PERFORMANCE PREDICTION AND MEASUREMENT OF A SEGMENTED PIEZOELECTRIC COMPOSITE INSERT

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ABSTRACT

Piezoelectric fiber composites (PFC) were previously introduced as an alternative to monolithic piezoceramic. This paper is an investigation into the improvement and optimization of PFC performance. A microelectromechanical model is developed in the aim to predict the piezoelectric properties of a beam with inserted composite with PZT fibers (periodically distributed). This model is used to examine the trends of composites properties versus three main parameters: Fiber volume ratio, segmentation length and epoxy joint thickness. Several beam with segmented fiber composite inserts were manufactured and tested. 20 and 25 % fiber volume ratio composites are manufactured with our process and segmentation length ranging from 1.0 to 3.8 mm. Experimental and numerical result show that 20% fiber volume ratio and about 4 mm segmentation length are a excellent compromise between easiness for manufacturing and efficiency.

INTRODUCTION

In the last ten years, a new kind of materials, such as composites with piezoelectric fibers (PZT fiber) have received considerable amount of attention due to their potential use in multiple applications like the control of vibrations [1,2,3], the electric energy recover on vibrating structures. This is due to the enhanced electromechanical properties obtained by combining the desirable properties of both polymers and piezoelectric fibers. Indeed, the composite have lower density, better fracture behavior (less brittle). In addition, the flexibility and shape variability are improved. However modeling and feasibility studies must still specify the performances of such active materials. Moreover, the segmentation of these composites in sections of a few mm (1 to 12 mm) is a usual method in order to facilitate the polarization operation and to avoid some phenomena as insulation breakdown. The polarization requires a high voltage about 2 kV/mm and a temperature of 80°C for PZT fibers. The aim of the present studies is to optimize a segmented piezoelectric composite in order to maximize the recover electric energy on a vibrating structure (beam). This optimization includes two levels: a) The optimization of the geometric and piezoelectric characteristics of the composite. b) The optimization of the electronic circuit connected to the composite. This paper deals only of the first optimization.

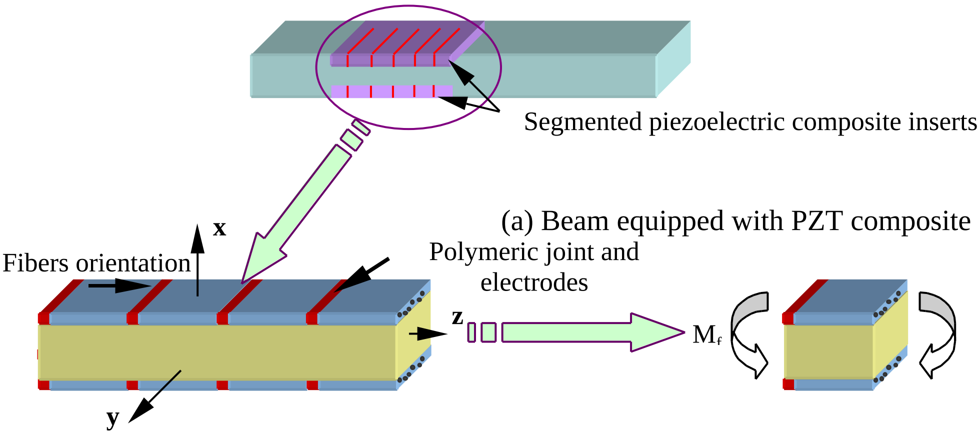
There are three essential steps in this article. The first is to present the model, which could predict the behavior of a beam with segmented PZT fiber composites. Several parametric studies emphasize the influence of different geometric characteristics (such the length of segmentation, the fiber volume ratio and the thickness of the epoxy joint). The second is to propose a simple process for manufacturing composite with exact desired fiber volume ratio and periodic spacing of fibers. The last one is to investigate experimentally the behavior of such inserted beams and to compare the numerical and experimental results.

MODELLING

Modeling

The studied structure is a polymeric beam (epoxy) with two inserted patches on the upper and lower side. These inserts have to change the mechanical energy in electric one, on the vibrating beam. These patches are segmented unidirectional PZT fibers composites. The whole fibers, aligned in the Oz direction (Cf. Fig. 1), are periodically segmented for the easiness of fibers poling (segmentation from 1 to 12 mm).

In the present work, the modeling is based on the periodic medium homogenization and the finite element method is used to solve this piezoelectric problem. This approach is applied to the analysis of the effect of different parameters on the effective response to the piezoelectric composite.



(a) Beam equipped with PZT composite

(b) inserted section

(c) Studied segment

FIG. 1 - Beam with 1-3 piezoelectric composite inserts

Taking into account the low number of fibers on the height of a composite (3 to 4 fibers), the total homogenization of the inserted layer is a too drastic assumption. Indeed, if the insert is substituted by homogenized materials, the contact support-insert of nature polymer/polymer becomes polymer/homogenized material (stiffer) what can alter the results. Because of our process of implementation, the insert includes nearly twenty fibers distributed periodically along the width. Accordingly, the three-dimensional representative volume (noted V) is a part of beam with only one composite segment and with a width corresponding to the spacing between two fibers (transversely periodic medium).

Experimentally, the whole structure is submitted to a sinusoidal bending with frequencies close to the first mode of bending vibration. Because of the low beam thickness in front of its length (6 mm x 10 mm x 150 mm), the assumption of Navier-Bernouilli is also justified.

So the volume V is subjected to a unit rotation of pure bending from one terminal section to another. Because of the transversely periodicity of the medium, decoupled conditions of periodicity are applied on each horizontal side (perpendicular to Oy axis). These conditions enable to put side to side the deformed volumes. Because of symmetries of our problem, only the quarter of our structure will be considered (figure 2). The corresponding conditions of symmetry and anti-symmetry are applied to the two interior faces, respectively vertical and horizontal. Moreover an equipotential condition is applied on the two ends of the composite (electrodes).

According to the viscoelastic theorem of correspondences of Lee and Mandel [4,5], we can study the dynamic calculations by substituting the real piezoelectric properties with their complex characteristic noted here visco-piezoelectric in the static equations. All the material properties are summarize in the Table 1, in their complex forms, except for the piezoelectric coefficients e_{ij} from the lack of experimental data.

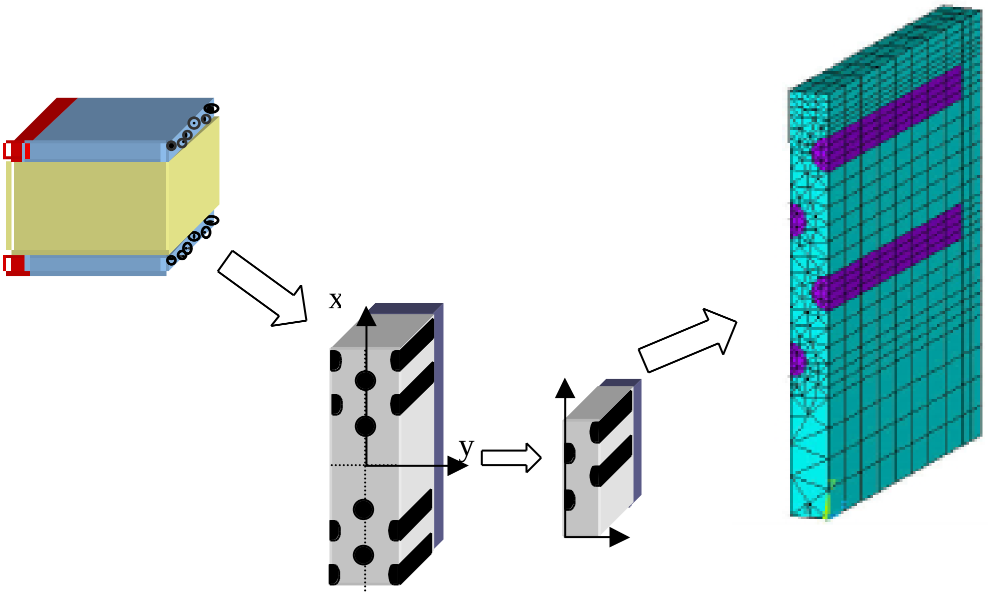


FIG. 2 - Schema of the studied section and its mesh 3D (4 composite layers).

The translation of the problem via the finite element method is too long to detail here, leads to a linear system in complex variables solved numerically. The problem is solved with the technique suggested by Pastor et al. [6,7] for the 1-3 acoustic transducers.

The final problem is solved by the finite element method by using prismatic elements with six nodes. Figure 2 displays the mesh of the section with about 750 to 2500 elements and 640 to 1700 nodes (with three displacement dof and one electric potential dof) according to segment length.

	PZT 5A Fibers	
	Real part	Imaginary part
C_{11}^{E} (Gpa)	140.14	1.75
C_{12}^{E} (Gpa)	99.04	1.24
C_{13}^{E} (Gpa)	95.15	1.19
C_{33}^{E} (Gpa)	124.95	1.56
C_{44}^{E} (Gpa)	20.12	0.25
C_{66}^{E} (Gpa)	20.53	0.26
e_{31} (C/m)	-7.76	-0.097
e_{33} (C/m)	14.85	0.185
e_{15} (C/m)	12.37	0.155
κ_{11}^{E} (10^{9}.F/m)	8.59	-0.42
κ_{33}^{E} (10^{9}.F/m)	7.62	-0.46

	Epoxy resin	
E (Gpa)	4.66	0.1794
ν	0.37	0.0
κ_{11}^{E} (10^9.F/m)	0.039	0.0
κ_{33}^{E} (10^9.F/m)	0.03	0.0

Table 1: Composite component material properties

Parametric study

The calculations were carried out for lengths of insert from 1 to 10 mm and for a fiber volume ratio between 10 and 50%. The joint length ranges from 0.3 mm to 0.75 mm. For each studied geometry, two sets of conditions are applied, the first related to the open circuit while the second related to the closed circuit. All the calculated properties will be indexed D or E for open and closed circuit respectively. The insert efficiency represented by the electromechanical coupling coefficient k, which is evaluated with the following relation: $k = \sqrt{1 - Real(W_E)/Real(W_D)}$ where W_E and W_D are respectively complex energies in closed and open circuit respectively.

Energies are defined here by the following expression: $W = \int_V \frac{1}{2}(\underline{\sigma} : \underline{\varepsilon}^* + \underline{E}\,\underline{D}^*)dV$ and the asterisk means the conjugated complex value.

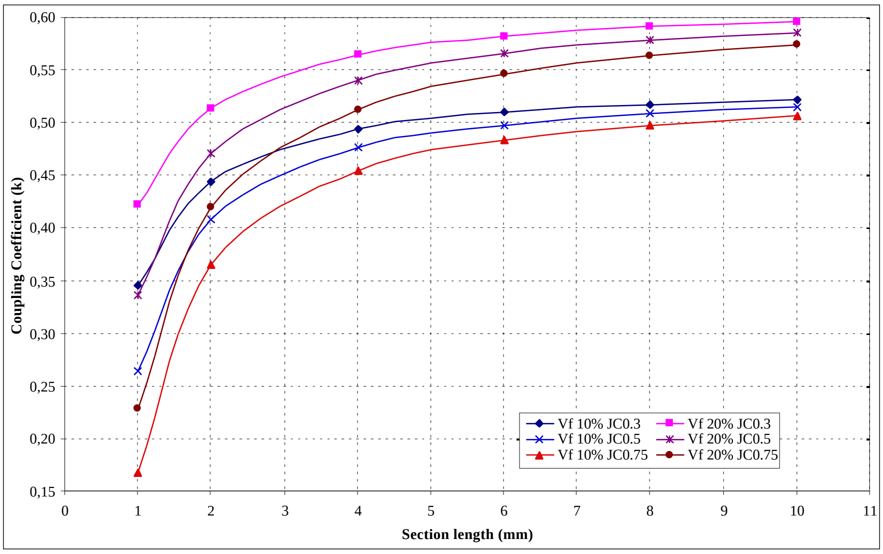


FIG. 3 - Coupling factor versus the segment length and the joint thickness (JC)

Figure 3 displays the evolution of the coupling coefficient according to the length of composite segment.

At once, this coefficient increases noticeably (about 40%) for the range of considered lengths. But, for the lengths of segmentation higher than 6 mm and each fiber volume ratio, the variations of k are small.

Likewise, the influence of joint thickness is small for segmentation length greater than 4 mm.

A length ranging between 4 and 6 mm seems a good compromise between the insert efficiency and the other constraints such as polarization, insert capacitance, rigidity…

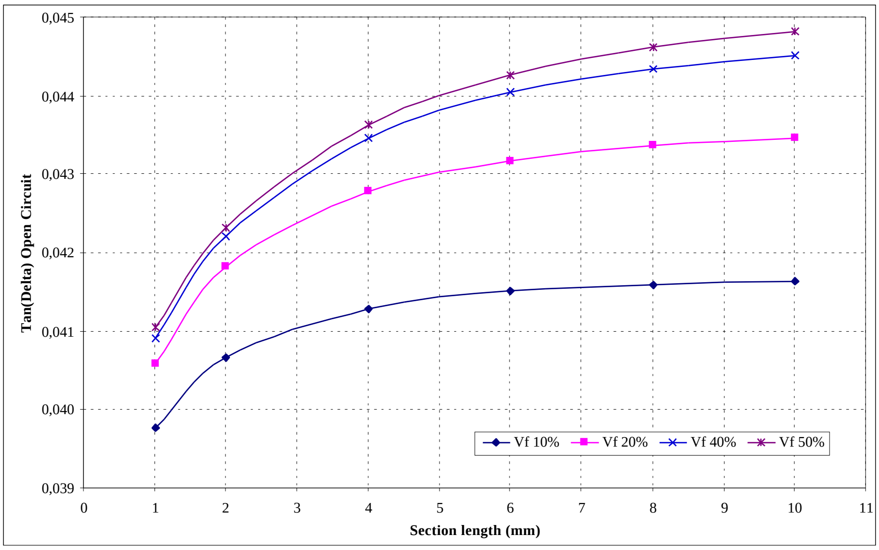


FIG. 4 - tan(δ) versus segment length (open circuit).

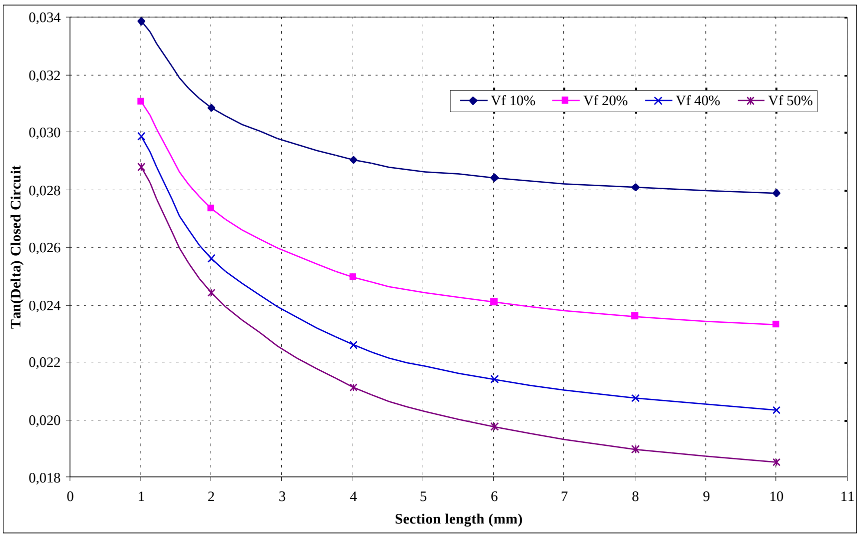


FIG. 5 - tan(δ) versus segment length (closed circuit).

With regard to the prediction of the structure damping, we emphasize that $\tan(\delta) = \mathrm{Im}ag(W)/Real(W)$ gives a measurement of the dissipated energy in permanent sinusoidal solicitation. The results represented on figures 4 and 5 for the closed and the open circuit respectively give a prediction of the damping. The preceding conclusion is confirmed that the range of 4-6 mm is optimal because the variations of $\tan(\delta)$ tend to balance simultaneously.

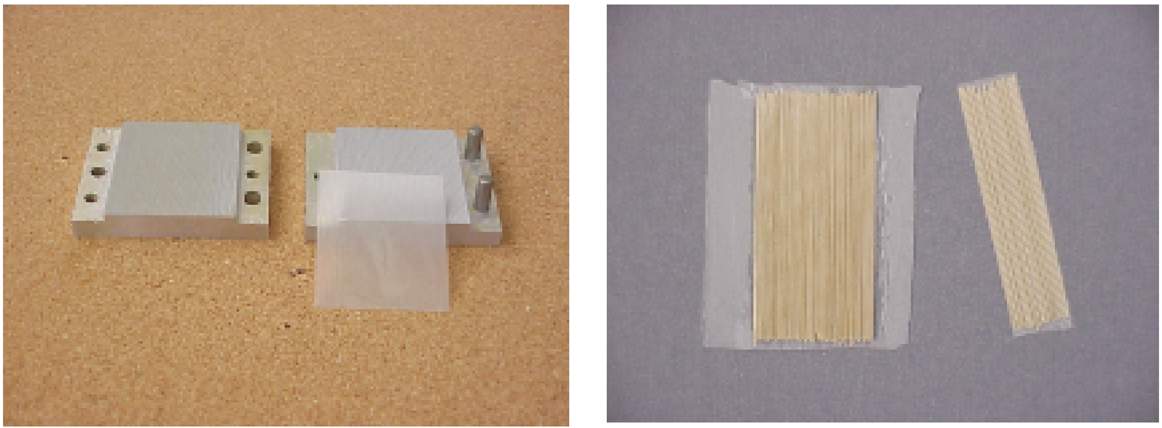
COMPOSITE MANUFACTURING AND TESTING

Composite manufacturing

Advanced Cerametrics supplies PZT 5A fibers in approximately 180 mm lengths for a diameter of 250 mm. Given the non-standard processing required, the fiber have certainly not the same properties that the bulk ceramic.

The commercially available epoxy resin XB 3297 and a low reactivity formulated amine hardener XB 3298 from Vantico polymer specialties were used in this study with a weight ration of 40 % (according to the manufacturer's data sheets).

PZT fiber composite manufacturing raises two major difficulties. First, the manipulation of the PZT fibers should be limited, because of their high brittleness. Then the PZT fibers must be polarized under a 2kV/mm voltage. So it is necessary to divide fibers in smaller section of few millimeters length.



a) Grooved mould and an epoxy film

b) PZT fiber layer

FIG. 6 - Piezoelectric fiber composite manufacturing.

A grooved epoxy film is mould with a step and thickness in terms of the desired fiber volume ratio. Following the cure, the PZT fibers are put in the grooved film coat with a small quantity of resin (for fixing fibers). This technique ensures a perfect alignment and a constant spacing of fiber inside composite (exact fiber volume ratio). The composite is then achieved by stacking the desired number of PZT fiber layer. Then the composite is inserted in an epoxy beam (same resin that for the composite). Then the composite is cut in several sections. The electrodes are manufactured by conductor resin deposing at each end of composite section. The length of fiber segmentation could be adjusted according to the chosen application. In the present study the range of electrode spacing is 1.8 to 10 mm. The different electrodes are connected together. The specimens are poled for 2 minutes at 80°C with a constant voltage of 2 kV/mm. Poling is achieved in a silicon oil bath to avoid the electric breakdown.

Testing

Experiments were conducted to evaluate the influence of the segmentation length and to test the validity of the herein numerical model. At once, all composite are characterized with an impedance analyzer (HP 4294 A) in order to check the poling. Then a set of 5 beams with different piezoelectric inserts is tested. The length of segmentation ranges from 1.5 to 3.8 mm and the volume ratio from 20 to 25%. Other specimens have been manufactured with segment of 6, 8 and 10 mm length. Unfortunately, these composites could not be poled correctly. This emphasizes the importance of the optimization of this parameter.

Numerous tests have been performed on beams. In this paper, only one mechanical experiment is detailed.

One end of the beam is clamped and the other one is subjected to a sinusoidal force. The bending is applied with an electromagnet supplied with AC current (no contact). The displacement is measure with an inductor probe (without contact with the beam). The test is summarizes on figure 7.

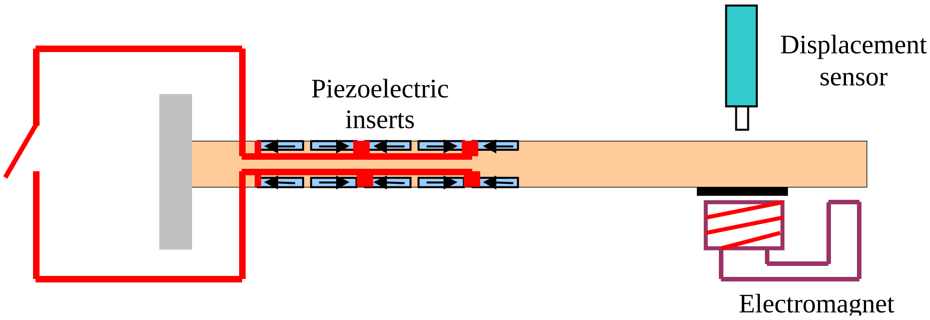


FIG. 7 - Schematic experimental test.

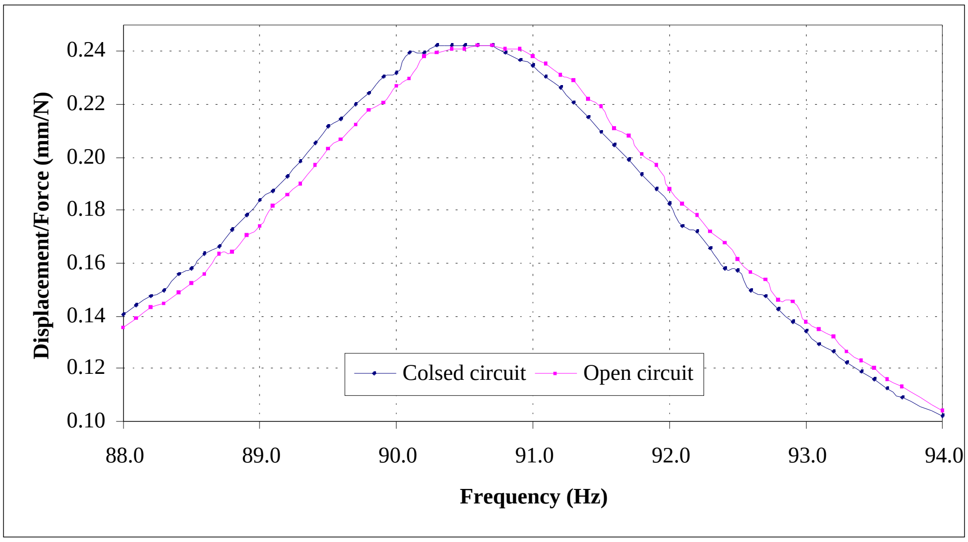


FIG. 8 – Example of measured ratio displacement/force versus frequency.

After the determination of the first bending mode, each specimen is tested around this frequency. Figure 8 displays the ratio $\frac{displacement}{force}$ versus frequency for the two cases (open or closed circuit). The frequencies of the peak for close-circuit and open-circuit are noted respectively f_{cc} and f_{co}. These two values enable to calculate the effective coupling coefficient (for the whole structure) k from the following relationship:

$$k = \sqrt{\frac{f_{co}^2 - f_{cc}^2}{f_{co}^2}}$$

The table 2 summarizes these results, for two fiber volume ratios and for different segmentation lengths.

$L_{segment}$ (mm)	V_f %	k (%)
2,0	20	5,19
3,8	20	5,82
1,5	25	4,77
2,0	25	5,31
3,8	25	5,56

Table 2: Measured effective coupling factor for different beams.

Although the experimental data k is not similar to the numerical because the first one concerning the beam and the second one concerning the inserted part of the beam, the kind of variation is analogous.

The following step of this work is to develop a simple model that should provide the effective value k of the beam from the data of the inserted part.

CONCLUSION

The principal contribution of this work consist of the following:

- The proposed numerical model is an efficient tool for optimizing the PFC (fiber volume ration, segmentation length…), which are inserted on beam for damping or electric energy recover.
- The process is efficient to obtain composite with periodically aligned fiber and with the desired fiber volume ratio.
- The test of the different beams with PFC inserted emphasizes the efficiency of such structure.

The first results display the efficiency of segmented fiber composite to convert mechanical energy in electrical energy. The rate of converted energy is rather low, in proportion to the small quantity of composite. Numerical and the first experimental results show the influence of the segmentation length on the efficiency coefficient k. A length between 4 and 6 mm and a fiber volume ratio about 20% seem to be the optimum value for easiness of poling and the efficacy of this composite. This work demonstrates the possibility of manufacturing and optimization of piezoelectric inserts for damping or electric energy recover application on a vibrating beam.

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