Passive Acoustic Transducer as a Fluid Flow Sensor

S. K. E. Yang[1], M. E. Kiziroglou[1,2], *Senior Member, IEEE*, E. M. Yeatman[1], *Fellow, IEEE* and A. S. Holmes[1], *Member, IEEE*.
[1]Imperial College London, United Kingdom
[2]International Hellenic University, Thessaloniki, Greece

Abstract— Autonomy and minimal disruption are key desirable features for sensors to be deployed in medical, industrial, vehicle and infrastructure monitoring systems. Using a passive structure to transduce the quantity of interest into an acoustic or electromagnetic wave could offer an attractive solution for remote sensing, lifting the requirements of installing active materials, electronics, and power sources in remote, inaccessible, sensitive, or harsh environment locations. Here, we report a simple cavity and ball structure that transduces fluid flow through a pipe into an acoustic signal. A microphone on the outside wall of the pipe records the intensity and arrival rate of the sound pulses generated by collisions between the ball and the cavity walls. Using this approach external measurement of flow is demonstrated with adequate repeatability before any acoustic signal processing. This result is expected to open the way to the implementation of passive, remotely readable sensors for fluid flow and other fluid properties of interest.

***Index Terms*—Autonomous sensor, wireless, fluid flow, acoustic, passive.**

I. INTRODUCTION

Non-invasive and minimally invasive sensing technologies will play a pivotal role in medical, industrial, vehicle and infrastructure monitoring. The rapid expansion of sensor population and diversity that is driven by Internet-of-Things (IoT) applications requires sensors of increased autonomy, reliability, and resilience as well as a simplified installation, reduced intrusion, and minimal interference with the monitored system. In the case of fluid-flow monitoring, the common sensor concepts, which include turbine counters for large systems, and heat dissipation probes and drag force sensors for smaller systems [1, 2], typically require the immersion of an active electronic device into the flow. A method for reduced invasiveness by probe miniaturisation has been demonstrated in [3] offering a practical minimally invasive method for multi-sensor installation. Non-invasive methods for flow monitoring include the Siemens ultrasound time-of-flight sensor [4] and the Pulsar Measurement ultrasound doppler effect sensor [5]. On the other hand, flow induced vibration in combination with active materials has been considered for energy harvesting as well as sensing [6-14].

Towards an autonomous, easy to integrate and reliable sensor, an approach of significant potential is to implement a passive structure that transduces the quantity of interest into an acoustic signal with a distinct signature. The acoustic signal can then be received wirelessly by a microphone, either within the same sensing device package or remotely at a different location. This approach has several key advantages including: (i) physical and electrical decoupling of the sensor from the electronics, offering for example reliable sealing; (ii) energy and communication autonomy for applications involving remote, inaccessible, or RF-shielded locations; (iii) simplification of the apparatus required at the sensing location, allowing sensing in toxic, extreme temperature, radiative and other harsh environments; and (iv) ability to integrate the required passive transducer into the manufacturing process of the monitored system.

In this work, we apply this approach to a fluid flow sensor. A passive flow-to-sound transducer is designed, fabricated, and tested in a laboratory-scale calibrated water flow test rig. The transducer is installed inside a plastic pipe and the acoustic signal is recorded by an external microphone. The experimental results are analyzed in comparison with independent flow rate measurements, and the potential of this method for simplified, autonomous, and remote flow sensing is discussed.

II. ACOUSTIC SENSOR

A. Operating Concept

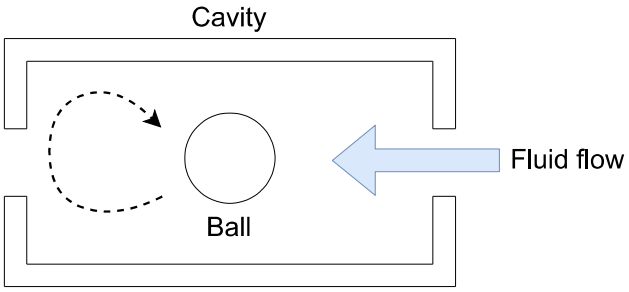


Fig. 1: Operating concept of the acoustic sensor. The cavity design and dimensions are conceptual only.

The passive acoustic transducer comprises a ball trapped inside a cavity with openings at the upstream and downstream ends (Fig. 1). Fluid flow through the cavity results in a drag force on the ball, which can drive an oscillatory motion, depending on ball size and cavity design. This motion may create a variable pressure field, driving an acoustic wave similar to the whistle operation principle [15-19]. Alternatively, the sound of the cavity enclosure vibration that occurs every time the ball hits its walls can be used, similar to the operating principle of a bell. A faster flow results in a higher ball-cavity hit rate, which can be counted by listening for the cavity signature oscillation remotely. The vibration signature may be analysed further to extract more information on the fluid properties and the infrastructure condition. In this work the latter operating principle is employed.

B. Sensor design

Fig. 2 shows the parts of the 3D-printed acoustic sensor: a square frustum (apex-less square pyramid) shaped cavity (A); a 5 mm-diameter plastic ball (B); a frame (C); and a mesh lid (D). The ball is larger than the inlet orifice (top base) of the cavity. A secondary inlet orifice is located at the center of one of the four cavity sides. Fluid flow through the two inlet orifices towards the mesh lid output results in an oscillatory ball motion, producing sound as the ball hits the cavity walls. The cavity vibration sound is measured by a microphone installed outside the pipe. An InvenSense ICS-40180 analog contact microphone with a gain amplifier was used for this purpose [20].

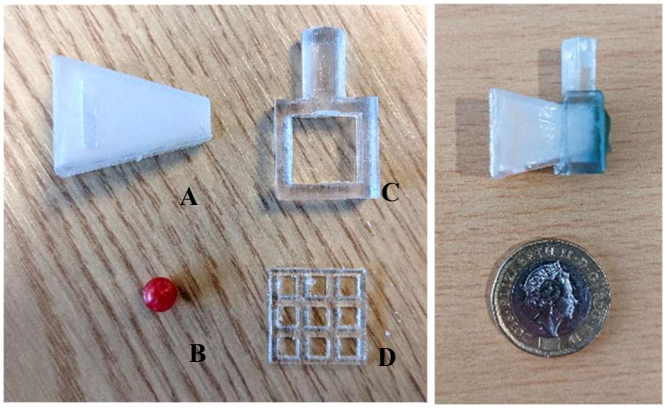


Fig. 2: Left: Individual parts of the acoustic sensor. Right: Assembled sensor compared to the size of a one-pound coin.

C. Experimental setup

A flow rig was used to evaluate the performance of the sensor. The flow rig uses the CRESTPUMP AM-50 to pump water into a 28 mm inner diameter polyoxymethylene pipe. The volumetric flow rate is controlled using the Parker AC10 motor controller, and the ABB FEP611 magnetic flowmeter with an accuracy of 0.5% is used as a reference meter. The microphone is placed on the surface of the pipe and powered by a 5V source as shown in Fig. 3. The signal line of the microphone is connected to a Picoscope 2000 which is connected to a laptop for data acquisition.

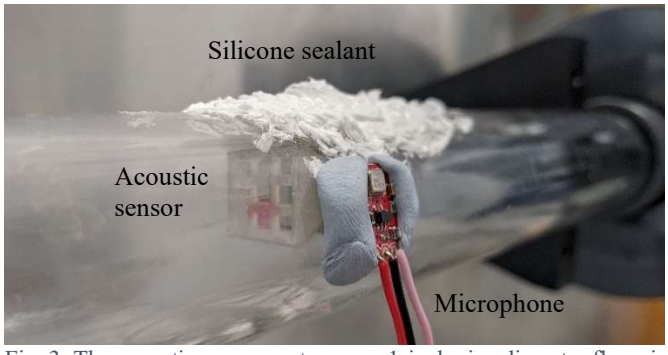


Fig. 3: The acoustic sensor system on a 1-inch pipe diameter flow rig. The contact microphone is attached to the pipe wall using blue tack.

III. Evaluation

The microphone signal is recorded and analysed using MATLAB. Fig. 4 shows an indicative 0.5 s sample recording from a reference flow rate of 58 L/min.

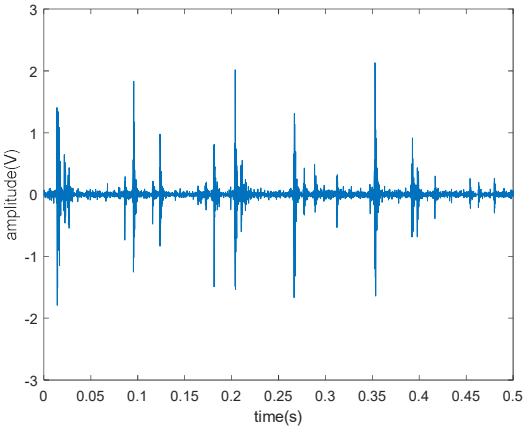


Fig. 4: Filtered signal plot of the microphone output for a flow rate of 58 L/min.

A high pass filter was applied to remove the 50 Hz mains noise, but it is otherwise as measured. The series of peaks observed correspond to the sound that occurs when the ball hits the cavity wall. Since we are interested in the pulses only, they are converted to positive peaks by taking the absolute value of the signal over 5 seconds. Using the motor controller, data is acquired for different flow rates, and they are shown in Fig. 5. An increase of the number and amplitude of the peaks with the flow rate can be observed. The 5th graph in Fig. 5 shows the signal at 72 L/min when the transducer is not present in the pipe, which confirms that the peaks are caused by the acoustic sensor.

To investigate the correlation between the peaks and the flow rate, the average of the signal for each flow rate over a period of 5 seconds is plotted in Fig. 6. A clear correlation is observed. The reproducibility of this result was studied by continuous data sampling for 5 mins and segregation into sixty 5s intervals. The average of each 5 s interval was calculated and the resulting deviations are plotted as error bars in Fig. 6. A good correlation between the signal average and the water flow rate is demonstrated. The standard deviation increases with flow rate as shown in Fig. 7. This can be caused by the increase in randomness of the collision frequency between the ball and the cavity walls. The minimum reliably detected flow rate is 28 L/min on this setup, corresponding to a flow speed of around 0.76 m/s. This sensitivity can potentially be improved by cavity design and ball size selection. These results demonstrate the functionality of the proposed concept. Further characterization of the sensor resolution and reliability for different averaging intervals and corresponding sensor response times is needed in order to make a performance comparison against state of art flow metering methods.

Further analysis can be done on the pulses produced by the acoustic sensor. Fig. 8 shows a zoomed-in plot of a typical pulse, and the extracted frequency when the ball hits the cavity wall is approximately 2.4 kHz. To calculate the frequency to bandwidth ratio, the formula below is used:

$$Q = \frac{f}{\Delta f}$$

where f is the peak frequency and Δf is the 3 dB frequency bandwidth of the 5 minutes signal. The ratio was calculated to be around 13. Further data analysis could allow distinction among signals from different sensors, noise filtering, evaluation of fluid properties and probing the transducer condition.

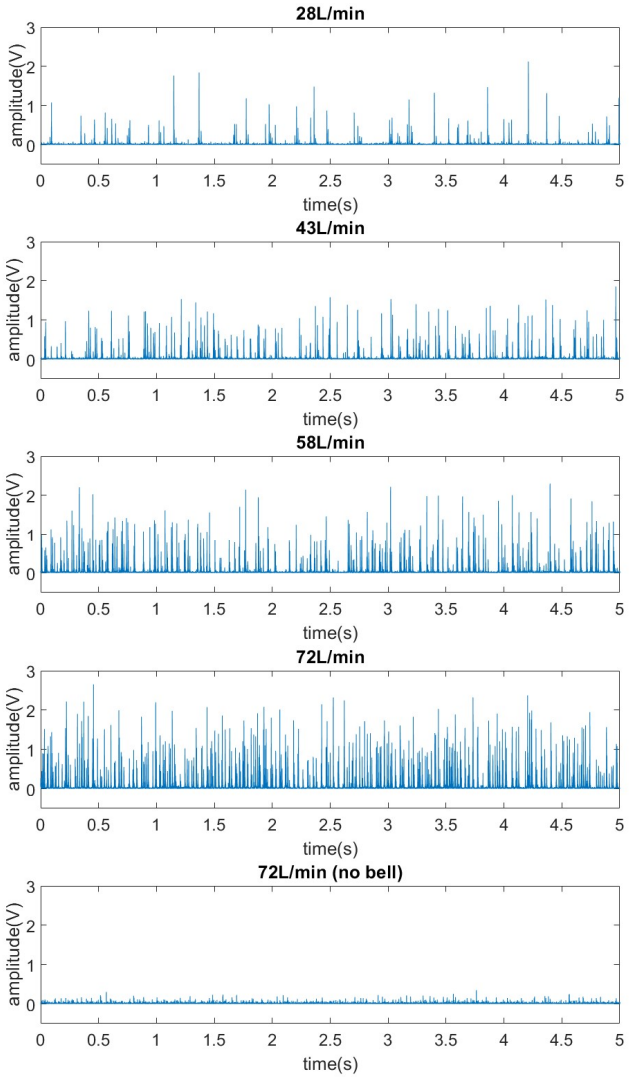


Fig. 5: Peaks corresponding to different flow rates.

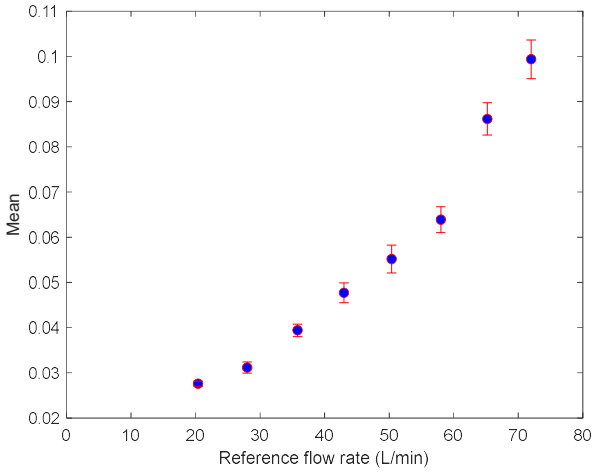


Fig. 6: Plot of signal means vs reference flow rates with error bars.

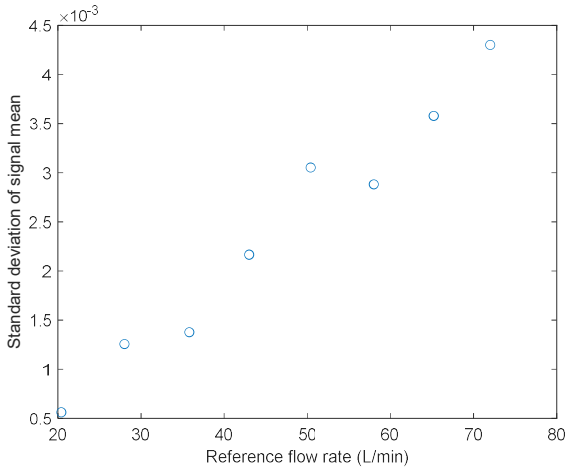


Fig. 7: Standard deviation vs reference flow rate.

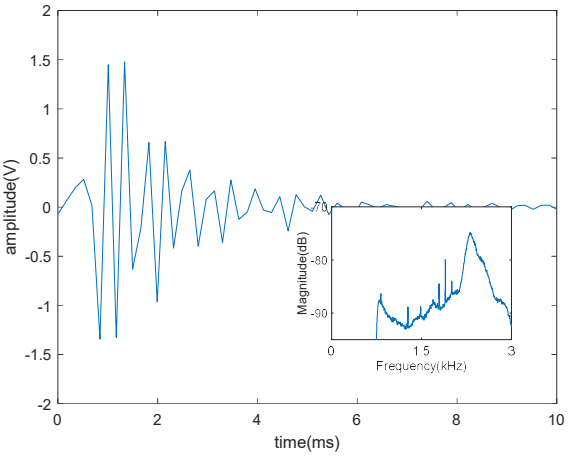


Fig. 8: Zoomed-in plot of a single pulse. Inset shows the Fourier transform of the filtered signal across a period of 5 mins.

IV. Conclusion

In this work, a sensing technique involving a passive structure that transduces fluid flow into a remotely read sound signal is introduced. A prototype cavity and ball structure are designed, fabricated, and tested, demonstrating remote acoustic sensing of flow speed. The microphone and electronics are installed on the outside surface. The system is thereby less invasive to the pipe. Tests from sixty samples for each measured flow rate confirm the repeatability of this demonstration. The sound wave packets resulting from ball-cavity collisions have a distinct frequency distribution and quality factor, that depend on the cavity structure and the fluid properties. This result is significant because it demonstrates the viability of remote acoustic sensing by use of only a passive structure instead of a full electronic sensor node at the location of interest, which is a key benefit for applications involving remote, inaccessible, sensitive, or harsh environments. The employment of optimised transducer structures and designs, signal processing and further analysis and exploitation of the detected acoustic waveform characteristics are expected to enable a new type of remote fluid sensors including flow rate, viscosity, and density, and inspire a new approach for autonomous wireless sensors.

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