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Review Article

Assessment of actuation performance regarding miniature mechanisms triggered by piezoelectric arrangements—A review

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ABSTRACT: This article aims to evaluate and analyze the role of piezoelectric actuation in miniature robots in general and converging towards systems using traveling waves on beams and plates of thin structures. In other words, examining the later in the general context of the first. The useful values of interest concerned by this subject are diverse: applications needing high specific power particularly suitable for miniaturized robots, vibrations supervision, damage and fatigue revealing, medical and other micro pumps applications, different controls in difficult access areas, harvesting of energy, etc. The characteristics and behaviors of actuation, which is accomplished by resonant and non-resonant piezoelectric systems, are first reviewed and examined. The amplification of the actuation is then highlighted. Next, non-resonant piezoelectric actuators for stepping functions are discussed. Then, the main principles of piezoelectric resonant ultrasonic motors are summarized allowing the illustration of the operation of traveling wave piezoelectric resonant beam robots. Next, traveling waves on thin structures are examined, reviewed and conferred. This involves, driving of piezoelectric patches in miniature robots, applications of thin structure embracing piezoelectric materials, and finally thin structure piezoelectric miniature beams and plate robots. Following the last sections, a discussion of the operations of locomotion and positioning of the piezoelectric actuators is presented.

KEYWORDS: piezoelectric actuation; ultrasonic motors; traveling waves; thin structures; miniature robots; beams and plate structures; locomotion and positioning

1. Introduction

Locomotion and positioning are often employed in advanced energy devices, e.g., optimal appliances, robot junctions, spatial arrangements, precision machineries, etc. This can be achieved by using actuators reflecting high displacement resolution and positioning precision as well as swift response, high rigidity and actuation strength, uncomplicated configuration and little volume. Piezoelectric actuators are perfect candidates for such attributes[1–8]. They can be integrated for locomotion or positioning in energy devices or constituting autonomous miniature robots. These actuators perform following the inverse piezoelectric effect. Indeed, a piezoelectric material engenders electric potential under the effect of applied compression, which is the direct effect, while an applied electric potential on the material produces mechanical deformation that is the in-verse effect. The direct effect is operated in pressure sensors and energy transducers while the inverse one is behaved in actuators. Piezoelectric actuators can be used straight or as amplified actuators. The amplified case reflects two energy conversions electric-mechanic and mechanic-mechanic typifying the movement produced by actuator. The first conversion exhibits the inverse effect of piezoelectric phenomenon that produces a small displacement while the second concerns a particular locomotion, which magnifies such a movement. The concerned locomotion sources are generally inspired after natural locomotion and could be classified by their movement across a fluid or at a solid surface[9].

Referring to piezoelectric actuators vibration condition, they can be categorized as resonant[10–12] and non-resonant[13–17]. In the resonant case, also named ultrasonic motors of rotating or linear structure, high frequency resonant vibrations of a fixed part (stator) will derive a moving part (mobile)[18–21]. They reflect high speed and lengthy whiplash but limited positioning precision. Furthermore, structures that are more recent have been developed in this resonant category, based on travelling waves on finite beams and plates robots[22–26]. The non-resonant case comprises four types of actuators: stack, inchworm stepper, seal and inertial steppers. The stack (multilayer) actuators[27,28] have linear axial movements created by inverse effect of DC voltage, reflecting high displacement resolution but poor strokes. The inchworm ones[29,30] use several stacks to increase their strokes, a part of stacks insure adhesive contact of the fixed driving part and the mobile part, and the others accomplish the propelling stepping. The inertial and seal steppers[31–36] drive the mobile with slow extending and fast shortening displacements of stacks, reflecting small yield force and rearward motion inconvenient.

Many works have been published on specific subjects involved in this topic. The proposed contribution aims to evaluate and amalgamate a synthesis of the problems dealt with in the field, focusing on efficient actuation of miniature piezoelectric robots.

The objective of this contribution is the evaluation of piezoelectric systems using traveling waves on beams and plates of thin structures in the context of actuation performance of miniature piezoelectric robots in general. This involves the analysis and discussion of the various features and characteristics of actuation methods. In addition, the information given will be supported in the article and can be supplemented from the important but not exhaustive literature provided in the list of references.

In the present assessment, after the introduction of characteristics and behaviors of piezoelectric actuation in general, different related features will be exposed, reviewed and discussed. First, the amplification of actuation will be highlighted. Then the non-resonant piezoelectric actuators regarding stepping performs will be conferred. The main principals of piezoelectric resonant ultrasonic motors will be then summarized. Relating to these principals the traveling wave piezoelectric resonant beam robots will be approached involving the excitation modes in finite beam structures through examples of traveling wave piezoelectric resonant, ultrasonic motor and beam robots. Next, the traveling waves on thin structures will be examined, reviewed and discussed. This involves actuation and driving of piezoelectric patches in miniature robots, applications of thin structures containing piezoelectric materials and thin structures piezoelectric miniature beam as well as plate robots. Subsequent to the last sections, a summarized review of locomotion and positioning operations of piezoelectric actuations is given. The last section discusses different details relative to the questions treated in earlier sections. Conclusions are then summarizing the contributions of the paper and the questions of interest raised by this subject.

2. Amplified actuation

Thanks to the inverse piezoelectric effect, these materials allow actuation. However, the distortion of one layer of piezoelectric is little to be operated straight in the majority of applications[37,38]. Greater deformations can be attained by stacking up several layers of ceramic piezoelectric with synchronized orientations of deformation and electrodes parallel associated[39,40], thus we have a piezo-stack actuator that permit a more important combined movement. Note that the importance of the displacement depends of the number of layers of the piezo-stack, which leads to outsized actuator for attaining a reasonable movement. However, even with this multiplied displacement, superior movement scale is habitually necessary in particular for robotic usages. Subsequently, attaining higher output motions with acceptable size actuators can be obtained by mechanical piloting tools associated with piezo-stacks named amplified actuators. Typically, an ordinary single cut fabricated elastic material forming a piloting tool, a flexure hinge, which produces movements by self-deformation under force application. Such structures have the advantages to be small with soft repetitive displacements, little inertia and no friction. Accordingly, they are often employed under different structures for conducting movements generated by piezo-stack actuators[41–46], thus offering movement guiding and motion amplification needed for robotic applications.

3. Non-resonant piezoelectric steppers

The amplifying appliance considerably augments the operational extent of piezoelectric materials. However, the resulted displacements are yet not enough for far-reaching procedure requests. Therefore, employment of stepper actuators seems more normal. Steppers whose locomotion is based on friction are categorized into inchworm, seal and inertial actuators.

3.1. Inchworm actuator

The inchworm actuator mimics the swarming attribute of the insect named likewise. Mimicking the insect, this actuator commonly encloses a feeding component and two fastening components all contain piezoelectric material, which resemble respectively to the bendable body, front and rear feet of the insect[29,30]. Note that the functioning of the two fastening components of the actuator are both sporadic.

3.2. Seal actuator

The seal actuator is also a sea seal imitating. If one of the two sporadic fastening components used in the last section is substituted by an incessant fastening one (corresponding to rear feet), the inchworm actuator is converted into a seal one[34–36].

3.3. Inertial actuator

If the sporadic fastening component used in the last section is substituted by an inertial piece, the seal actuator converts to an inertial one, which is composed of a feeding component, an incessant fastening one and an inertial piece[31–33].

4. Piezoelectric resonant ultrasonic motors

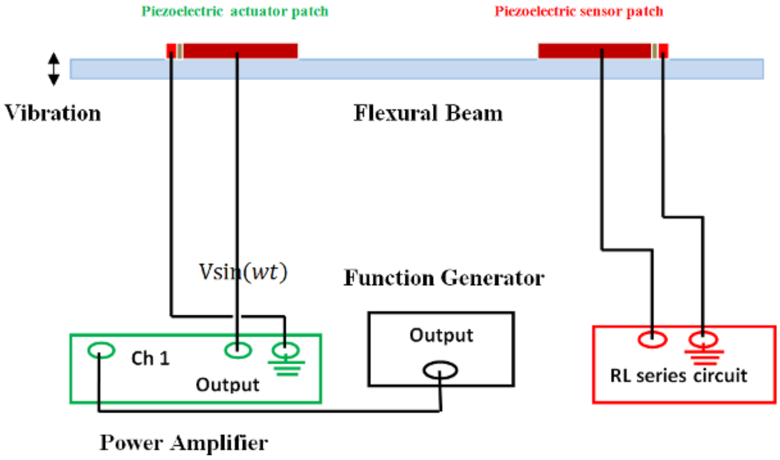
The piezoelectric resonant ultrasonic motor (PRUM) is composed of two parts, a stator and a mobile (slider). The stator is excited by a wave producing an elliptical movement, which is transformed into movement of the mobile by friction with the stator. The nature of the stator excitation wave (driving part) can be traveling wave (TW) or standing wave (SW) or hybrid. The difference between these waves is related to their ability of energy transfer. TW can convey energy through a distance of matter, while in SW the energy stays linked to a given position. The movement of the mobile relative to the drive stator may be rotary or linear[6]. In the following sections of this contribution, we will focus on structures whose functioning is based on TW PRUM. However, other types of PRUM like SW and L1B2, exhibit very interesting performances[19–21].

5. Traveling wave piezoelectric resonant beam robots

The linear TW PRUM motor mentioned in the last section originates the idea of TW piezoelectric resonant beam robots (PRBR). In this case, the completely robotic system progress itself instead of progressing the slider in the case of PRUM. Motion can be generated using single or dual mode excitation. Indeed, pure traveling waves can exist on lengthy configurations. On the other hand, in finite structures such as beams, the vibration wave is partway returned when it hits the borders. The mentioned excitation modes permit avoiding such wave reflection.

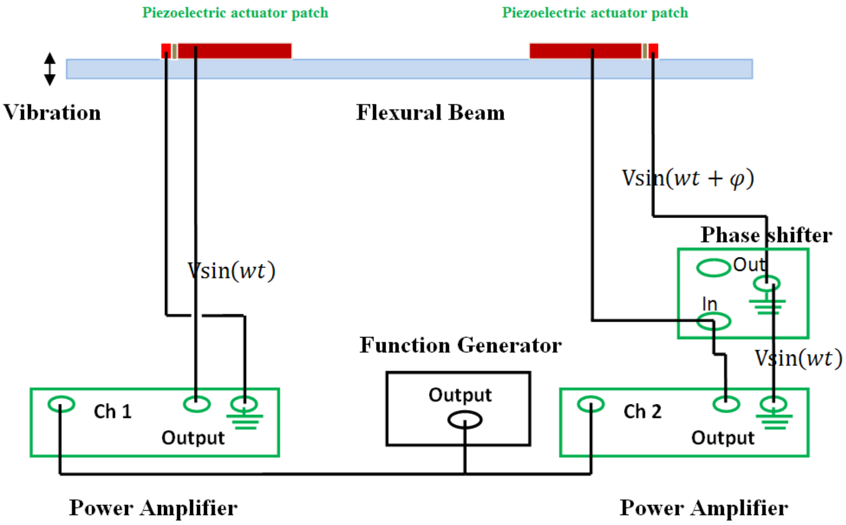
5.1. Excitation modes in finite beam structures

TW excitation in finite structures in general can be achieved as mentioned before in one or two-mode. In the one-mode excitation, a piezoelectric transducer driven at resonance frequency is placed at one end of a beam, creating beam vibration (actuator action-electric source) generating a TW, while another transducer placed at the other end of the beam to avoid the wave reflection (sensor action-electric load). This permits the conversion of vibrations into heat and can be done using a passive RL electric circuit or an active control technique permitting the regulation of the vibration of the TW down the beam. In the two-mode excitation, two piezoelectric transducers placed one at each end of the beam working as actuators creating beam vibration resulting in a TW. This is done using active control techniques permitting beam vibration resulting of applying at once by the two transducers, two close beam natural mode shapes at the same frequency (between two resonance frequencies) but 90° phased. **Figure 1** illustrates these two excitation types.



(a) One mode excitation.

Figure 1. (*Continued*).



(b) Two modes excitation.

Figure 1. Schematics of one and two mode excitations in the case of PRBR[4].

Note that the inverse TW direction and hence motion direction can be obtained by the inversion of the two transducers roles in the one-mode excitation and changing phase difference between the signals of the two transducers from 90° to −90° in the two-mode case. In addition, the transducers positions, the source frequency as well as circuit and control parameters permit to supervise the character of the TW and therefore the motion[4,22].

Comparisons of the performances of one and two-mode excitations will be considered in section 8 through realized examples.

5.2. Examples of TW PRBR

Various applications concerning TW PRBR as well as PRUM can be found in literature, we will give some examples of them. In the case of linear PRUM, see for one-mode excitation[47] and for two-mode excitation[48]. In the case of TW on finite beam structures in general[49]. Specific applications for TW on finite beams, see, e.g., the cases of a TW PRBR[4,22] and of a linear liquid micro pump working in one-mode excitation (two transducers: vibrator-absorber) or two-mode excitation (transducers: vibrator-vibrator)[3,50,51]. **Figures 2** and **3** show the principles of such beam robot and micro pump.

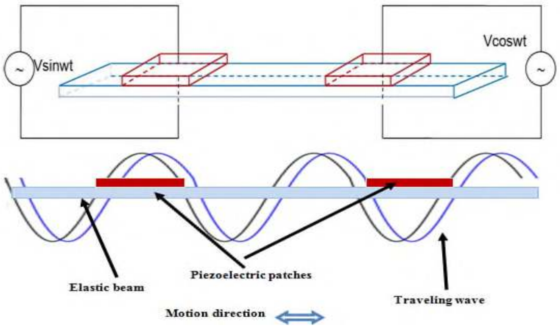


Figure 2. Schematic representation of the principle of a TW PRBR with two-mode excitation[4].

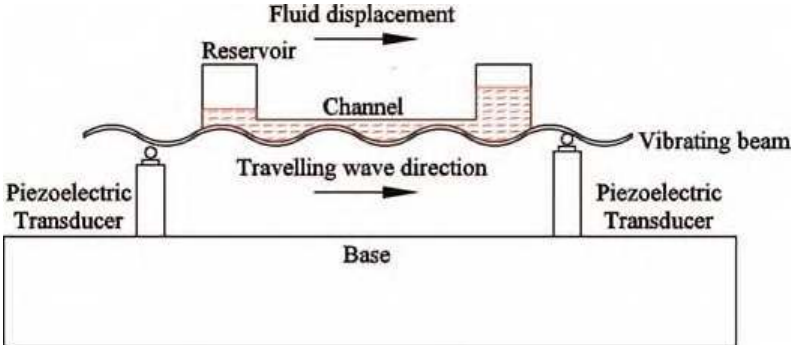
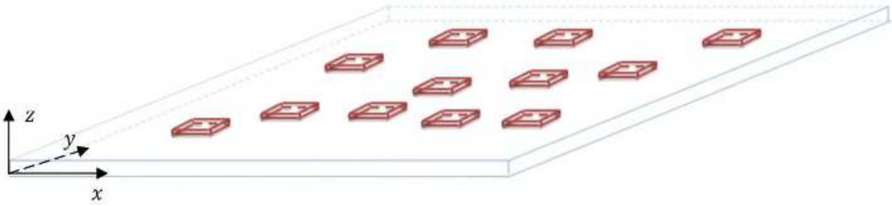


Figure 3. Schematic representation of the principle of a micro pump of π-like structure of a linear actuator[3].

6. TW on thin structures

A mechanical wave can be generated in a material by an oscillating source in interrelation with this material. This wave will propagate through matter carrying energy from one position to another. The ability to create and control wave motion through finite matter can be achieved by actuation mechanisms. The choice of thin structures as a support for the propagation of mechanical waves makes it possible to obtain one-dimensional progressive waves in beams actuated at their ends. Similarly, two-dimensional traveling waves can be initiated in plates with actuators placed at different points of the plate chosen according to the desired propagation. These actuators generate controlled oscillations corresponding to their specific excitations, which determine the different characteristics of the resulting traveling waves. The organization of the actuators may or may not be symmetrical depending respectively on whether or not they are collocated on the thin structure. In the symmetric case, the actuators are positioned face to face on both sides of the structure (collocated) while in the asymmetrical situation, the actuators are only on one side (non-collocated); **Figure 4** illustrates such non-collocated actuators for beam and plate cases. The use of thin beams or plates permits easy actuation by patches fixed on the structure. Miniaturization in such configuration becomes attainable.

(a) Beam case.



(b) Plate case.

Figure 4. Non-collocated piezoelectric patches bonded on a beam or a plate.

6.1. Actuation and driving of piezoelectric patches in miniature robots

Piezoelectric materials are used in various forms, in miniature robots for actuation due to their aptitudes to engender large forces under conforming driving voltages[52–62]. These materials are distinguished by a high specific power particularly suitable for miniaturized robots[63]. Moreover, the characteristic drawback linked to the control of piezoelectric materials by a high voltage, via an on-board source in the case of miniature robots, is no longer challenging. Indeed, many works have been carried out to surmount this difficulty[64–69]. Therefore, it is likely to incorporate compact on-board electronics to drive miniature piezoelectric robots, thereby increasing their packaging energy density[70].

6.2. Applications of thin structures including piezoelectric materials

Thin structures enclosing piezoelectric matters are broadly exploited for vibrations supervision[71–75], for structure damage and fatigue (e.g., health indicator for gear degradation monitoring) revealing[76–83], for designing and building actuations regarding inchworm motion, micro pumps, motors, etc.[84–88], for sensors design and for harvesting of energy[89–95]. Miniature robots using piezoelectric patches bonded on thin structures (PPBTS) are used in many applications involving beam and plate structures as will be discussed in following sections.

6.3. Thin structures piezoelectric beam robot

Thin structure piezoelectric robots are mainly miniature robots using PPBTS. An important category of these concerns beam robots, which permits linear motion due to actions of two piezoelectric patches bonded generally on the two beam extremities. As described in section 5.1, such actions can be of actuator-sensor mode type or actuator-actuator one.

As mentioned before, the piezoelectric matters fixed on the beam extremities, as, e.g., PPBTS, can be collocated or not (see **Figure 4**). The behaviors of such systems can be analyzed by analytical or numerical modeling[96]. In the case of collocated matters (symmetric on both beam sides)[72,97–102], while for the case of non-collocated matters (asymmetric on one side)[71,98,103–105]. Note that the analysis could be done using 2D discretized surface elements (using, e.g., finite elements method—FEM). A considerable reduction in the complexity and the computation time can be achieved by using 1D linear elements while considering the second dimension in the solved equation. This is possible through the consideration of a neutral axis. Such axis is confused with the symmetry axis corresponding to the mid plane of the system in the case of collocated patches. Such neutral-symmetry confusion in collocated patches structure case does not exist in the case of non-collocated patches case; see section 8 for details. Thus, in the last case, the neutral axis should be determined[96].

6.4. Miniature piezoelectric plate robot

These miniature plate robots use PPBTS and permit motions in different orientation depending on actions and positions of different piezoelectric patches bonded on specific locations of the plate. As in the case of beams the piezoelectric matters can be collocated or not (see **Figure 4**). The conducts of such structures can be analyzed by numerical modeling. Similarly, to the treatment considered in the last section for beams, the modeling of plates could be achieved using 3D discretized volume elements (FEM). A great diminution in the computation time can be attained by using 2D surface elements whereas counting the third dimension in the modeled equation. As for beams case, this is feasible using a neutral plane. Such plane is confounded with the symmetry mid plane of the system in the case of collocated patches[72,97,98,106–108]. Such neutral-symmetry confusion in collocated patches plate structures is inexistent in the case of non-collocated patches case and the neutral plane, as the case of neutral axis, should be determined[96], see section 8. Note that, in some particular geometrically simple structures, analytical solutions can be used. However, in complex plate structures, we have to exercise discretized FEM solution. **Figure 5** shows the meshed domains corresponding to some examples of complex plate structures. The small colored rectangles represent different patches bonded on circular or rectangular thin structures with or without holes.

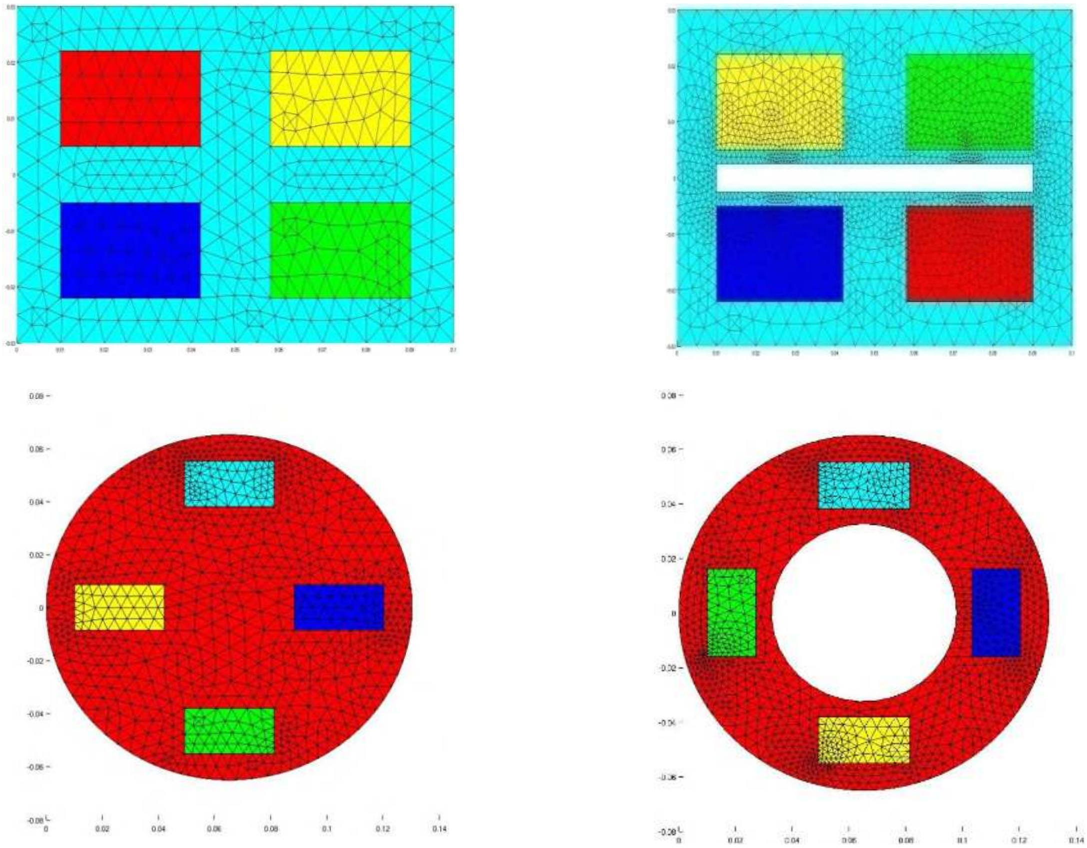


Figure 5. FEM meshing in different complex structures of non-collocated piezoelectric patches bonded on thin structures[4].

7. Locomotion and positioning

7.1. Locomotion

We have seen in section 2 that amplified actuation is indispensable for robotic purposes through locomotion obtained by such amplification. Most of encountered locomotion types are relative to motion on solid substrates and in fluids.

In the case of locomotion on solid ground, different forces are involved. These are relative to gravity, normal reaction, friction and active motion generation. Such locomotion is of different styles. The most popular are wheeling[109,110], walking[111–114], inchworm[84,115,116], inertial[117–120] and resonant[97–108].

In the case locomotion in fluids, we will consider liquid and air mediums[9,121]. In this type of locomotion, the movement is fully inspired from biological locomotion. In the liquid instance, movement can be inside or at the surface of the liquid. Different works have been published for movement on water surface, underwater and air[23,24,122–127].

7.2. Positioning

The requirement for accuracy positioning requests has immensely motivated the exploration and advancement towards the development of actuators owning high precision. Several mentioned actuations in the last sections, match such specification[5,14,16,17,35–37,42]. As well, different works are available for positioning needs[128–131].

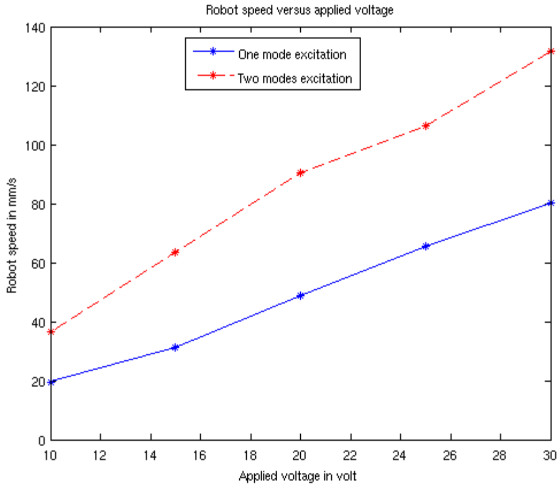
8. Discussion

In this work, the practiced investigation and review of the role of miniature robots, using resonant and non-resonant piezoelectric actuations, in locomotion and positioning have shown that such a topic is fully valuable. At this point, different questions are worth commenting on:

- Functioning of PRUM following to section 4: In PRUM, the driving force comes from the inverse piezoelectric effect. In such a case, this effect transforms a harmonic electrical signal into a cyclic deformation of matter. This force behaves linearly in conjunction with the specific length scale, actually allowing the production of useful amounts of work from small-scale motors. This is all the more factual since the motor is intended to operate close to the mechanical resonance of the stator. Moreover, PRUM has other advantages including high torques, straight drive, no coping mechanism, fast response, moderate voltage, not affected by electromagnetic noise, and simple in structure.

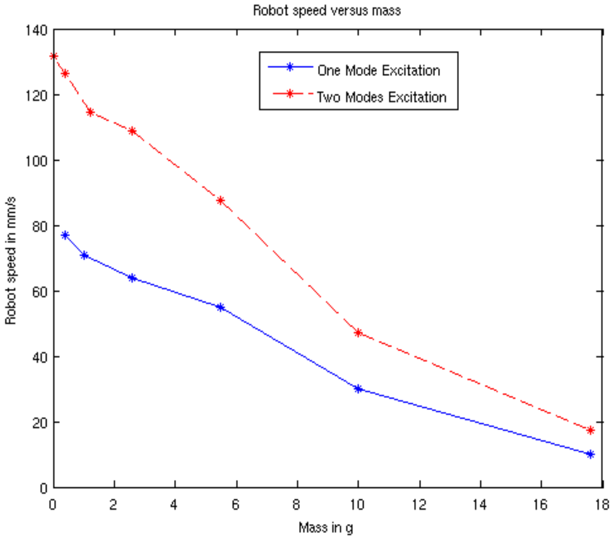
- Performances of one and two-mode excitations: The one and two-mode excitations described in section 5 behave with different performances depending on application. An example of beam robot of 2 PZT patches of 32 × 17 × 0.27 mm placed on an elastic substrate of 180 × 17 × 0.5 mm. Patches are positioned at $X = 24$ mm from each end. Measurements have been realized for the robot speed, with different applied voltages and embedded masses, on a smooth glace flat surface for the one-mode and two-mode excitations[4]. **Figure 6a**,**b** shows respectively, the speed function of the applied voltage and the mass. One remark that the curves of the two-mode excitation are always higher than the one-mode. This effect increases with the applied voltage increase and decease with mass increase.

- Miniaturization through PPBTS and compact on-board driving electronics: As discussed in the above sections, the use of piezoelectric actuation permits high specific power. In addition, it is possible to incorporate compact on-board driving electronics using specific technologies. Due to these features, which are particularly suitable for miniaturized robots, the use of PPBTS embedding compact driving control seems an adequate solution offering high packaging energy density. The corresponding self-running piezoelectric robot compared to the case of slider derived by a stator, seems simpler in structure and lesser in manufacture cost. In addition, such structure permits high load ratio and speed as well as easier abilities of evolution in different mediums. Moreover, besides the capacity of self-running robots to move solid loads[23,24], its structure permits to move liquids, e.g. in micro pumping devices[50,51]. The use of this last application permits high precision delivery time and quantity of liquid in medical applications.



(a)

Figure 6. (*Continued*).



(b)

Figure 6. Robot speed versus **(a)** applied voltage; and **(b)** embedded mass, one mode and two modes excitation[4].

- Neutral locations notion in thin structures with bonded patches: In section 6, the notions of neutral, axes in beams and surfaces in plates, have been mentioned. These neutral axes or surfaces are confused with respectively median geometric axes or surfaces in case of beams and plates with symmetrical sections. Such symmetry in the case of bonded patches on thin structure beams and plates is present only in case of collocated patches (in correspondence on both sides). In the case of non-collocated patches, the confusion of neutral with median references is lost.

Indeed, in mechanics, the neutral axis or surface is a fictitious reference within a structure of beam or plate. Once a bending force weighs on the structure that tends to bend, causing the inner surface (under the force) to be in compression while the outer surface is in tension. **Figure 7** illustrates the well known representation of a thin elastic beam or plate under force action illustrating neutral axis (or plane), compression stress zone and tensile stress zone. The neutral axis or surface is the location within the structure between these regions, where the substance of the beam or plate is not stressed by compression or tension. When the section of the structure is constant with homogeneous matter, the neutral site is confused with the median site. In fact, this is the situation of the beam or plate shown in **Figure 7**. Otherwise, with inhomogeneous material in the section of the structure, the two neutral and median locations will be distinct depending on the matter properties of the section of the structure. The identification in this case of the neutral location will be necessary as indicated in the following point.

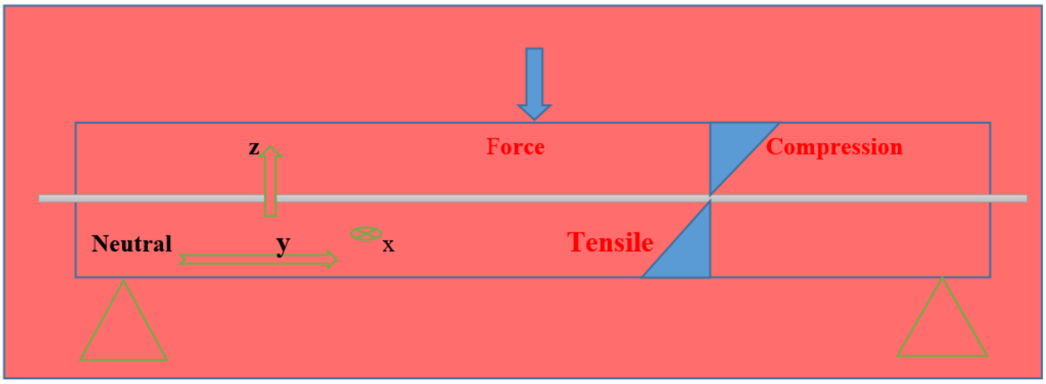
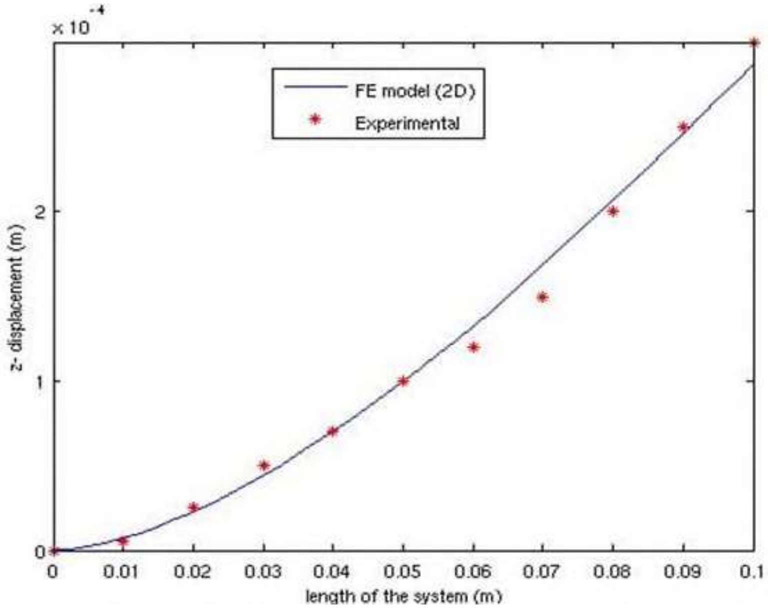


Figure 7. Schematic representation of cross-section of a thin elastic beam or plate under force action illustrating neutral axis (or plane).

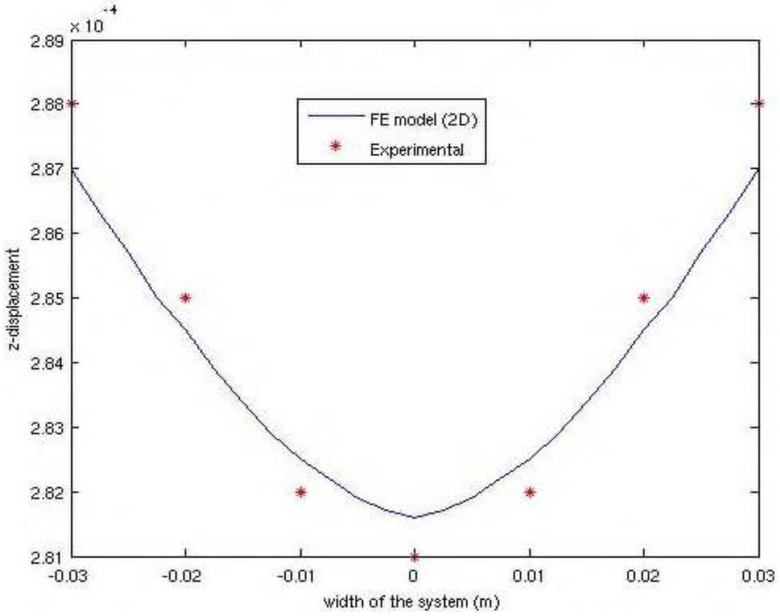
- Modeling of piezoelectric robots involving patches bonded on thin structures: As mentioned in section 6, an efficient determination of the behavior of thin structures with bonded piezoelectric patches can be attained through numerical modeling by techniques as finite element methods FEM. The precision of such models is related to their capacity to account for local conduct in material due to their discretized nature. The beam structure case corresponds to 2D analysis involving the axial wave propagation direction "*x*" and its perpendicular direction on the surface and in-depth "*z*" of the beam (see **Figure 7**), in this case, the discretized elements are surface ones. Such a model can be reduced to 1D by incorporating the second dimension "*z*" in the solved equation and the used elements will be linear segment ones. Similarly, in the case of plate structures, the natural 3D (surface *x, y* and in depth *z*) can be reduced to 2D by considering the "*z*" component in the equation. These reductions, to 1D in beams and to 2D in plates simplifies considerably computations. However, these reductions implies the identification of neutral references: axis for beams and plane for plates, which is trivial in the case of collocated patches because these references are confounded with median geometrical ones. Conversely, in case of non-collocated patches, these references deviate from the median ones and their locations should be mathematically calculated[96].

The two reductions to 1D for beams and 2D for plates have been validated in case of the beam described before and corresponding to **Figure 6**, and to a plate[4]. The dimensions of this plate in mm are given by: 2 PZT patches of 32 × 17 × 0.27 placed in x-axis direction on an elastic substrate of 100 × 60 × 0.5. The patches positions correspond to $x = 10$ for each patch from the two plate X-axis ends and $y = 21.5$ for patches from each of y-axis ends. **Figure 8** shows z-displacement along **Figure 8a** the length and **Figure 8b** the width of the plate at the first resonance frequency obtained from measurements and with 2D FEM.



(a)

Figure 8. (*Continued*).



(b)

Figure 8. Experimental and FEM 2D results of the z-displacement along the length **(a)** and the width **(b)** of the plate at the first resonance frequency[4].

The results obtained in **Figure 8** indicate that the reduction of computation dimension through the notion of neutral location is efficient and give accurate results.

9. Conclusion

In this contribution, the evaluation of piezoelectric actuators concerning the performance of miniature robots in general, and focusing on systems using traveling waves on beams and plates of thin structures has been carried out. Examination of the various questions addressed in this review has shown that there is a continuous evolution in this field. The questions of interest raised by this subject are diverse, the most important of which are:

Applications requiring high specific power particularly suitable for miniaturized robots, different miniaturization characteristics, traveling wave characteristics on thin structures, positioning of piezoelectric patches bonded on beams and plates, precise discretized numerical methods with the lowest calculation time, performance of miniature beam and plate robots and their wide application in various fields.

These questions relate to different industries, health sectors, security communities, etc., and of course researchers in different fields. Recommendations for future work could be applications of miniature beam and plate piezoelectric robots in damage and fatigue control in hard-to-reach areas.

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Conflicts of interest

The author declares no conflict of interest.

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