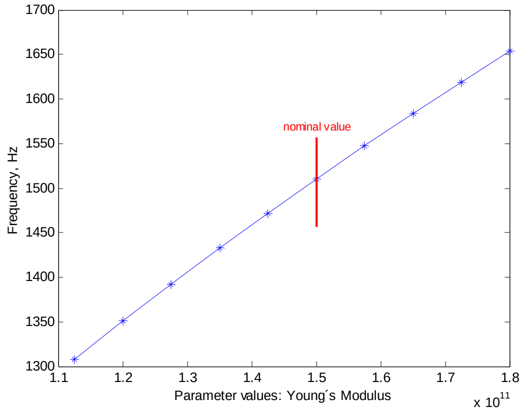
Figure 7. The first mode shapes of the fluid-only model. Nodal solution is pressure.

It should be mentioned that the natural boundary condition of Neuman is considered at the boundaries of the space reserved for the DPS structure. Observe that the mode shapes are similar to those of the acoustic pressure in an acoustic cavity. These modes are demonstrated for the sake of comparison between structure, fluid-structure and fluid-only mode shapes.

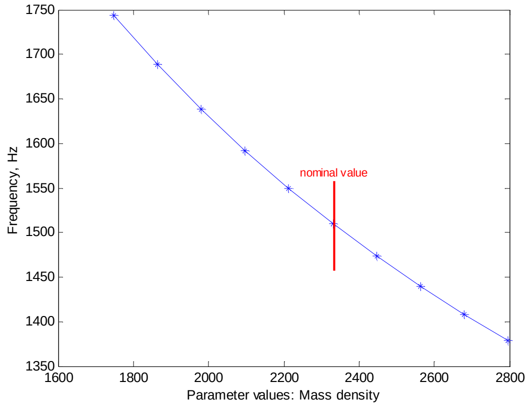
5. Influence of material parameter variations on the dynamic behavior

The DPS utilized was made of Silicon (Si), following the well-known process of fabrication. Normally, in modeling these kind of structures, the material properties, such as Young's modulus, Poisson ratio and mass density, are considered to vary isotropicaly, where constant values are used. These values are usually chosen from the different available material libraries, but they could have distinct values due to fabrication process changes or due to different material library sources.

The dynamic analysis of the DPS structure were conducted with respect to possible changes specifically with respect to the three mentioned parameters. The third mode of vibration is the mirror deflection mode, which is the mode of interest in this work. The natural frequency of the third mode is calculated, using FEA, according to variations of each one of these parameters respectively. Variations of –25% to +20% are considered in the analysis. The changes of third mode natural frequency with respect to changes in the three parameters are shown in Figure 8(a,b,c). Observe that the change in natural frequency varies from –12% to 12% for the case of variations in Young's modulus and mass density. This changes is observed to be less in the case of variations in Poisson ratio, around 1%.



(a) Third mode natural frequency changes with respect to variations in Young’s modulus.



(b) Third mode natural frequency changes with respect to variations in mass density.

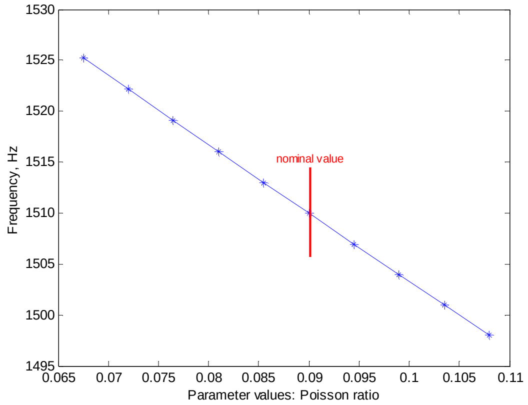


Figure 8. (c) Third mode natural frequency changes with respect to variations in Poisson ratio.

6. Concluding remarks

In this preliminary work, the dynamic behavior of a monolithic single-cristal Double-Paddle Scanner (DPS) was investigated. It consists of two similar plates (wings) connected to other plate (mirror) and is suspended by one torsion bar. One desired operational mode characterized by the deflection of the mirror about its axis is found to be an appropriate one. The dynamic characterization was conducted numerically using Finite Element Analysis. In this analysis, the material properties are chosen from world-wide available material tables. These values could suffer some changes due to handling and fabrication processes and thus modifying the dynamic characteristics of the investigated microsystem. For this purpose, the effect of the change in these properties was investigated. A maximum change of around 12% in the natural frequencies was observed as a result of changes of around 20% in Young’s modulus and mass density. For Poisson ratio, the changes were minimum and could be disregarded. The investigated DPS is in the project stage and is to be excited acoustically by a device under investigation. Due to the tiny size of the DPS that is being fabricated, the effect of the acoustic pressure of the surrounding media could become critical in modifying the dynamic behavior of the DPS. For this sake, it was observed from this work that a new mode was introduced by the acoustic cavity causing the DPS structure to vibrate. Nevertheless, the desired operational deflection mode shape was maintained to vibrate at the same frequency. Another similar mode was observed, which seems to be more suitable as its vibrating frequency is higher (4394Hz). Further investigations will be carried out to investigate this mode and experimental predictions will be conducted in order to validate the current numerical analysis.

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