Engineering Structures 84 (2015) 140–151

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Static and dynamic analysis of a flextensional transducer with an axial piezoelectric actuation

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ARTICLE INFO

Article history:
Received 5 June 2014
Revised 31 October 2014
Accepted 18 November 2014

Keywords:
Piezoelectric transducer
Geometrical nonlinearity
Static and resonant behaviour
Natural vibration frequency

ABSTRACT

The objective of this paper is to describe the mathematical modelling and numerical testing of the static behaviour and natural frequency of a flexure hinge transducer. The actuator is constructed of two parallel beams mounted by stiff links with an offset to a piezoceramic rod. A monolithic hinge lever mechanism is applied by cutting constricted hinges at the links to generate and magnify the in-plane displacement created by the application of a voltage to the piezorod. This mechanism enables the piezoelectric transducers to amplify displacement efficiently. A non-linear analytical model of the actuator is developed on the basis of Hamilton's principle and solved with use of the perturbation method. During the numerical analysis, the static deflection and internal axial force generated by the electric field application are determined by changing actuator properties such as the distance between the beams and the rod as well as the stiffness of the constricted hinges. It is shown that for the flextensional actuator with a very high flexibility of constricted hinges, the generated transverse displacement is limited by the maximum electric field as the characteristic property for each piezoceramic material. In the dynamic analysis, the fundamental vibration frequency and the adequate modes are studied in relation to the piezoelectric force. The natural vibration frequency, affected by the piezoelectric force, also depends on the stiffness of the beam supports, the matched beam and rod materials, the ratio of the cross section of the rod to the beam and the direction of the electric field.

1. Introduction

Flextentional piezoelectric actuators, which are characterized by large deformation and large strokes, are applied as efficient electromechanical amplifiers. The principle of operation of such transducers is magnification of the longitudinal in-plane strains in a piezoceramic disc or bar into out-of-plane bending of a metal shell or beam. Hence numerous designs of those devices have been proposed and studied in literature. Niezrecki et al. [1] reviewed the architectural trends in amplifying small piezoelectric strains and categorized these architectures into internally, externally and frequency-leveraged schemes. Contemporary producers offer a large number of mechanically amplified piezoelectric transducers of different forms, dimensions and geometries related to industrial applications and destined for both static and dynamic work conditions including resonance. Product development in regard to flexure actuators has led to the introduction of a monolithic hinge lever mechanism by cutting constricted hinges in the body of the device [2]. The idea behind that solution was to reduce the bending stiffness at the hinges, while maintaining enough axial (extensional) rigidity of the active parts (beams) of the actuator and, as a result, to obtain greater magnification of the out-of-plane displacement.

Accepting the crucial role of flextensional piezoceramic–metal composite actuators in various applications, tailoring their electro-mechanical performance has received the attention of several authors for, first of all, Moonie and cymbal type transducers. Erhart and Panoš [3], after modifying a Moonie transducer within the finite element method model in order to use shear stress in PZT ceramics, stated that due to the complicated transfer of the hydrostatic pressure to the shear stress, the shear-Moonie design had a performance much lower than that of a conventional Moonie. After their investigation, the authors declared that the Moonie is one of the most successful piezoelectric hydrophone transducers. The influence of the stiffness of the metallic cap, the piezoelectric coefficients of the ceramics and the characteristics of the epoxy bond on cymbal actuator performance was evaluated by Fernández et al. [4]. It was found that the higher the transverse piezoelectric coefficient, the higher the displacement of the actuator. The stiffness of the metal reduces the displacement but allows the composite to support higher loads. Taking into account the thermal factor,

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http://dx.doi.org/10.1016/j.engstruct.2014.11.025
0141-0296/

the authors found out that by selecting appropriate materials, it is possible to avoid this thermally induced displacement. A simplified model for the analysis of Moonie actuator functioning was developed by Lalande et al. [5]. The model consisted of two beams symmetrically arranged around the actuator neutral axis and attached to the actuator at the ends with an offset. The authors found that the offset distance of the beams had a large impact on the behaviour of the system.

Piezoceramic smart materials are thoroughly applied for vibration control in civil engineering structures of beams, trusses, steel frames and cable-stayed bridges. A review of more than 90 papers including active, passive, semi-active and hybrid vibration control systems was presented by Song et al. [6]. The authors concluded that despite some limitations, piezoceramic materials are lightweight, low-cost, easy-to-implement and as a result can be easy incorporated into a structure to meet any particular requirements. Finite element analysis was employed to study the properties of cymbal-type flextensional transducers [7,8]. Tressler et al. [7] investigated the effect of the material properties and dimensional changes on the dynamic properties of the cymbal actuator to calculate its vibration mode shapes, resonance frequencies, and admittance spectra. The computations showed that the fundamental resonance frequency can be manipulated easily by changing the cymbal cap material or dimensions. Dogan et al. [8] stated that the underwater performance of piezocomposite cymbal transducers can be tailored by changing the ceramic driving element and the end cap material because that material has a strong effect on resonance frequency. Moreover, changing the PZT leads to changes in the sensitivity and transmitting voltage of underwater transducers. By combining geometric parameter studies with those results, the cymbal transducer requirements for specific applications can be also optimized. Ochoa et al. [9–11] performed a thorough study on the modelling of coupled electrical–mechanical characteristics of cymbal ceramic–metal composites. The first problem concerned the electric potential and mechanical stress distributions of the cymbal actuator for both the resonant and off-resonant modes. In order to reduce the stress concentration, a new strategy was investigated by finite element analysis leading to removing a portion of the ceramic just below the point where the maximum stress concentration was observed, or by differentiating the thickness and distribution of the bonding layer [11]. A new design concept of the cymbal actuator was also the object of interest of Narayanan and Schwartz [12], who developed a novel end cap shape for this device called a donut. Analysing the change in the end cap dimensions through finite element modelling coupled with experimental testing, the authors noticed that these devices have got higher flextensional resonance frequencies and a higher effective electromechanical coupling coefficient compared with cymbals of similar dimensions. Lin [13] introduced an improved version for the cymbal transducer by substituting the standard piezoelectric ceramic disc of radial vibration in the new design consisting of an inner piezoelectric ceramic ring and an outer metal ring. In the analysis, the design theory for the new cymbal transducer was developed and the effect of the geometrical dimensions on the vibrational characteristics was studied. Among the vast number of presented conclusions, Lin [13] stressed the dependency between the effective electro-mechanical coupling coefficient and both the geometrical dimensions and vibration modes. The generation of a piezoelectric force results in creating internal prestressing in the transducer, which is necessary for its precise operation. In the flextensional actuator, the beams due to the way of their fastening to the piezoelement, are working parts transferring the axial displacement of the actuator into their out-of-plane bending. The effectiveness of inducing favourable in-plane stress by using piezoelectric elements to enhance the mechanical efficiency of beams has been investigated by Oguamanan et al. [14] and Faria [15]. In both works, the piezoelements were co-locally bonded to the top and bottom surfaces of a beam with a rectangular cross section and longitudinally restrained ends. Oguamanan et al. [op. cit.] showed that the natural frequency of the beam might be tuned by using piezoelectrically induced stress stiffening. An investigation into the free vibrations of a horizontal beam with complete axially restrained ends and stress stiffening caused by a longitudinal force exerted on the system by two co-locally bonded ceramic piezoactuators was presented by Przybylski in [16]. In that case, the non-linearities arising due to the axial stretching of the beam during vibrations were modified by the internal axial piezo-force, which could either stretch or compress the system depending on the piezoceramics polarization. It was shown in [17] that an actuator in the form of a piezoceramic rod, which is discretely attached to a host column, can be successfully adopted for the purpose of suppressing the lateral deflection when the structure is eccentrically loaded due to an unintentional imprecise manufacturing or improper assembling processes of supporting or loading heads. An analogical control of the transducer operation, in which the beams are eccentrically mounted with respect to the exciter, are the object of this investigation.

The main purpose of this paper is to the describe the influence of piezoelectric actuation on the static and resonant behaviour of a flextensional actuator consisting of two rectilinear metal beams, mounted by means of two rigid hinged links with an offset to a centrally located piezoceramic rod. In the proposed design, the hinges are placed in elements which can be made of a fatigue resistant material and not prone to high stress concentration. As one of the main static features of the actuator is no-load flexural displacement, whereas in dynamics – the resonance frequency, those two quantities being determined and analysed in this work, are taken as the fundamental measures for application purposes. The structural design makes, due to the d_{31}-effect, the application of an electric field to the piezorod leads to its contraction or extension depending on the polarization vector and finally to the flexural displacement of both beams. During coupled vibrations of the transducer, the rod vibrates axially, whereas the beams vibrate transversally with respect to their deflected axes. The knowledge about the effect of material properties and dimensional changes on the fundamental resonance frequency makes the flextensional device adequate for resonant applications, especially in ultrasonic piezomotors.

2. Problem formulation

Due to the double symmetry of the actuator, only the upper part of its simplified model is presented in Fig. 1. The static and dynamic characteristics of the device are studied depending on its structural features: the offset distance of the metal beams with regard to the piezoceramic rod (e^*) and the flexural stiffness of the hinges. In the model, the hinges are represented by pins strengthened by linear rotational springs of stiffness (C). The flexural stiffness of the hinges and the flexural stiffness of the beams may be mutually tuned to enhance actuator amplification efficiency. The

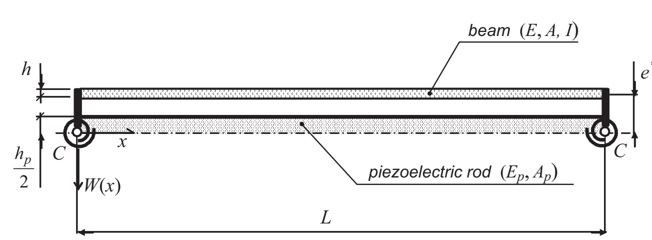

Fig. 1. Model of flextensional transducer with constricted hinges.