IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 20, 2019, accepted July 29, 2019, date of publication August 1, 2019, date of current version August 14, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2932459

An Intelligent Self-Powered Pipeline Inner Spherical Detector With Piezoelectric Energy Harvesting

XIAOBO RUI, ZHOUMO ZENG, (Member, IEEE), YU ZHANG, YIBO LI, XINJING HUANG, YUE LIU, AND TIANSHU XU

State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin 300072, China

Corresponding author: Yu Zhang (zhangyu@tju.edu.cn)

This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFF0212201 and Grant 2016YFF0101802, in part by the Tianjin Key Research and Development Program under Grant 19YFSLQY00080, and in part by the Natural Science Foundation of Tianjin under Grant 17JCYBJC19300.

ABSTRACT To break the limits of traditional pipeline inner spherical detector (PISD) application distances, this paper proposes a design of a piezoelectric energy harvester to develop an intelligent self-powered PISD. The harvester converts rotating mechanical energy into electrical energy. Due to restrictions in internal space and prohibition of magnet application, the harvester consists of a piezoelectric cantilever beam without any auxiliary structures. The fixed end of the harvester is fixed to the PISD shell and the free end extends in the direction of the center. A dynamic model was derived through the Euler–Lagrange method and an experiment platform with macro fiber composite was built. The harvester was designed in three schemes, and the longest harvester of 100 mm achieved optimum performance. After load optimization, 15.27 μW was obtained at 2.6 Hz, which is the rotational frequency of the PISD. A PISD prototype with a harvester was built and a pipeline experiment was conducted to analyze the output characteristics of the smooth operation and the passing weld operation. The results demonstrate that the proposed piezoelectric energy harvester has the potential to establish an intelligent self-powered PISD.

INDEX TERMS Energy harvesting, piezoelectric, pipeline inspection, spherical detector.

I. INTRODUCTION

To ensure the safety of pipeline transportation, regular inspections for pipeline structural integrity are required. The Pipeline Inner Spherical Detector (PISD) is a novel intelligent pipeline inspection device [1]. The PISD is based on a sealed ball moved by the pressure from oil or gas flow. With a variety of sensors, the PISD can obtain different parameters of the pipeline, such as small leak location, pipe orientation, weld location and so on [2], [3]. The existing pipeline inspection methods mainly include negative pressure wave method [4], optical fiber method [5], and cylinder-shaped pipeline inspection gauge method [6]. Compared with these methods, the PISD has higher leak detection sensitivity, and the PISD has a good application prospect with higher flexibility and cost performance [7].

The associate editor coordinating the review of this manuscript and approving it for publication was Mahdi Zareei.

However, energy supply is the obstacle of the development and application of the PISD. The length of long-distance pipelines is usually several hundred kilometers, while the economic flow rate of oil pipelines is about 0.8∼2 m/s, and the gas pipelines are 8∼12 m/s. Within the flow rate range, it can be estimated that the PISD will run for dozens or even hundreds of hours in the pipeline. The sensing system of the PISD is powered by lithium batteries currently. In order to meet the long-term detection requirements, it is necessary to increase the battery capacity while reducing the system power consumption. However, the batteries are limited in the small internal space of the PISD, and it is still unable to meet the application of more than 100 kilometers. Moreover, the lack of power not only limits the distance of the application, but also the function expansion of the PISD [8].

The newly developed energy harvesting technology (EHT) in recent decades offers a new possibility for powering this closed system [9]. As a common source of energy, mechanical energy harvesting is an important part of EHT, which can convert ambient mechanical energy into electricity. The commonly used mechanisms are based on piezoelectric, electromagnetic and electrostatic conversion principles. Among them, the piezoelectric energy harvester has obtained the most research, due to its simple structure and high electromechanical conversion efficiency [10]. Since the PISD has electromagnetic components inside and requires calibration of the position by magnetism, the electromagnetic energy harvester is not selected. The PISD is propelled by fluid in the pipe, and the fluid has abundant mechanical energy. The spherical detector cannot have an external structure to harvest energy directly from the fluid. However, the rotational mechanical energy from the PISD has the potential to be harvested. Similar to vibration, rotation is also a common mechanical motion, while rotational energy harvesting is less investigated [11].

Recently, some literature on rotational energy harvesting are available [12], which can be mainly divided into methods based on plucking, magnet, and gravity. The plucking method utilizes the relative motion between the strikers on the rotating structure and the fixed cantilever beam to create an excitation [13]. Similar to the plucking method, the magnet method is based on the magnetic force generated by the relative motion of the magnets to create an excitation of the piezoelectric structure [14]. The mechanisms of the above two methods are similar, and the methods can perform energy harvesting in a single plane rotation in any direction. The method with magnets is typically ruled out due to the magnetic sensors in the PISD. The PISD is a closed structure and all the devices inside rotate together. Thus, neither of the above methods can be applied to the energy harvesting application of the PISD. A scheme with gravity may be more suitable for PISD, which utilizes the vertical rotational gravity excitation. This method can only be used for applications that rotate in the vertical direction, which is suitable for PISD. Unlike single-axis vibration, there is a centrifugal force effect in the rotational motion. Some related literature proposes to utilize the centrifugal force to improve the frequency band of the harvester [15], [16]. However, the above method will reduce the system response due to the increase of stiffness and the resonance frequency will be increased. Guan et al. proposed a solution for placing the cantilever beam mass on the center of rotation to reduce the effect of centrifugal force on the harvester [17]. This method has a high response and a narrow frequency band. Due to the speed stability of the pipeline fluid, the frequency of the PISD is relatively simple. However, in Guan's research, huge masses and stoppers were used, which were not suitable for the PISD inner structure.

In order to solve the above problems, this paper proposes the design and analysis of piezoelectric energy harvester for PISD. This paper shows the possibility of developing the PISD into an intelligent self-powered pipeline inner spherical detector (ISPISD) that break through the limitations of traditional batteries and can be used for pipeline inspection of any length. Three different structures were designed and compared to the motion characteristics of PISD.

FIGURE 1. Schematic diagram of the PISD prototype.

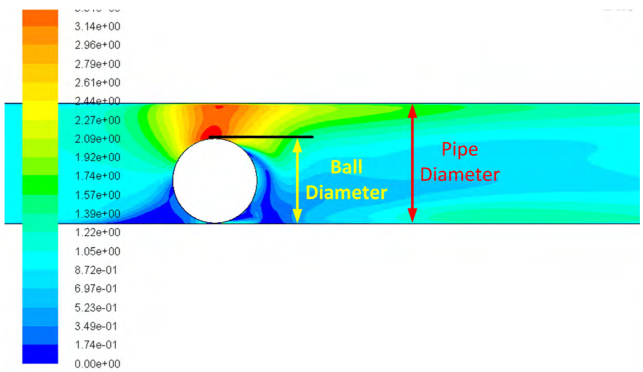


FIGURE 2. The flow rate map of the pipeline with PISD.

The electromechanical coupling model of the harvester was established and verified by experiments. The energy harvesting capacity of the designed harvester in ISPISD was verified by pipeline experiments.

The paper is organized as follows: The methods and the dynamics model are shown in Section 2. Experiments in the lab and pipeline are presented in Sections 3 and 4, respectively. The conclusion is in Section 5.

II. METHODS

A. MOTION ANALYSIS OF THE PISD

The PISD is a standard sphere, and its outer shell is mainly composed of a polyurethane layer, which plays a role of anti-friction and shock absorption, as shown in Figure 1. The inner casing is made of an aluminum alloy material. The PISD is equipped with modules inside such as a hydrophone and the data acquisition storage module.

The harvesters in this paper will be analyzed and designed based on horizontal pipelines, as most pipes are horizontal straight pipe sections without large bends. The following is an analysis of the motion state of the PISD under fluid propulsion. The density of the PISD is greater than that of the liquid, so it is located at the bottom of the pipe. The flow velocity cloud diagram in the pipeline was simulated by CFD software FLUENT 14.0, the ball diameter is 0.7 times the pipe diameter and the flow rate is v = 1 m/s as an example, as shown in Figure 2. The ball diameter is the external diameter of the PISD, and the pipe diameter is the internal diameter of the pipeline. Under the action of the fluid, the upper and

FIGURE 3. PISD rolling acceleration test in the pipeline.

lower parts of the sphere are not evenly loaded. It can be seen from the figure that the flow velocity of the upper part is larger than that of the lower part. Therefore, the upper part also more stressed. It is known from the mechanics that the combined thrust point of the fluid is located in the upper half of the ball, producing a clockwise moment. The surface of the sphere is in contact with the bottom surface of the pipe section, and there is friction, which produces a counterclockwise moment. When the fluid velocity reaches a certain level, the clockwise torque overcomes the counterclockwise moment and the PISD can roll forward.

The characteristics of the rotation are analyzed below. The moment of inertia of the sphere can be calculated when designing with Solidworks software. The role of the moment of inertia in rotational dynamics is equivalent to the mass in linear dynamics. The larger the moment of inertia, the less likely it is to rotate, and the smaller the moment of inertia, the easier it is to rotate. After assembly, the moment of inertia of PISD on the X, Y, and Z-axis are 20695, 9707, and 19743, respectively. The Y-axis has the smallest moment of inertia and is half of the other two axes. Under the action of the pipe fluid, the detector will roll around the Y-axis. Therefore, when analyzing the rotation of the PISD, it can be simplified to the case of rotating around a fixed axis.

In order to analyze the rotational motion of the PISD in the pipeline experimentally, a MEMS triaxial accelerometer based on MPU9250 with 50 Hz sampling rate was installed in the PISD for testing. The accelerometer was mounted at the center of the SD. In the experiment, a horizontal straight pipe with a diameter of 219 mm was selected, which was 77 km in length from Zhongshan to Doumen in Guangdong Province, China, as seen in Figure 3. Part of the acceleration results is selected and shown in Figure 4. It can be seen from the results that the rotation frequency of the PISD is relatively stable and mainly rotates around the Y-axis. Although there are some disturbances, the periodic sinusoidal motion characteristics are still evident. 500 sets of acceleration data were selected from the experimental data, each set of data contains 1000 data points, and separately analyze the spectrum. The results show that the rotation frequency of the PISD is mainly concentrated in the range of 2.3-2.9 Hz, most of which It is 2.6 Hz. Figure 3 is a bar graph of the rotational frequency distribution. Therefore, 2.6 Hz will be designed as the resonant frequency of the harvester.

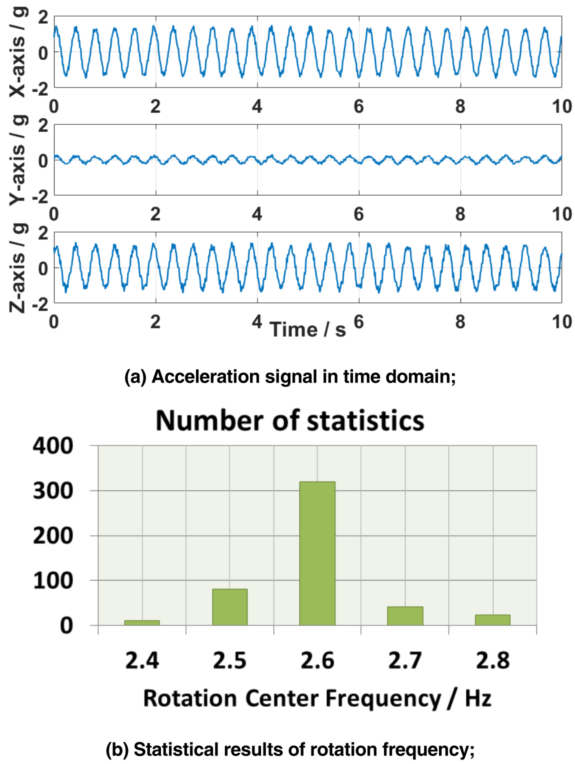


FIGURE 4. Results of the rolling acceleration test.

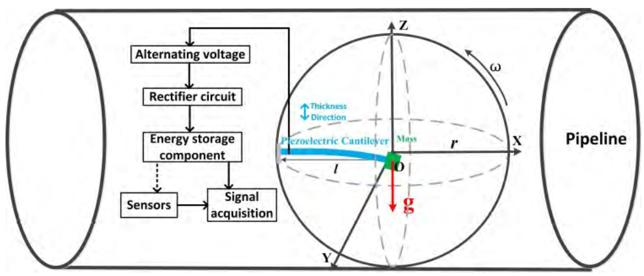


FIGURE 5. Schematic diagram of the structure and function of ISPISD.

B. PHYSICAL DESIGN PROPOSAL

This section will introduce the structure and working principle of the harvester in the PISD. A piezoelectric cantilever beam will be mounted in the PISD to evolve into an ISPISD. The harvester setting in the ISPISD is shown in Figure 5. The three-dimensional motion of the ISPISD can be approximated as a single-axis rotation. During the movement, the ISPISD will rotate around the Y-axis, because the moment of inertia of the Y-axis is much smaller than the X-axis and the Z-axis. The ISPISD studied in this paper is driven by the fluid in the pipeline and the speed is relatively stable, as explained in the last section.

The size design of the cantilever beam is very important for the efficiency of energy harvesting. As can be seen from the previous section, the PISD designed in this paper has

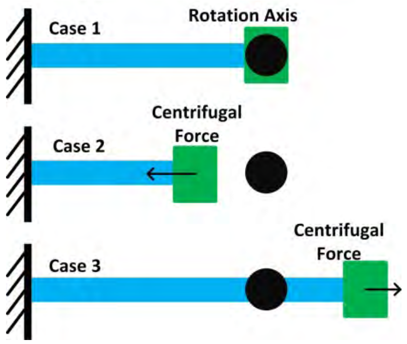


FIGURE 6. Three schemes of harvester embedded in ISPISD.

a rotation frequency of 2.6 Hz, which is relative low for a cantilever beam energy harvester. It is difficult to design a matching of resonant frequencies in small applications, which requires very large masses or very thin cantilever beams that will have a very short lifetime. In the next generation of ISPISD, the middle mezzanine will be added for energy harvesting. The cantilever beam in the resonance state will have a very large amplitude, and it will strongly impact other electronic devices in the narrow sphere. Therefore, this paper does not aim at achieving the resonant frequency matching. It is hoped that the design of this paper will prove the possibility of energy harvesting in PISD. In the future, the harvesting performance will be gradually optimized through further structural design.

Unlike uniaxial vibration, the rotational motion has a centrifugal force. Usually longer cantilever beams are better in vibration energy harvesting, but in rotating applications, they cannot be selected and evaluated directly. Therefore, this paper discusses and compares the dimensions of the three methods, as seen in Figure 6. The mass of Case 1 coincides with the center of rotation, which is a solution without centrifugal force. In Case 2, the cantilever beam is shorter in size and the shorter dimension gives greater rigidity. However, the centrifugal force has an inward axial force on the cantilever beam, which will reduce the stiffness of the beam. In Case 3, contrary to Case 2, the cantilever beam is longer in size, and centrifugal force increases the stiffness of the beam. The specific parameters will be introduced in the experimental section.

C. MODELING

This paper plans to establish a piezoelectric coupling model based on the Euler–Lagrange theorem. Firstly, the influence of centrifugal force is not considered. During the rotational moving, the displacement of the mass relative to the origin of the coordinate is $u(t)$, and the angle is $\theta(t)$, then the displacement of the mass in the Cartesian coordinate system is:

$$\begin{cases} u_x = u\sin\theta \\ u_y = -u\cos\theta \end{cases} \tag{1}$$

The speed can be obtained as follows:

$$\begin{cases} \dot{u}_x = \dot{u}\sin\theta + u\dot{\theta}\cos\theta \\ \dot{u}_y = -\dot{u}\cos\theta + u\dot{\theta}\sin\theta \end{cases} \tag{2}$$

The kinetic energy and potential energy of the harvester can be written as:

$$\begin{cases} T = \frac{1}{2}m(\dot{u}_x^2 + \dot{u}_y^2) = \frac{1}{2}m(\dot{u}^2 + u^2\dot{\theta}^2) \\ U = \frac{1}{2}ku^2 - mgu\cos\theta - \frac{1}{2}C_pV^2 \end{cases} \tag{3}$$

where C_p is the piezoelectric material capacitance. The Euler–Lagrange quantity is $L = T\text{-}U$. According to the Euler–Lagrange theorem, for the generalized coordinate displacement u, the angle θ and the output voltage V, the system response equation can be obtained:

$$\begin{cases} \frac{d}{dt}(\frac{\partial L}{\partial \dot{u}}) - \frac{\partial L}{\partial u} = -c\dot{u} + \Theta V u \\ \frac{d}{dt}(\frac{\partial L}{\partial \dot{\theta}}) - \frac{\partial L}{\partial \theta} = \sigma \\ \frac{d}{dt}(\frac{\partial L}{\partial \dot{V}}) - \frac{\partial L}{\partial V} = Q \end{cases} \tag{4}$$

Among them, c is the equivalent damping; Θ is the piezoelectric coupling coefficient; V is the obtained voltage; σ is the generalized torsional force; Q is the charge obtained by the piezoelectric effect. The equation can be expressed by:

$$\begin{cases} m\ddot{u} - m\dot{\theta}^2u + ku + c\dot{u} - mg\cos\theta + \Theta V = 0 \\ mu^2\ddot{\theta} + 2m\dot{\theta}u\dot{u} + mgu\sin\theta = \sigma \\ \Theta u - C_pV = Q \end{cases} \tag{5}$$

where R is the load resistance of the system. The displacement and voltage are the key parameters in this paper, the second equation in equation (5) is ignored and the third equation is derived for time.

$$\begin{cases} m\ddot{u} + c\dot{u} + (k - m\omega^2)\quad u + \Theta V = mg\cos(\omega t) \\ \Theta\dot{u} - C_p\dot{V} = \frac{V}{R} \end{cases} \tag{6}$$

During the rotation process, considering that the mass of the cantilever beam is small compared to the mass, the centrifugal force that the harvesters receive is:

$$F = m_t\omega^2 r \tag{7}$$

Centrifugal force is the axial tensile force of a composite beam that can produce a change in the stiffness of the beam. The synthesized resonant frequency can be expressed as:

$$\omega_n' = \omega_n\sqrt{1 + D\frac{5}{14}\frac{Fl^2}{EI}} \tag{8}$$

$$D = \begin{cases} 0(Case1) \\ -1\,(Case2) \\ 1(Case3) \end{cases} \tag{9}$$

where ω_n can be expressed as:

$$\omega_n = \sqrt{\frac{k - m\omega^2}{m}} \tag{10}$$

Thus, the final model can be obtained as:

$$\begin{cases} m\ddot{u} + c\dot{u} + (k - k_c)u + \Theta V = mg\cos(\omega t) \\ \Theta\dot{u} - C_p\dot{V} = \dfrac{V}{R} \end{cases} \tag{11}$$

The change in stiffness k_c can be expressed as:

$$k_c = (m - D\frac{15}{14}\frac{r}{l}m_t)\omega^2 \tag{12}$$

In the above, the model of the harvester has been established.

III. EXPERIMENTS IN THE LAB

A. DESIGN

This section will design the dimensions of the harvester. The PISD is available in a variety of different sizes to handle different pipe inspection tasks. The outer diameter of the PISD used in this paper is 165 mm. The thickness of the outermost polyurethane layer damping shell and the aluminum inner casing of the PISD are considered, and the available sizes are approximately 120 mm inside. The piezoelectric harvester designed in this paper is made of red copper with 8.96 g/cm^3 density and 108 GPa elastic modulus. The commercially available piezoelectric material composed of macro fiber composite (MFC-2807-P2) is selected, which has a size of 37 × 10 × 0.21 mm and the MFC is glued to the beam with epoxy adhesive (3M DP460). The width of the cantilever beam is consistent with the piezoelectric material and is 10 mm. The mass is chosen to be 50g, and an oversized mass will threaten the life of the harvester and take up too much space. Thin beams are good for energy harvesting but cannot withstand long hours of work. Considering the life and efficiency, the thickness of the cantilever beam is chosen to be 0.8mm. The three schemes are 60, 40, and 100 mm in length, respectively, and their corresponding stiffnesses are 2150, 5230, and 342 N/m, respectively.

B. ROTATION EXPERIMENT PLATFORM

The platform for the rotational experiment is shown in Figure 7(a). In order to prevent the vibration of the motor itself from affecting the experiment, the equipment required for the rotating platform system is fixed on the optical vibration isolation platform. Rotation is generated by the motor and connected to the acrylic turntable through the shaft. The rotation of the motor is controlled by a computer through the 485 communication method with good anti-noise interference. The rotation frequency can be observed in real time by the 5166FR type tachometer. The acrylic turntable consists of two layers, because in part of the experiments, the mass needs to coincide with the center of rotation, and the flange blocks the space. The electrode of the MFC is directly connected to the measuring circuit, and the principle is shown in Figure 7(b). The circuit board is rounded for easy installation in the ISPISD. The circuit avoids the use of the traditional slip ring and can store the voltage output and acceleration signal in the TF card for subsequent data processing.

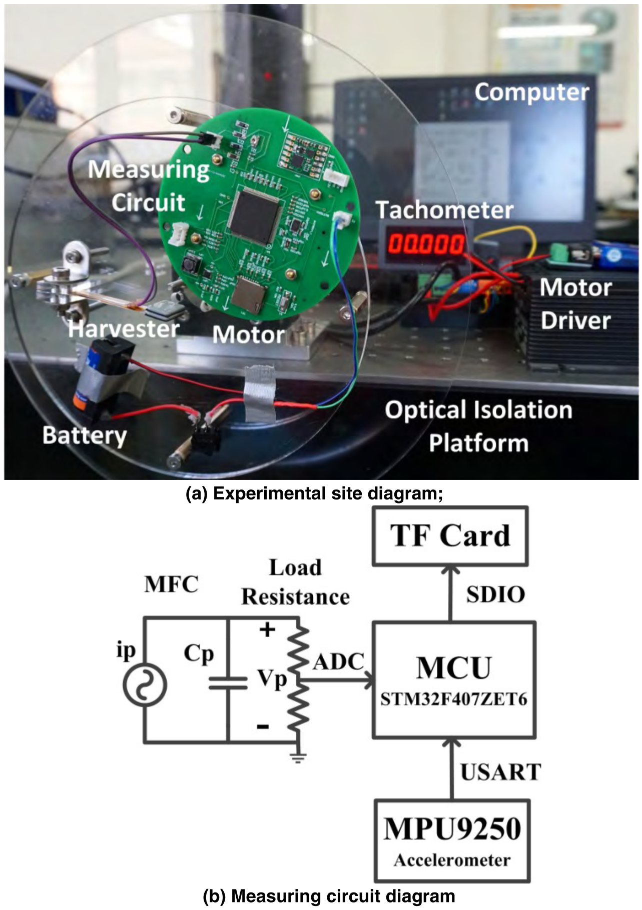


FIGURE 7. Schematic diagram of the rotational experiment platform.

C. LOAD RESISTANCE ANALYSIS

This paper focuses on the application level of the harvester, so the optimal load resistance will be studied firstly. As the load resistance increases, the output voltage increases, but the output power does not increase all the time, and there is an optimum value. Experiment with three different schemes by setting the system rotation frequency to 2.6 Hz. The experiment was performed at intervals of 500 kΩ. Figure 8 shows the effect of load resistance values on output power in numerical simulations and experiments. As can be seen from the results, Case 1 and Case 2 obtained the maximum power at 3 MΩ, and Case 3 was obtained at 3.5 MΩ. In order to get a better comparison, 3.5 MΩ was chosen as the optimal resistance value for subsequent study.

D. OUTPUT VOLTAGE ANALYSIS

This section will analyze the output voltage time domain signals. The output voltage results in different cases are shown

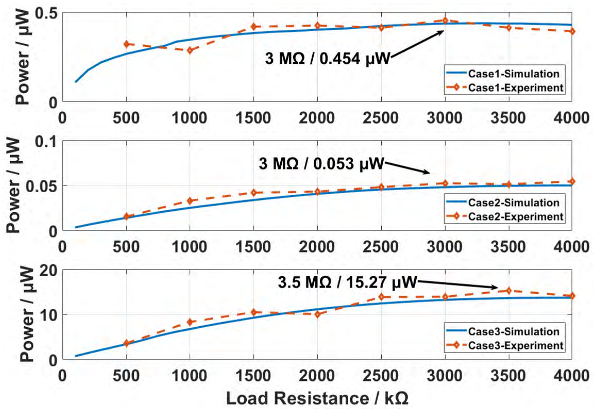


FIGURE 8. Effect of different load resistances on output power.

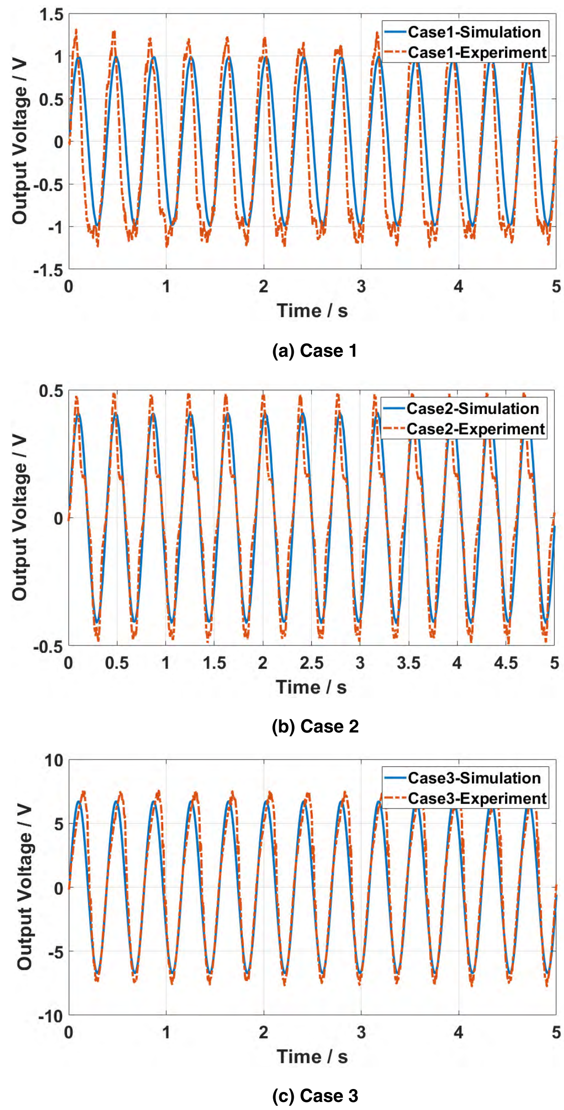


FIGURE 9. Output voltage results in different cases.

in Figure 9. First of all, from the simulation point of view, the outputs of the three cases are approximately sinusoidal, and similar results are obtained with the simulation, in which the output in Case 3 is the most regular. The model established in this paper can make a reasonable prediction of the output of the system. From the output point of view, the output in Case 3 is significantly higher than the other two. The beam in Case 3 is the longest and its stiffness is significantly smaller than the other two. Although the presence of centrifugal force will increase its stiffness during operation, due to the lower rotation frequency of 2.6 Hz, the stiffness is less affected by the centripetal force. In Case 1, although the axial force of the beam reduces the stiffness of the beam, the stiffness of the beam itself is very large due to its short size, which affects its output performance.

IV. EXPERIMENTS IN THE PIPELINE

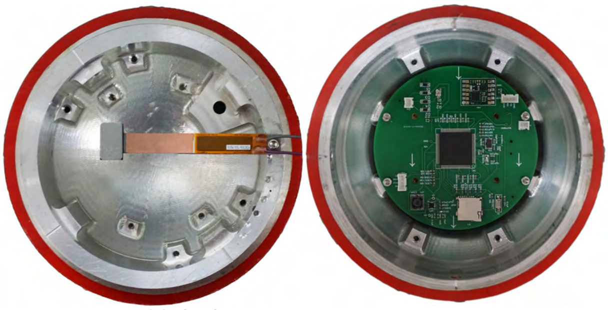
A. PIPELINE EXPERIMENT PLATFORM

In order to further verify the performance of the designed harvester in the PISD, this section performs a pipeline experiment. The cantilever beam energy harvesting structure and the circuit board are respectively fixed inside the spherical inner detector, as shown in Figure 10 (a). The fixed direction of the cantilever beam is different from the above, because the ball used in the experiment is not equipped with other structures such as a battery, and is a relatively uniform sphere. In the experiment, the rotation of the PISD is controlled by the placement of the initial test position. The experiment selects the case of uniaxial rotation for analysis. The circuit board used here is the same as the circuit board used in the rotational platform experiment, and can collect and store the data of the rotational acceleration and output voltage of the harvester in the pipeline. The experimental pipeline and site diagram are shown in Figure 10 (b) and (c), where the length of the pipeline is 50 m and the diameter is 200 mm. The experiment uses a blower to push the PISD to move in the pipeline to simulate the actual working state.

B. RESULTS

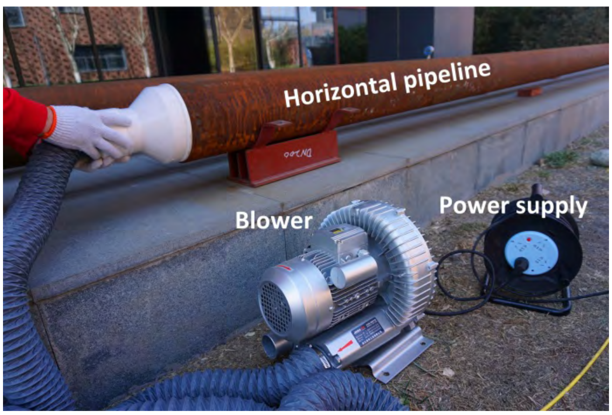
Some representative output voltage time domain data are selected for display, as shown in Figure 11. Figure 11(a) shows the data of the ISPISD during smooth operation. It can be seen that the peak value fluctuates because the PISD in this experiment is not equipped with devices inside, and its moment of inertia is not set according to the difference for different axis. Therefore, the rotation in the experiment is not very stable, but it can be seen that the output voltage is similar to that of the laboratory, and it still maintains sinusoidal characteristics, and the frequency is relatively stable. In future experiments and applications, a separate assembly study will be conducted for the harvester, and the gap of the moment of inertia will be further expanded to make the rotational characteristics of the PISD more in line with the requirements of the harvester.

The long-distance pipelines are joined by welding, and the welded joints produce welds with a small projection. The pipeline tested in this paper also have welds, and the ISPISD will collide with the welds when passing through



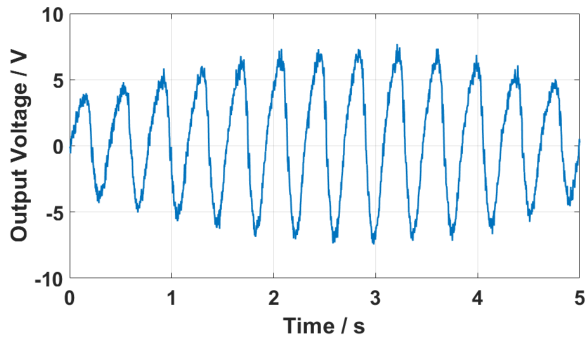
(a) ISPISD prototype with a harvester inside

(b) Experimental pipeline

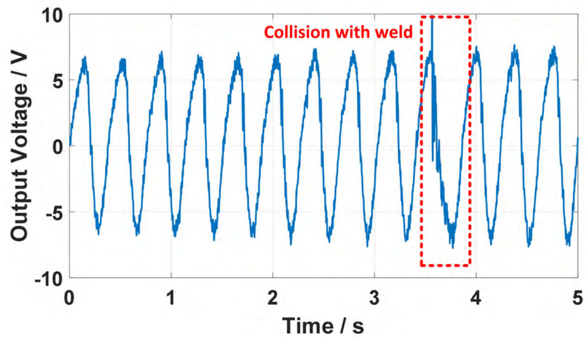


(c) Experimental site diagram

FIGURE 10. Schematic diagram of the experiment in the pipeline.



(a) Data when running smoothly



(b) Data when passing through the weld

FIGURE 11. Output voltage time domain data in the pipeline.

the welds. The data when colliding with the weld is shown in Figure 11(b). As can be seen from the figure, in the event of a collision, the output voltage produces a spike, which in turn produces a more turbulent vibration that returns to steady state after about half a cycle.

C. DISCUSSION

It can be seen from the above experiments and analysis that the harvester studied in this paper can obtain electric energy in the rotational motion of PISD and has the potential to develop ISPISD. Under laboratory conditions, at a frequency of 2.6 Hz, power of 15.27 μW can be obtained. This energy is sufficient to power some low power devices, for example, the commercial acceleration sensor ADXL362 from ADI consumes 3.6 μW. From the perspective of the excitation of the mass, the efficiency of the harvester can be calculated by the following equation, where a and v are the instantaneous acceleration and velocity of the mass, respectively.

$$\eta = \frac{W_{out}}{W_{in}} = \frac{Pt}{\int_0^t |mav| \cdot dt} \tag{13}$$

With the simulation data of Case3 in Figure 9, the calculated efficiency was 8.64%. However, for all electronic devices in the PISD, the power is still insufficient, and the harvested power can be further increased in an array manner in the future. At the same time, a separate assembly design of the internal structure of the PISD containing the energy harvester will be considered, considering a separate layer with a boundary for the harvester in the middle. The limiter up and down will be set to limit the amplitude of the harvester to prevent interference with other electronics. At the same time, in the mechanical structure design of the ISPISD with the harvester, the difference of the moment of inertia of the different axes should be designed to be larger, so that the PISD is more in line with the characteristics of single-axis rotation, which is convenient for the design of the harvester.

The PISD designed in this paper is the smallest model and is difficult to design at a frequency of 2.6 Hz. Longer cantilever beams can be used in other larger models of PISDs, making it easier to achieve better performance. At the same time, because different flow rates and fluid types will affect the operating frequency of the PISD, separate designs should be used in different applications.

V. CONCLUSION

Piezoelectric energy harvesting is a promising way to develop self-powered wireless systems. For the pipeline inner spherical detector (PISD), novel pipe damage inspection equipment, such technology supplies the potential to power the electronic device inside. In order to break through the limitations of traditional batteries for PISD application distance, this paper proposes an intelligent self-powered PISD with a piezoelectric energy harvester inside.

Due to the limited space in the PISD, the harvester designed in this paper consists of only one piezoelectric cantilever beam with its fixed end connected to the PISD shell. Due to the difference in the moment of inertia, the motion of the PISD can be reduced to a single-axis motion. Taking the 165 mm size detector designed in this paper as an example, the motion is performed in a horizontal pipe at 2.6 Hz. This paper proposes three harvester schemes whose lengths are shorter than, equal to and larger than the radius, and establishes a response model. Simulation and experimental results show that the last scheme with 100mm long is optimal. The centrifugal force will stretch the beam to increase stiffness, which is not conducive to low-frequency design. However, since the length has a greater influence on the stiffness of the beam itself, the 100 mm harvester achieves the optimum properties, yielding 15.27 μW of energy at a load resistance of 3.5 MΩ.

A prototype experiment was performed in the pipeline, and the results showed that a sinusoidal response similar to that of the laboratory was obtained in the pipeline. When passing through the weld, an impact response will be produced and then the steady-state will be restored.

In general, the energy harvester proposed in this paper has the application prospect of developing an intelligent self-powered PISD.

REFERENCES

[1] X. Huang, S. Chen, S. Guo, T. Xu, Q. Ma, S. Jin, and G. S. Chirikjian, ''A 3D localization approach for subsea pipelines using a spherical detector,'' *IEEE Sensors J.*, vol. 17, no. 6, pp. 1828–1836, Mar. 2017.

[2] G. Lin, Z. Zhoumo, H. Xinjing, L. Jian, and C. Shili, ''Vibration detection of spanning subsea pipelines by using a spherical detector,'' *IEEE Access*, vol. 7, pp. 7001–7010, Dec. 2018.

[3] S. Guo, S. Chen, X. Huang, Y. Zhang, and S. Jin, ''CFD and experimental investigations of drag force on spherical leak detector in pipe flows at high Reynolds number,'' *Comput. Model. Eng. Sci.*, vol. 101, no. 1, pp. 59–80, 2014.

[4] Y. Li, L. Sun, L. K. Wang, and L. L. Zhang, ''Design of leakage detection and location system for long range crude oil pipeline,'' in *Proc. IEEE ICCA*, Xiamen, China, Jun. 2010, pp. 1742–1746.

[5] Z. Sha, H. Feng, Y. Shi, W. Zhang, and Z. Zeng, ''Phase-sensitive OTDR with 75-km single-end sensing distance based on RP-EDF amplification,'' *IEEE Photon. Technol. Lett.*, vol. 29, no. 16, pp. 1308–1311, Aug. 15, 2017.

[6] S. T. Tolmasquim and A. O. Nieckele, ''Design and control of pig operations through pipelines,'' *J. Petrol. Sci. Eng.*, vol. 62, nos. 3–4, pp. 102–110, Sep. 2008.

[7] T. Xu, S. Chen, S. Guo, X. Huang, J. Li, and Z. Zeng, ''A small leakage detection approach for oil pipeline using an inner spherical ball,'' *Process Saf. Environ.*, vol. 124, pp. 279–289, Apr. 2019.

[8] Z. Yu, X. Yameng, H. Xinjing, L. Jian, and C. Shili, ''Pipeline inclination measurements based on a spherical detector with magnetic proximity switches,'' *IEEE Access*, vol. 6, pp. 39936–39943, Jul. 2018.

[9] Y. Bai, H. Jantunen, and J. Juuti, ''Energy harvesting research: The road from single source to multisource,'' *Adv. Mater.*, vol. 30, no. 34, Aug. 2018, Art. no. 1707271.

[10] H. Elahi, M. Eugeni, and P. Gaudenzi, ''A review on mechanisms for piezoelectric-based energy harvesters,'' *Energies*, vol. 11, no. 7, p. 1850, Jul. 2018.

[11] M. Febbo, S. P. Machado, C. D. Gatti, and J. M. Ramirez, ''An out-of-plane rotational energy harvesting system for low frequency environments,'' *Energy Convers. Manage.*, vol. 152, pp. 166–175, Nov. 2017.

[12] P. L. Díez, I. Gabilondo, E. Alarcón, and F. Moll, ''A comprehensive method to taxonomize mechanical energy harvesting technologies,'' in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS)*, Florence, Italy, May 2018, pp. 1–5.

[13] X. Fu and W. Liao, ''Modeling and analysis of piezoelectric energy harvesting with dynamic plucking mechanism,'' *J. Vib. Acoust.*, vol. 141, no. 3, Jun. 2019, Art. no. 031002.

[14] H. Fu and E. M. Yeatman, ''A methodology for low-speed broadband rotational energy harvesting using piezoelectric transduction and frequency up-conversion,'' *Energy*, vol. 125, pp. 152–161, Apr. 2017.

[15] L. Gu and C. Livermore, ''Passive self-tuning energy harvester for extracting energy from rotational motion,'' *Appl. Phys. Lett.*, vol. 97, no. 8, Aug. 2010, Art. no. 081904.

[16] J.-C. Hsu, C.-T. Tseng, and Y.-S. Chen, ''Analysis and experiment of self-frequency-tuning piezoelectric energy harvesters for rotational motion,'' *Smart Mater. Struct.*, vol. 23, no. 7, Jun. 2014, Art. no. 075013.

[17] M. Guan and W.-H. Liao, ''Design and analysis of a piezoelectric energy harvester for rotational motion system,'' *Energ. Convers. Manage.*, vol. 111, pp. 239–244, Mar. 2016.

[18] N. Aboulfotoh and J. Twiefel, ''On developing an optimal design procedure for a bimorph piezoelectric cantilever energy harvester under a predefined volume,'' *Mech. Syst. Signal Process.*, vol. 106, pp. 1–12, Jun. 2018.

XIAOBO RUI received the B.S. degree from Tianjin University, in 2014, where he is currently pursuing the Ph.D. degree. His main research interests include piezoelectric energy harvesting and intelligent sensing technology.

ZHOUMO ZENG (M'06) was born in 1962. He is currently a Professor and the Dean of the Precision Instruments and Optoelectronic Engineering School, Tianjin University. He is a member of the China Society of Optics and Optoelectronics Professional Committee, the Director of the China Microelectronics Society, and the Director of the Tianjin Microcontroller Society.

YU ZHANG received the B.E. and Ph.D. degrees from Tianjin University, in 2004 and 2009, respectively, where he is currently an Associate Professor with the School of Precision Instrument and Opto-electronics Engineering. His research interests include detection technology and equipment, automatic measurement and control systems, and system integration and optimization.

YIBO LI received the M.S. degree from the Harbin University of Science and Technology, in 1998, and the Ph.D. degree from Tianjin University, in 2004, where he is currently an Associate Professor and a Ph.D. Supervisor. His main research interests include structural health monitoring and energy harvesting.

XINJING HUANG received the B.S. and Ph.D. degrees from Tianjin University, in 2010 and 2016, respectively, where he is currently an Assistant Professor. His research interest includes pipeline damage detections.

YUE LIU received the B.S. degree from Tianjin University, in 2016, where he is currently pursuing the M.S. degree. His main research interest includes energy harvesting for inner-detector of pipelines.

TIANSHU XU received the B.S. degree in measurement and control technology and instrumentation from Tianjin University, Tianjin, China, in 2012, where he is currently pursuing the Ph.D. degree in instrument science and technology. His research interest includes small leak detection and location in pipelines