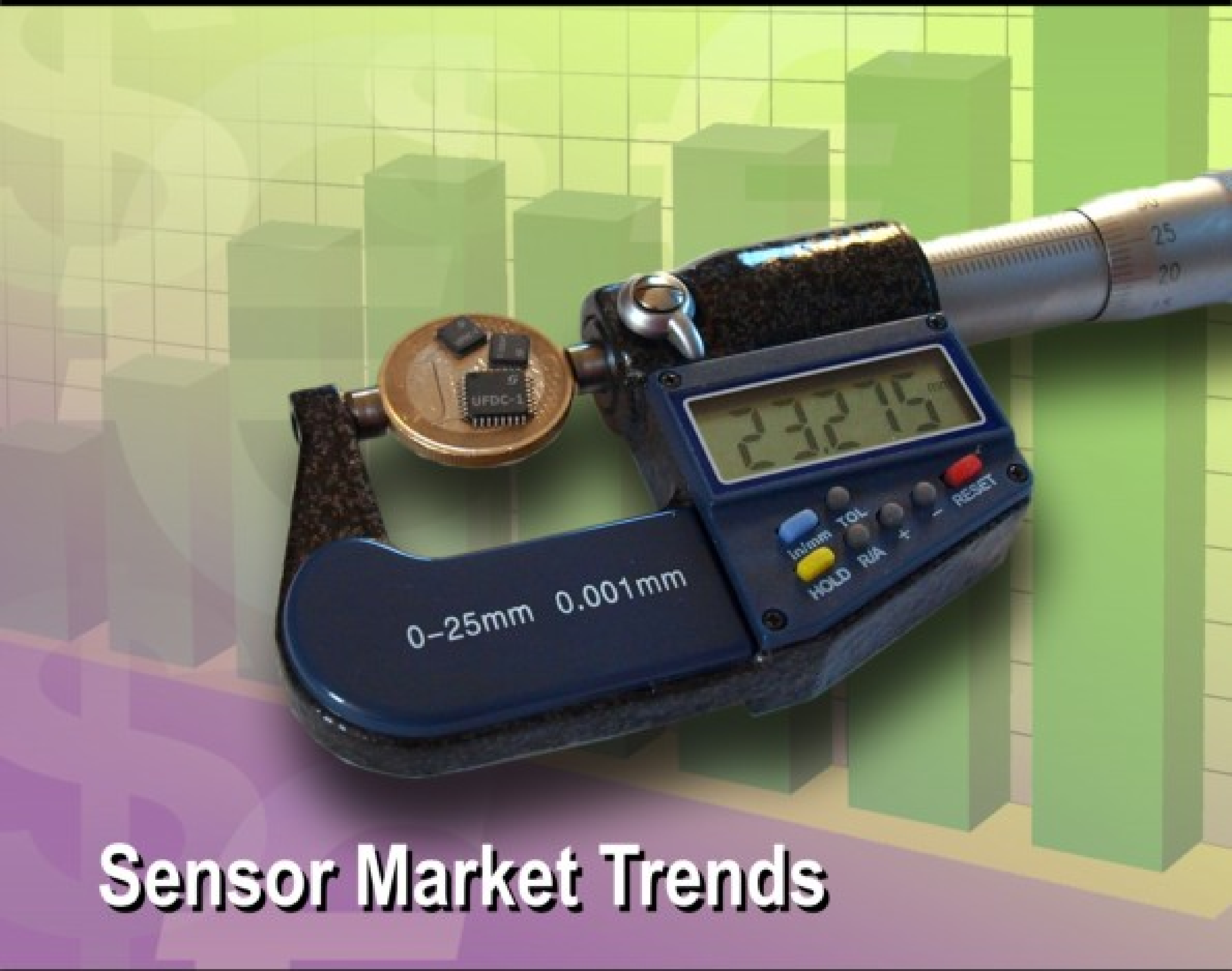
ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 99
12/08



Sensor Market Trends

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 99
December 2008

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
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Sensors & Transducers Journal

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Volume 99
Issue 12
December 2008

www.sensorsportal.com

ISSN 1726-5479

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International Frequency Sensor Association (IFSA).

Sensors & Transducers Journal, Vol. 99, Issue 12, December 2008, pp. 33-42

www.sensorsportal.com

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

A New Rotational Velocity Meter for Dynamic Testing

Hou Xiaoyan
Department of Civil Engineering, National University of Singapore
Singapore 117576
E-mail: houxiaoyan@gmail.com

Received: 25 November 2008 /Accepted: 22 December 2008 /Published: 30 December 2008

Abstract: Information for rotational Degree of Freedom (DOF) is automatically included in theoretical analyses of structures. It is also believed that rotational DOFs are of increasing importance for future applications. However, in current status they only play little role in dynamic testing for they are difficult to be measured in experiments. One main problem to be tackled is rotational motion measurement. This paper reports a novel Rotational Velocity Meter which can accurately measure rotational motion of elastic structures. Compared with conventional methods, besides high accuracy, this new sensor has advantages of simple structure, less local stiffening effect, less inertial loading, and point measurement. *Copyright © 2008 IFSA.*

Keywords: Piezoelectric bimorph, Rotational DOF, Rotational velocity, Rotational acceleration, Velocity meter

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1. Introduction

Information for rotational degrees of freedom is automatically included in theoretical analyses but is generally ignored in experimentally-based studies for the simple reason that they are very difficult to measure [1-2]. Nevertheless, they are generally an essential feature in applications such as structural coupling and model modifications [3].

Now rotational motion is usually measured with a pair of matched linear accelerometers which are placed a short distance apart on the structure [4-6]. The principle of operation is measuring both linear acceleration signals to deduce the rotational data. This method has the advantage of performing a measurement using ordinary laboratory equipments. But it also has several problems in real applications. Firstly, as the signals output from the two accelerometers have high similarity, their tiny difference is sometimes buried in the noise floor. Secondly, due to the involvement of the two sensors, point measurement is hardly to achieve. The installation of the sensors is sometimes difficult or even impossible because of the limited available space on site. Finally, the inertial loading and local stiffening effect affect measurement accuracy. This method is also not applicable for mini or micro-structures.

Besides twin-accelerometer method, Scanning Laser Doppler Velocimeter (SLDV) is also widely used for rotational response detection [1]. As a non-contact transducer, SLDV avoids the loading and local stiffening problem. It also has distinct advantages for measurements which have to be made in hostile environments, for example, in a high temperature environment. The main limitations of this kind of sensor are the line of sight requirement and speckle noise. It is also expensive and cumbersome.

As discussed above, existing methods and equipment are sometimes inconvenient or inaccurate in measuring rotational motion at a point. New transducers and sensing techniques are in great needs.

In this paper, a novel rotational velocity meter which can accurately and easily measure rotational motion is developed. As shown in Fig. 1, this meter employs two piezoelectric bimorphs (Fuji Ceramics C-6 Series, 63 mm × 15 mm × 1 mm) as the essential sensing elements, which are identical in both dimensions and materials. The bimorphs are attached to the tested structure via a rigid supporting block (15 mm × 15 mm × 11.8 mm), thus point measurement can be approximated. To avoid charge convection, a Glass Epoxide insulating layer (15 mm × 15 mm × 1 mm) is inserted between the bimorphs and the supporting block. As illustrated in Fig. 1, *x* axis is along the bimorph length direction, *y* axis along the width direction and *z* axis along the thickness direction.

The piezoelectric bimorph is an invention by C. Baldwin Sawyer in 1931 [7]. In a bimorph, two piezoelectric patches are bonded together. A center metal shim is laminated between the two piezoelectric patches to add mechanical strength and stiffness [8]. A bimorph element usually also has four electrode layers and two adhesive layers, but since these layers are much thinner than the PZT and metal layers, their effect is normally neglected in theoretical and numerical analysis [9]. Bending bimorphs possess high motion and voltage sensitivity. They are widely used as electromechanical transducers since they can effectively convert electrical energy to mechanical energy and vice versa. They widely serve as accelerometers [10], pressure sensors [11], air acoustic transducers [12], etc.

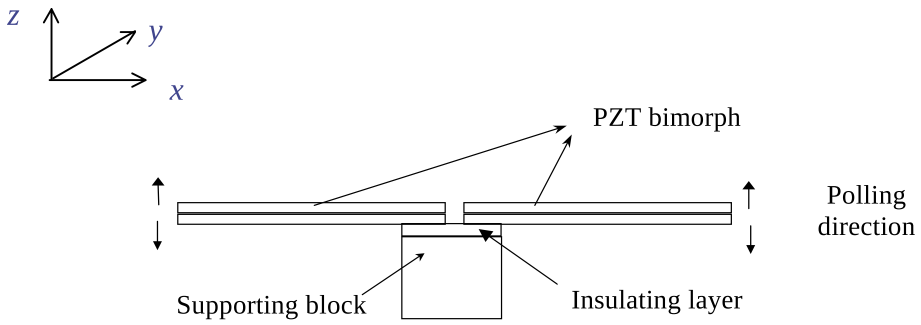
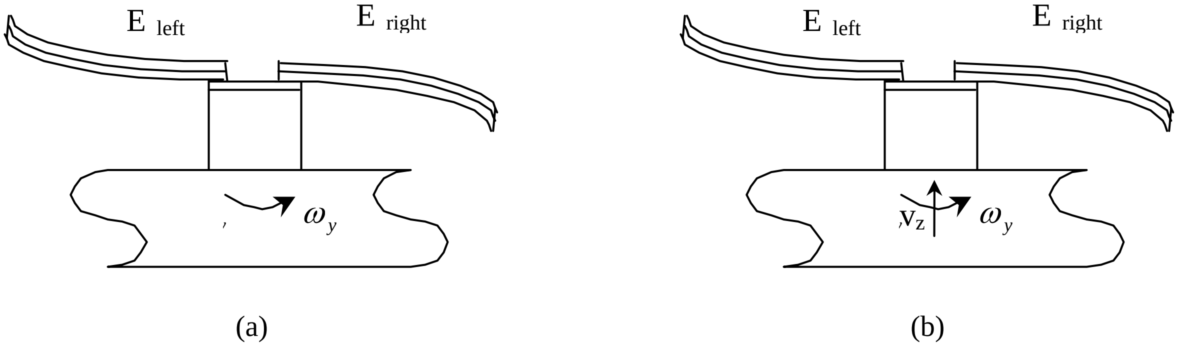


Fig. 1. The Rotational Velocity Meter.

As illustrated in Fig. 2(a), when rotational motion exists at the input port of the velocity meter, the bimorphs bend upward and downward in opposite directions. The bending of the bimorph places one PZT layer of the bimorph in tension and the other PZT in compression. As a result of the induced stresses, the bimorph generates an electrical output signal due to the direct piezoelectric effect. As a sensor, the bending bimorph has the advantage of detecting even small mechanical deformation.

As the transducer is strictly symmetric, the output voltages or charges from the two bimorphs have the same amplitudes but opposite directions. However, in real world, as most structures are multi-DOF systems, the motion at a measurement point is often complex. The rotational motion is usually accompanied by translational motion [4], as shown in Fig. 2(b).



(a) (b)

Fig. 2. Rotational Velocity Meter subject to vibrations.

Due to the symmetric configuration of the transducer, it is only sensitive to motions in two Degrees of Freedom: one translational DOF along *z* direction and one rotational DOF about *y* axis. Owing to the electromechanical interaction between the structure and the sensor, the translation motion results in the identical bending vibrations of the bimorphs and identical voltage output (E_{left_trans} and E_{right_trans}); while the rotation response introduces the out-of-phase bending of the bimorphs and then opposite voltage (E_{left_rot} and E_{right_rot}).

The electrical voltages on the left and right bimorphs caused by the translational and rotational vibrations of the structure are therefore:

$$E_{left} = E_{left\_trans} + E_{left\_rot} \tag{1}$$

$$E_{right} = E_{right\_trans} + E_{right\_rot} \tag{2}$$

Owing to the symmetric structure of the sensor, we have:

$$E_{left\_trans} = E_{right\_trans} \tag{3}$$

$$E_{left\_rot} = -E_{right\_rot} \tag{4}$$

Thus the difference of the voltages on the bimorphs becomes

$$E_{left} - E_{right} = 2E_{left\_rot}, \tag{5}$$

where E_{left} (E_{right}) is the output voltage on the left (right) bimorph caused by the rotation motion of the structure.

From the above discussions, it can be seen that the information on the rotational vibration of the measurement point is embedded in the difference of the output voltage of the left and right bimorphs. It can also be seen that the rotational measurement is independent of the translational motion at the point, which means that the translational DOF is successfully decoupled from the rotational measurement.

To evaluate the rotational motion at a point, the sensor has to be characterized first by identifying the relationship between the input rotational velocity and the output voltage:

$$T = \frac{input\ rotational\ velocity}{difference\ of\ the\ output\ voltages\ of\ bimorphs} = \frac{\omega}{E_{left} - E_{right}} \tag{6}$$

2. Numerical Calibration

In ANSYS, the piezoelectric elements in the bimorphs are modeled with 3-D Coupled-Field Solid Element SOLID5, which handles the electromechanical coupling taken place in PZT patch by calculating the appropriate element matrix. SOLID 5 is a 3-D coupled field solid element with eight nodes. Each node has six degrees of freedom, namely, translations in the nodal x, y, and z, temperature, voltage, and magnetic degrees of freedom. Here SOLID 5 does not use temperature and magnetic capability and the corresponding degrees of freedom are set inactive.

For the middle metal layer sandwiched between the upper and lower PZT layers in a bimorph, since its length and width are hundreds of times larger than its thickness, solid elements are not suitable in modeling as that will produce huge element numbers and consequently long calculation time. In order to achieve both accurate simulation and short calculation time, Structural Elastic Four Node Shell Element, SHELL 63, is chosen as the modeling element. To model the supporting block and the insulating layer, SOLID 73, which is widely used for three-dimensional modeling of solid structures, is employed. The FEM model of the velocity meter is shown in Fig. 3.

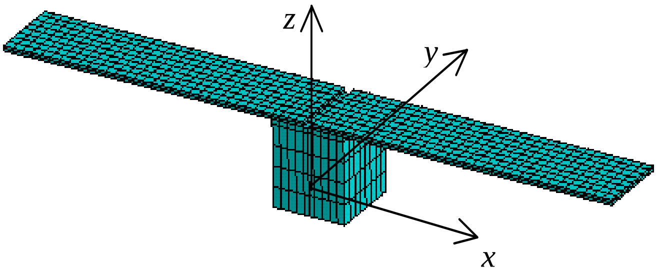


Fig. 3. FEM model of the sensor.

To numerically determine the calibration function *T* in Equation (6), simply-supported boundary condition is simulated by restricting the translational DOFs of the nodes on the middle line of the bottom of the supporting block to zero, as shown in Fig. 4. To apply an excitation moment about the *y* axis to the sensor, a sinusoidal force couple is exerted to n_1 (1.05x10^{-3},0,0) and n_2 (-1.05x10^{-3},0,0).

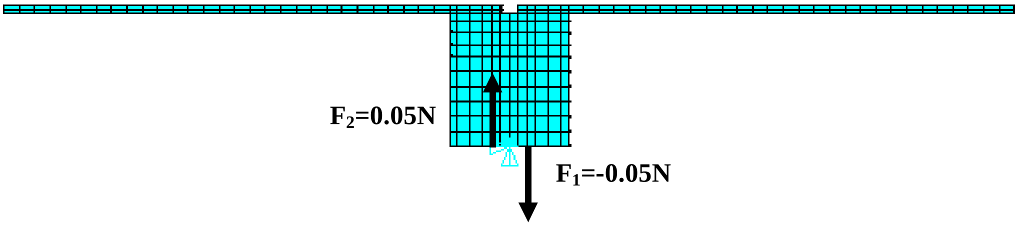


Fig. 4. Set-up for numerically calibrate the sensor.

For the sensor, the PZT layers in the bimorphs are fully electroded on top and bottom surfaces, resulting in equal-potential surfaces. To simulate this, in numerical analysis, the voltage DOFs of the nodes on each electrode surfaces are coupled so that the output electrical potential on the surface can be conveniently read out from a single node. After applying the boundary conditions and the force couple, harmonic response analysis, a technique to determine the steady-state response of a linear structure to sinusoidally varying loads, are carried out. The output voltages of the bimorphs and the input rotational velocity are numerically determined to calculate the calibration function *T* (Fig. 5). The input rotational velocity is calculated through nodal displacement *uz* at each node on the bottom of the supporting block.

$$\omega_y = \frac{2\pi f j}{k} \sum_{i=1}^{i=k} \frac{uz_i}{x_i}, \tag{7}$$

where:
f is the excitation frequency;
k is the number of the nodes on the bottom surface;
uz_i is the nodal displacement along z direction;
x_i is the x coordinate.

Using the numerically calculated input rotational velocity and output voltage, the sensitivity curve of the prototype sensor is also calculated as illustrated in Fig. 6. It is found from Fig. 5 that the calibration function is frequency dependent. At 141 Hz and 793 Hz, the sensor reaches its 1st and 2nd bending resonances respectively, where the calibration function has minimum magnitudes. This means that for a same input acceleration value, the sensor will produce much higher output voltage around resonances. It can also be observed from Fig. 6 that the sensitivity is more stable in the frequency range from 200 Hz to 800 Hz, which is preferred to produce stable measurement performance.

Generally, for a sensor, its working frequency range better avoids its resonances so that in real experiments the measurement errors can be minimized. The prototype sensor in Fig. 1 does not have steady performance in low frequency range from 0Hz to 200Hz. However, as this paper focuses on proposing a novel concept of rotational motion sensor, only a prototype sensor is developed and fabricated. Its effectiveness in measuring rotational velocity in all the frequency range from 0 to 1200 Hz will be numerically proved in the following section. The sensor can be further optimized by revising its dimensions (like bimorph length and thickness) and materials so that it has high resonant frequencies and therefore working well in low frequency range in experimental studies as well.

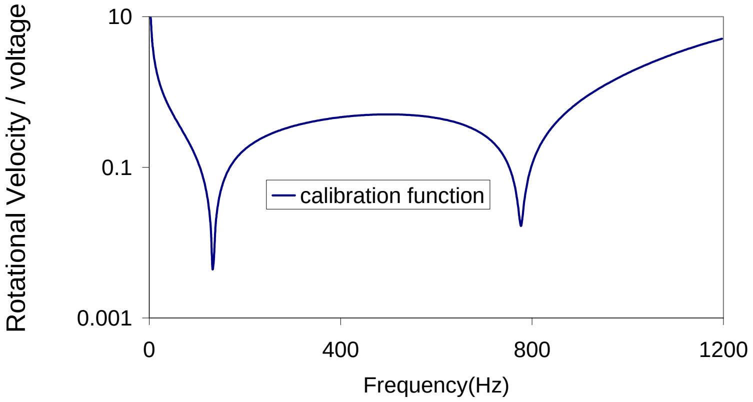


Fig. 5. Numerically identified calibration function.

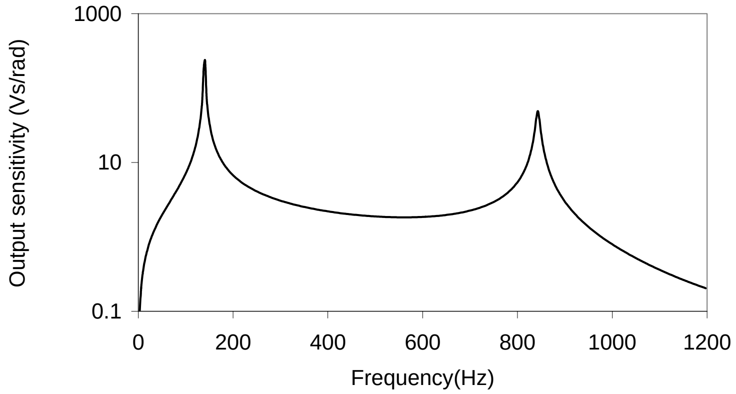


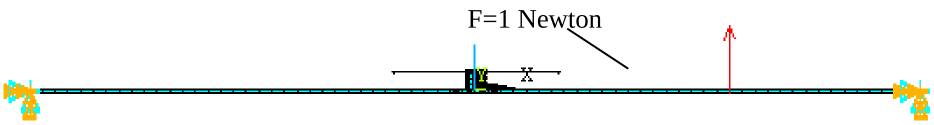
Fig. 6. Output sensitivity of the sensor.

3. Measuring Rotational Velocity Using the Sensor

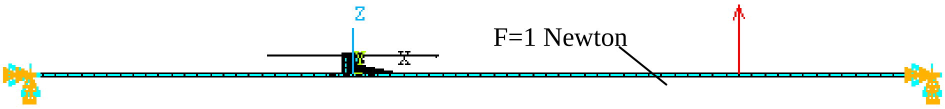
In this section, numerical simulations will be carried out to investigate the effectiveness of the velocity meter in rotational measurement. Taking advantages of the calibration function determined in last section, rotational velocities of some points on a one-dimensional beam and a two-dimensional plate will be numerically detected by the new sensor. To check the accuracy of the sensor, rotational motion at the same measurement points will also be numerically calculated for comparison.

3.1. Case Study 1: One-dimensional Beam

A beam clamped at both ends is chosen as the first test structure to study the effectiveness of the new transducer. The beam is made of aluminum and is 700 mm in length, 50 mm in width and 3 mm in thickness. Two DOFs are sufficient to describe the beam’s vibration: one translational and one rotational. To thoroughly investigate the feasibility of the sensor, here the rotational motion at two points is examined: the middle point and the point at 250 mm to the left clamped end. Finite element models of the transducer & beam system corresponding to the two measurement points are depicted in Fig. 7. A sinusoidal force with amplitude of 1 Newton is applied to the beam to set the beam into vibrations. For both points, the applied force excites both rotational and translational motion. The output voltages of the two bimorphs are calculated via harmonic analysis (Fig. 8).

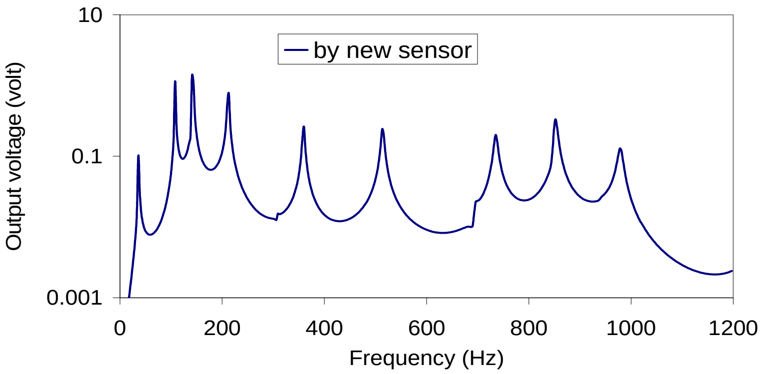


(a) middle point.

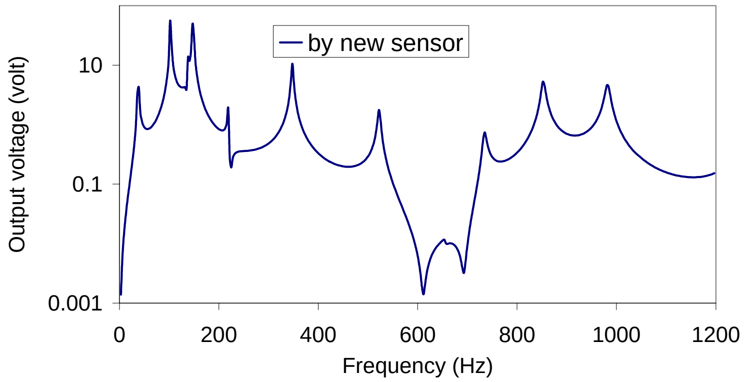


(b) 250 mm point.

Fig. 7. FEM model of the beam and the sensor.



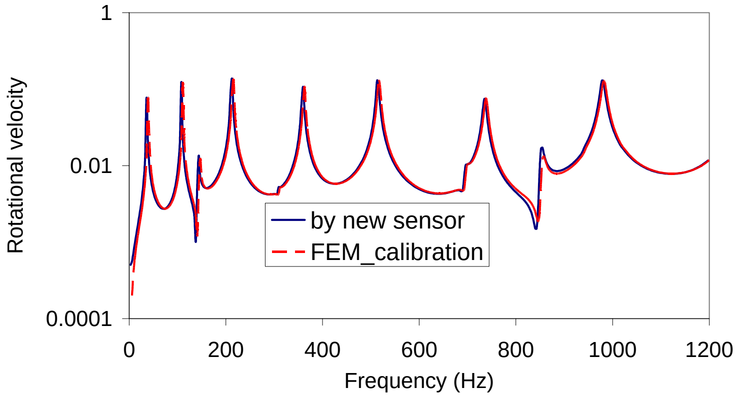
(a) middle point.



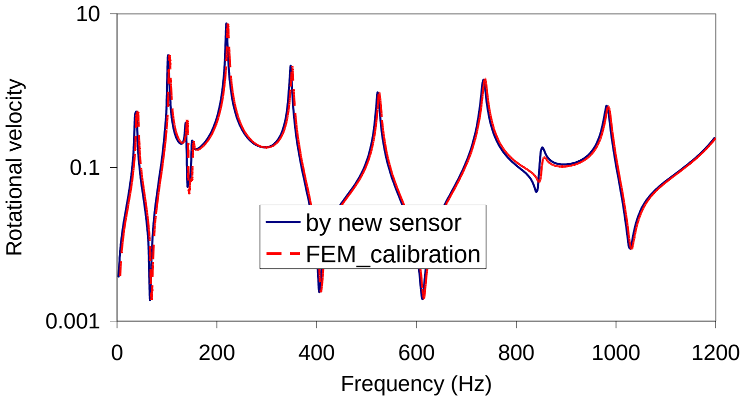
(b) 250 mm point.

Fig. 8. Output voltage of the sensor when it is attached to the measurement points.

For comparison, the rotational displacement at the attachment point φ is also simultaneously recorded in harmonic analysis to derive the corresponding rotational velocity. Now, for each measurement point, we have two set rotational velocity: one set is detected via the new sensor ($\omega_y = T(E_{left} - E_{right})$); the other set is directly obtained from the rotational displacement ($\omega_y' = 2\pi fj \cdot \varphi$). As shown in Fig. 9, they match very well in the whole frequency range, the difference between the two sets of data is within 1.5 %, even when the rotational motion at the points are accompanied by a translational vector and at low frequency range when the sensitivity is not stable. It is therefore concluded that the new transducer is effective in measuring rotational velocity of 1-D beam structure.



(a) middle point.



(b) 250 mm point

Fig. 9. Comparison of the rotational velocity at the measurement points.

3.2. Case Study 2: Two-dimensional Plate

In addition to the one-dimensional beam, a two-dimensional plate is utilized as another test structure to further investigate the effectiveness of the new transducer in measuring rotational motion. The aluminum plate is clamped with two adjacent sides, having dimensions of 700 mm x 500 mm x 3 mm (Fig. 10). Any point on the plate has three active Degrees of Freedom: translational along *z* axis (*uz*), rotation about *x* axis (*rotx*), and rotation about *y* axis (*roty*). As shown in Fig. 10, the velocity meter is attached to the center point. When a force is applied to the plate, the center point is subject to translational vibration in *z* direction, rotational vibration about *x* axis, and rotational vibration about *y* axis. Following a similar procedure in Section 3.1, we have two set rotational velocity about y axis at the center point. It can be observed from Fig. 11 that even vibrations in all the three directions simultaneously exist at the measurement point (center point), the rotational velocity in the desired direction (*roty*) can be accurately detected by the prototype sensor. It is therefore concluded that the new sensor is also effective in measuring rotational velocity of two-dimensional structure.

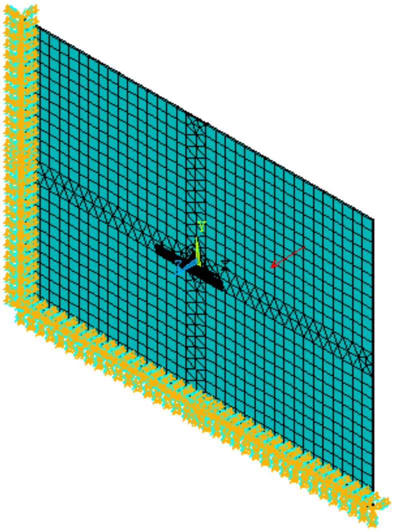


Fig. 10. FEM model of the plate and the sensor.

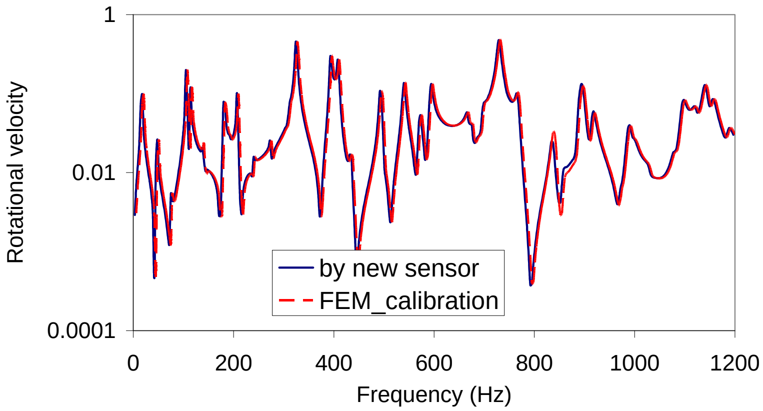


Fig. 11. Comparison of the rotational velocity at the center point of the plate.

4. Conclusions

In this paper, a novel concept of rotational velocity meter has been developed for measuring rotational motion of elastic structures. This transducer employs piezoelectric bimorph cantilevers as essential sensing elements. As symmetric structure is adopted, the sensor can successfully decouple the influence of translational motion which occurs at the measurement point to minimize transverse sensitivity. Through numerical simulations, it has been proved that the new sensor is very accurate in detecting rotational velocity of both one-dimensional and two-dimensional structures. Compared with the conventional twin-accelerometer method, this sensor provides a neat and convenient way in rotational DOF measurement.

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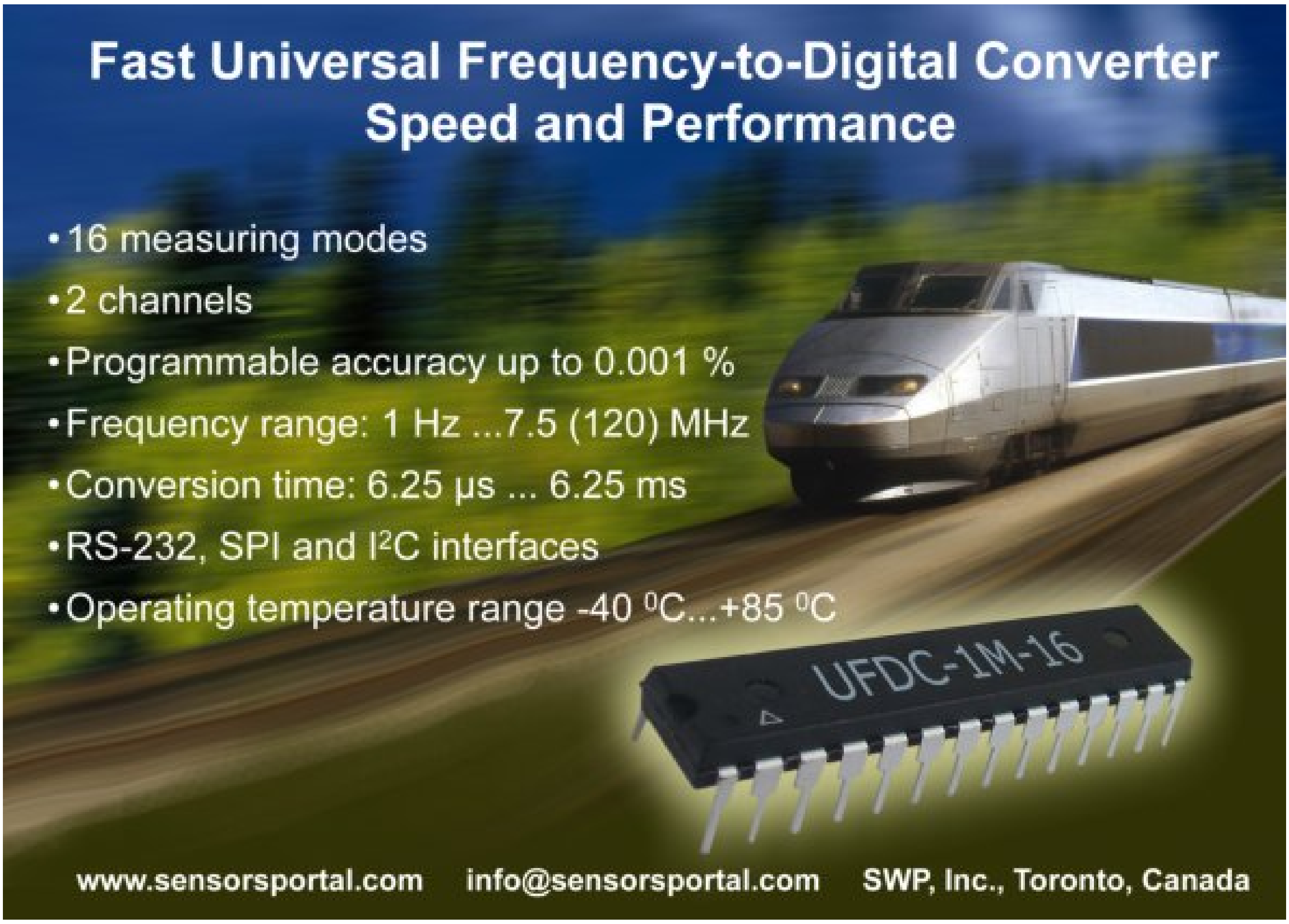

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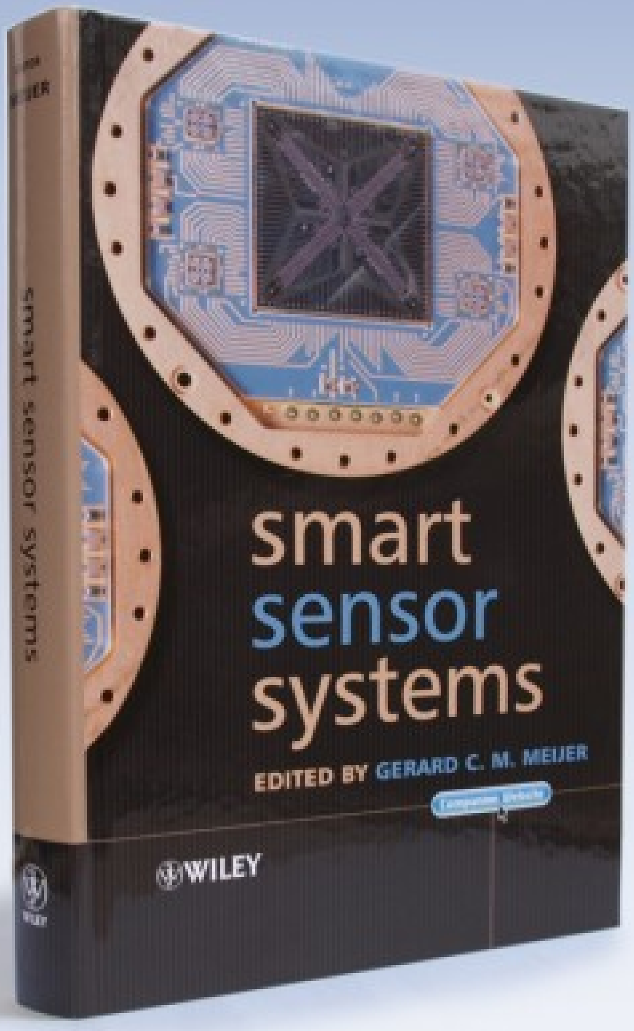
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