Low Flow Rate Measurement and Leak Detection for Health Monitoring of Water Equipment

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Abstract. This paper presents recent research into low-cost flow meter designs to measure dripping leaks for health monitoring of water equipment. Water handling equipment is pervasive in our society, to the point it is often overlooked; including plumbing, faucets, bathtubs, showers, toilets, water heaters, water softeners, filtration systems, dish washers, washing machines, etc. Monitoring of the health and usage of water equipment will be a major contribution to the internet of things, providing information about equipment's need for maintenance or re-placement to both conserve water and prevent costly flood damage.

Detection of leaks and flow rates are core to monitoring the condition of water equipment. However, commercially available flow meters capable of measuring flow on the order of a dripping leak are too expensive for mass deployment in consumer products (>$300). This paper presents parametric studies of low cost in-line flow meter designs, intended to measure extreme low flow rates (<50 ml/min on the order of a dripping leak in ½ inch pipe). Designs were created based on a hybrid of traditional orifice and target meters. Part counts were kept minimal and synthesis methods were kept simple with the goal of minimizing cost.

Parametric studies were performed to evaluate the effects of geometric dimensions on the sensitivity, pressure drop, and other traits of the flow meters. Testing was performed both with custom equipment and in the Badger Meter Flow Lab at the Global Water Center in Milwaukee Wisconsin. Results were compared to electromagnetic and mass-based measurements.

Keywords: Flow meter · Leak detection · Water · Low-cost · IOT · Internet of things

1 Introduction

This paper presents recent research into low-cost flow meter designs intended to measure dripping leaks for health monitoring of water equipment. Detection of leaks and flow rates are core to monitoring the condition of water equipment including faucets and bathroom fixtures, water heaters, home filtration or water softening equipment, industrial reverse osmosis systems, and municipal desalination [1, 2].

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However, commercially available flow meters capable of measuring flow on the order of a small drip or leak such as Acoustic Detectors [3, 4], Fiber Optic Sensing [5, 6], Infrared Radiometric Method [7, 8], or Electromagnetic Flow Meters are too expensive for mass deployment or consumer products (>$300) [9, 10]. As the internet of things grows there is an increasing need for low-cost flow meters capable of detecting low flow rates. This paper presents recent parametric studies evaluating low-cost flow meter designs tuned to leak detection for health monitoring of water equipment.

2 Materials and Methods

Designs were created based on a hybrid of principals from traditional target and orifice plate meters using strain as the directly sensed property. Momentum based target meters measure the force applied to an obstruction placed in the flow [9–14]. The force exerted on the target is proportional to the pressure drop across the meter and varies with flow rate squared. Typically, this force is measured by sensing rotation of the sensor body, at a hinge, caused by the incident flow.

Orifice plate flow meters also function by creating a pressure drop with an obstruction in the flow. However, they typically are a more rigid structure that cause a larger pressure-drop than target meters and a pressure gauge is usually installed to compare the pressure upstream to the pressure downstream. Bernoulli's equation [9–12, 14–18] and continuity of incompressible liquids (water) [19–21] can be employed to find flow velocity in terms of measured pressure drop [11, 12, 22].

Once a basic geometry was determined and synthesis methods were established, samples were created with slightly varying geometries and tested to determine which dimensions had the biggest effect on flow meter performance and sensitivity.

Design employed several tactics to keep the costs minimal including: 1) Minimal part count or assembly. 2) Avoiding high precision moving parts. 3) Employing strain as the directly sensed property because strain gauges are basic, inexpensive, and easy to interface. Moreover, the sensor was designed to bend out of the way in higher flowrate regimes to minimize pressure drop in use.

2.1 Flow Meter Geometry

Several geometric designs were created and tested. A symmetrical design as shown in Fig. 1 was found to have good stability and initial performance while satisfying other criteria. The design was comprised of two flexible flaps supported by a central beam. A strain sensor was attached to the flowmeter body to sense the strain in the x direction caused by water flow bending the flaps. In this study, Specimens were dimensioned to fit in a 12.7 mm (½ inch) diameter pipe.

2.2 Simulation

The body of the flowmeter was simulated in ANSYS 2020 R1 [23] to verify how it would deform under load and the optimal orientation and location for strain measurement as shown in Fig. 2. A simplification was made where a constant pressure was

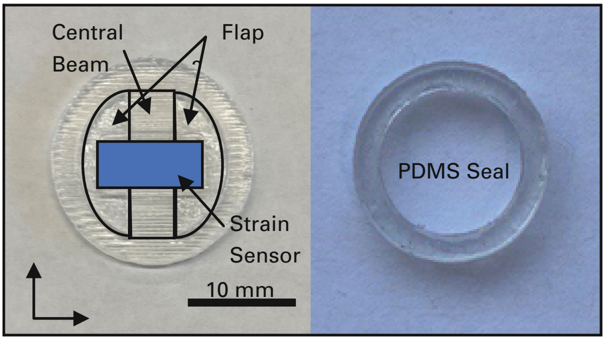

Fig. 1. Symmetrical flow meter body

applied to the upstream side of the sensor body. The flap deflection increased with flow rate and the optimal location for the strain gauge was at the center of the sensor, aligned to detect strain in the x direction.

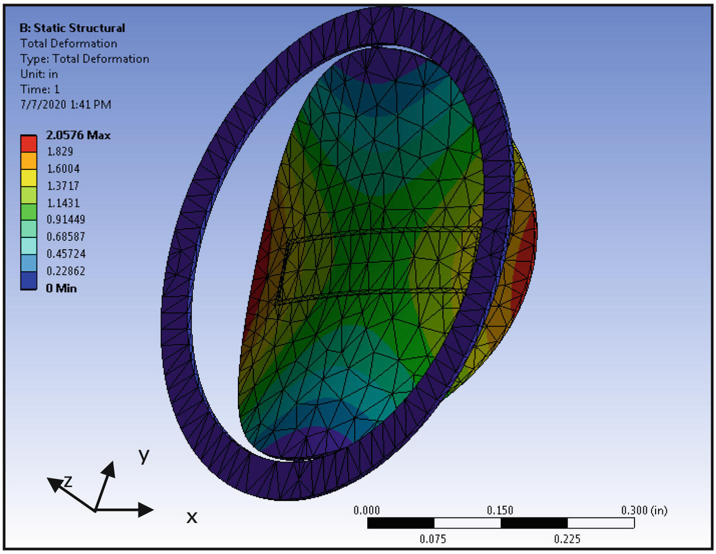

Fig. 2. Sensor deflected shape simulation by ANSYS 2020 R1

2.3 Sensor Synthesis

Molds were designed using PTC Creo 6.0 [24] software and created with a MakerBot Replicator + [25]. Dow SYLGARD™ 186 Silicone Elastomer Polydimethylsiloxane (PDMS) was cast into the molds and cured in an oven at 55 °C for 3 h resulting in sensor bodies like that is shown in Fig. 1. Strain gauges were applied to the body oriented in the x direction and interfaced to an Arduino Mega data acquisition computer (DAC) [26] through a Wheatstone bridge [26–28].

2.4 Testing

A series of tests were performed with variants of the design geometry supporting a factorial analysis to determine their effect on the performance including variations in: A) flap thickness, B) middle beam thickness, C) middle beam width, D) PDMS seal existence (the seal was a ring of PDMS that was placed immediately upstream of the meter body), and E) flowrate. The flowrate was measured by mass (weight) at low flow rates and using a BADGER METER M2000 electromagnetic sensor at higher flow rates [29]. Pressure drop was measured with a pair of Blue-Robotic Bar30 High-Resolution Pressure Sensors with one located upstream and the other located downstream of the flow meter [30]. Relative resistance change (ΔR/R) was set as the response in the analysis. Levels for each factor were selected as follows: flap thicknesses were 1.016 mm and 1.524 mm, middle beam thicknesses were 1.651 mm and 2.159 mm, middle beam widths were 2.54 mm and 5.08 mm, PDMS seal existence Yes or No, and flow rates of 90 ml/min and 150 ml/min were tested. Test specimens were placed in the space between two 12.7 mm long pipes that were connected by a coupler shown in Fig. 3. Lead wires for data collection were run through a small hole drilled in the coupler and connected the strain gauge to a Uni-T UT61c-Digital Multimeter with accuracy of 1% for FS of 600 kOhm (6 kOhm) [31]. Testing were performed in the BADGERMETER' Flow Lab at the Global Water Center in Milwaukee, Wisconsin and each experiment was repeated 3 times.

The results of the factorial analysis were used to inform the design of a highly sensitive flow meter for low flow rates. This design was then tested at flow rates from 1 to 125 ml/min.

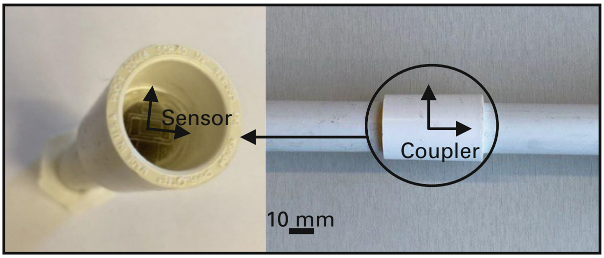

Fig. 3. Sensor in the coupler at the space between two pipes

3 Results and Discussion

3.1 Factorial Analysis

A factorial analysis with a significant level of 0.5 was performed on the results of testing to determine which geometric parameters most affected sensitivity. The Pareto chart shown in Fig. 4 indicates that the flowrate had the most significant effect on the output signal, which is a good quality for a flowmeter. The next trait that had the largest effect on the output signal was the existence of the PDMS seal, where the presence of the seal improved sensitivity. The next few most impactful geometric considerations were combined effects of middle beam thickness and width with thickness of the beam indicating that these factors did not individually affect the performance as much as their combination. The thickness of the flaps was the most important individual geometric trait, followed by the thickness of the central support beam while the width of the central support beam had the least effect on flowmeter sensitivity.

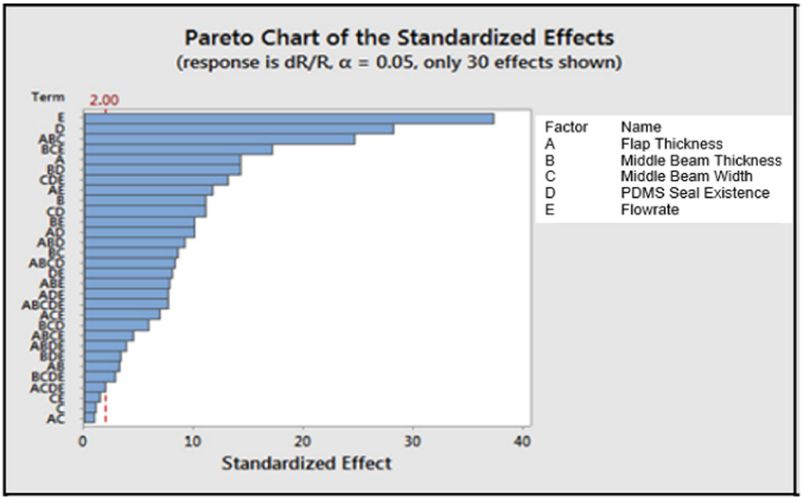

Fig. 4. Pareto chart of the symmetrical design's factorial analysis

3.2 Sensor Performance

Based on the Factorial analysis, the most sensitive sensor with the flap's thickness and middle beam's thickness and width of 1.016, 1.651, and 5.08 mm, respectively, were selected for further investigation of its transfer function. The water flow rate was varied from 0 to 123 ml/min and relative resistance change of the sensor ($\Delta R/R$) was measured. This sensor showed sensitivity of 6E−03 ($\Delta R/R$)/(ml/min) calculated by a linear fit with a coefficient of determination (R^2) of 0.9595. Data indicated a better fit with a quadratic transfer function of $\Delta R/R = 0.00004\ V^2 + 0.0014\ V$ depicted in Fig. 5 with V being the flow rate and a good R^2 of 0.9881.

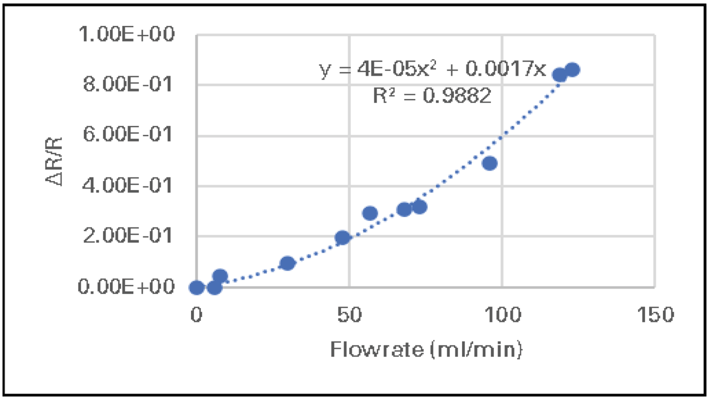

Fig. 5. Relative resistance change at different flow rates

3.3 Pressure-Drop

The flowmeter showed the maximum pressure drop of 18.3 kPa at 40 l/min. compensating for a pressure loss of 3.86 kPa caused by friction in the 45.72 cm long length of PVC pipe with the 12.7 mm diameter and the water flow, calculated based on Hazen–Williams Formula [32] results in 14.44 kPa of pressure drop caused by the sensor itself. Pressure drops at multiple flow rates are shown in Fig. 6. This demonstrated that the flow meter was properly moving out of the way at high flow rates.

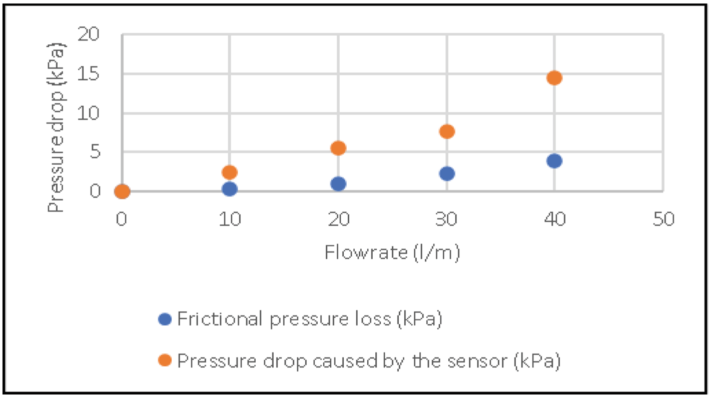

Fig. 6. Pressure-drop caused by the sensor vs. pipe's friction

4 Conclusion

This paper presented a simple, low-cost flow meter design intended for leak detection for monitoring the health of water equipment as part of the internet of things. Part count was kept minimal, consisting of a cast PDMS body, strain gauge, and wiring. The design was intended to fold out of the way to limit pressure drop at use level flow rates. An experimental parametric study was performed to evaluate the effects of various geometric properties on the sensitivity of the flowmeter. The parameters with greatest influence to produce high sensitivity were the presence of a sealing ring, thickness of the flaps and thickness of the central supporting beam while central supporting beam width were found to have insignificant influence on the performance of the flow meter. Strain measurement on the meter body resulted in a reasonable liner response at low flow rates, and an excellent fit to a second order transfer function with a coefficient of determination (R^2) greater than 0.98. The resulting design produced a maximum pressure drop of 14.44 kPa at a flow rate of 40 l/min in a ½ inch (12.7 mm) diameter pipe.

The ability to measure extreme low flow rates with low-cost sensors that can be widely employed enables key capabilities in monitoring the health of water handling equipment. The simple & inexpensive nature of the sensors further supports their mass deployment in the internet of things.

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