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A flow sensor exploiting magnetic fluids

B. Andò, S. Baglio, A. Beninato

DIEEI, University of Catania, Catania, Italy

Abstract

Flow sensors are widely used in several application contexts. In this paper a novel sensing approach to implement a low cost flow sensor is presented. The proposed methodology is based on the use of a ferrofluid volume to convert the flow rate into a measurable mass displacement. The ferrofluid movement is detected by an external inductive readout strategy. In this paper, the sensing strategy is illustrated along with a laboratory prototype and experimental results assessing the suitability of the methodology implemented.

Keywords:flow measurement, ferrofluid, low cost, invasive media

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1. Introduction

Flow measurement is an important issue in several application contexts and several kinds of flow sensors are used on the basis of the specific application context.

In this paper a novel and low cost sensing approach to implement a flow sensor is presented. The proposed methodology exploits a ferrofluid mass dispersed in water to convert the flow rate into the measurable mass displacement. Advantages in the use of a magnetic fluid as the active mass of the device are: tunable specifications such as operating range and responsivity, high robustness against mechanical shocks, the electric isolation between the device electronics and the liquid media and their physical decoupling which allows the use in hostile contexts involving invasive liquid media. The latter feature is also boast from the low cost of the disposable device structure housing the liquid media and the re-usability of the external electronics implementing the readout strategy.

Above features allow for the device application in several real context (from bio-medical systems to contexts where non invasive measurement on liquids are required).

Ferrofluids are synthetic compounds, in either aqueous or non aqueous solutions, composed by colloidal suspensions of ultra-fine (5-10 nm) single domain magnetic particles [1]. In literature sensors and actuators actively using magnetic fluids have been proposed [2-3].

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Focusing on the device presented in this paper requires a brief reference to instabilities phenomena occurring when a ferrofluid is subject to suitable magnetic field. Actually, the exploitation of such instabilities represents a convenient way to overcome drawbacks related to static friction and wall adhesion of a ferrofluid mass. In fact, magnetic fluids show interesting patterns coming from ferrohydrodynamic instabilities which can be exploited to implement suitable sensing strategies. An example is the Rosensweig instability which consists in the formation of ferrofluid spikes due to high magnetic pressure gradient in the ferrofluid surface [4].

The flow sensor proposed in this paper exploits the Rosensweig effect to create a spike of ferrofluid inside a pipe filled with de-ionized water. A liquid media flowing inside the pipe produces a movement of the spike free-end which is detected via a suitable readout strategy. The working principle of the sensing strategy, the device architecture, the sensor implementation and experimental results aimed to demonstrate the efficiency of the proposed methodology are discussed in the following sections.

2. The ferrofluidic flow sensor

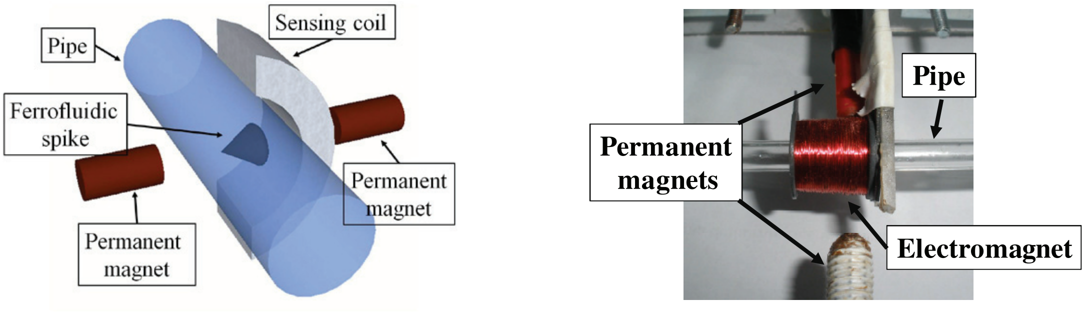
The device consists of a glass pipe filled with de-ionized water and a drop of ferrofluid. External components are used for shaping the ferrofluid volume and sensing its deformation. In particular, the shaping system is composed by two permanent magnets placed on the top and on the bottom of the pipe producing a spike on the ferrofluid volume due to the Rosensweig effect. In order to realize this spike shape, the magnet on the top of the pipe is placed very close to the glass surface, while the magnet on the botton is far from the glass surface. The permanent magnet on the top of the pipe is also used to implement a retaining magnetic force. In fact, the magnetic force acting on the ferrofluid mass resembles an equivalent elastic force which maintains the ferrofluid drop in a compliant position. A schematization of the device is shown in Fig. 1a.

The ferrofluid volume acts as the inertial mass of the system. An imposed flow rate produces a deformation of the ferrofluid spike around its equilibrium position. The readout system converting the ferrofluid displacement into an electric signal is implemented through a coil wounded on the pipe.

A real view of the sensor prototype developed is shown in Fig.1b where the pipe, the sensing coil and the spike shaping system are evincible.

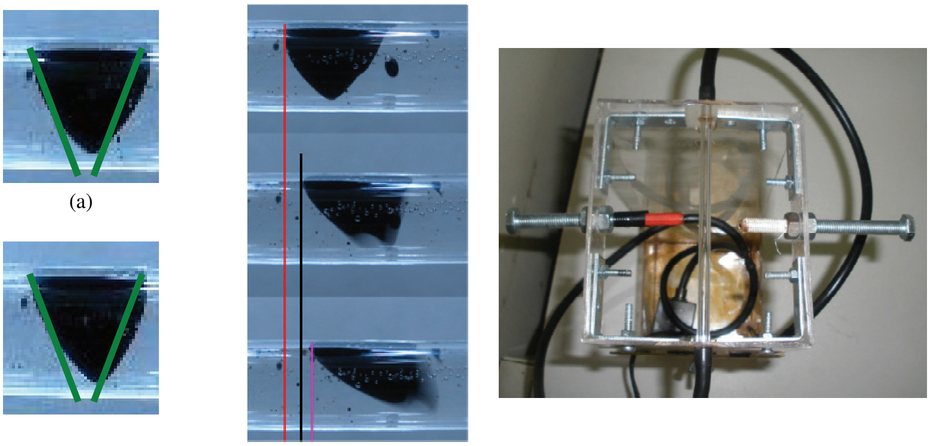
Flow rates under a fixed threshold value produce the displacement of the ferrofluid free-end in the direction of the flow. Flow rate larger than the threshold value will cause also a displacement of the whole ferrofluid mass from the compliant position is observed. Fig. 2 shows the low flow rate case: Fig. 2a shows the ferrofluid volume position for a null flow rate; Fig. 2b shows the spike deformation in case of a flow rate of 0.3 ml/s. Two bold lines highlight the free-end movement while evidence the fixed position of the spike. Frames in Fig. 2c show the mass behavior for a high flow rate. In particular, the ferrofluid shape and its position for a null flow rate, rates of 1ml/s and of 1.7 ml/s are shown. Two effects are evincible: the spike free end movement and the displacement of the whole mass in the flow direction. Three solid vertical lines highlight such behavior. The entity of both shape deformation and displacement of the ferrofluid mass depends on the magnetic retaining force generated by the permanent magnet placed on the top of the pipe. Actually, modulating the distance between the pipe and the magnet (or alternatively the magnet intensity), it is possible to change the operating range of the device and its responsivity. Such behavior is well evidenced by experimental results presented in Sec.3.

As already evidenced, the ferrofluid spike deformations is related to the flow rate: larger the flow rate larger is the displacement/deformation. To sense the spike deformation/displacement an inductive readout strategy is used. To such aim a sensing coil is wrapped around the pipe. The reading systems uses an AC bridge electronics to produce a voltage signal related to the imposed flow rate.



(a) (b)

Fig. 1. (a) Schematization of the flow sensor; (b) A detail of the inductive readout system implemented in the prototype.



(a) (b) (c) (d)

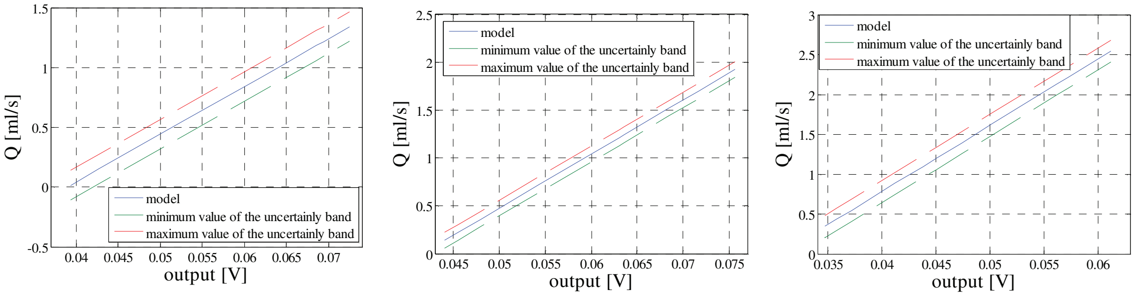
Fig. 2. The ferrofluid spike inside the pipe for the following flow rates: a) 0 ml/s, b) 0.3 ml/s, (c) from top to bottom 0 ml/s, 1 ml/s, 1.7 ml/s. (d) A real view of the developed system (the readout coil is omitted for the sake of convenience).

3. Experimental results

Figure 2d shows a real view of the experimental set-up adopted to characterize the behavior of the flow sensor prototype developed. The sensing coil has been omitted to perceive the ferrofluid mass. A sliding mechanism ruling the position of the magnetic actuators can be distinguished: the possibility to regulate the distance between magnets allows for defining the spike length (and thickness) and consequently some specifications of the device, such as the operating range and the responsivity. The glass pipe, filled with de-ionized water and a ferrofluid volume of 0.01 ml, has an inner diameter of 5 mm and a length of about 180 mm. The adopted ferrofluid is the EFH1 by Ferrotec. The sensor is supported by a plexiglass structure which is positioned over a tank. A pump was used to force inside the channel a controlled water flow rate. The flow rate was independently measured by a graded outlet tank.

Moreover, a hall effect sensor has been used to estimate the magnitude of the retaining magnetic field in the proximity of the ferrofluid spike.

As already stated the distance between the permanent magnets and the pipe defines the magnitude of the magnetic field acting on the ferrofluidic mass. The behavior of the flow sensor for different values of the magnetic field have been investigated.



(a) (b) (c)

Fig. 3. Calibration diagram of the sensor for retaining magnetic fields of (a)133 G, (b) 153 G and (c) 186 G.

Fig. 3 shows experimental results obtained for a retaining magnetic field of about 133 G, 153 G and 186 G. The device operating range, responsivity, resolution and uncertainty, in the different operating conditions are given in Table 2. As expected, for increasing value of the magnetic field, the operative range increases and the sensitivity decreases.

Table 1. Sensors characteristics

Sensor parameters	133 G	153 G	186 G
Max flow rate	1.5 ml/s	2 ml/s	2.5 ml/s
Responsivity	0.0241 Vs/ml	0.0184 Vs/ml	0.0172 Vs/ml
Resolution	0.0120 ml/s	0.0091 ml/s	0.0097 ml/s
Uncertainly	5.41 %	3.58 %	3.40 %

4. Conclusions

In this paper a ferrofluidic flow sensor is presented. The device developed boasts traditional advantages of ferrofluidic transducers such as the reliability conferred by the liquid inertial mass, the low cost and the intrinsic isolation between the electric part and the liquid medium. Experiments performed for different operating conditions demonstrate the reliability of the proposed methodology and the coherence with the expected behavior. Work in progress will be dedicated both to investigate basic models describing the device behavior and experimental activities aimed to better understand the ferrofluid spike dynamics and its relationship with the water flow rate.

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