Sensors and Actuators A 189 (2013) 17–23

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A flow sensor exploiting magnetic fluids

B. Andò*, S. Baglio, A. Beninato

DIEEI, University of Catania, Catania, Italy

ARTICLE INFO

Article history:
Received 22 February 2012
Received in revised form
20 September 2012
Accepted 21 September 2012
Available online 17 October 2012

Keywords:
Flow sensor
Ferrofluids
Inductive readout
Conductive liquids

ABSTRACT

Flow sensors are widely used in several applications. 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 spike shaped mass of ferrofluid to convert the static (slow varying) flow rate into a measurable displacement. The ferrofluid movement is detected by an inductive readout strategy. In the following the proposed methodology is described along with theoretical considerations and simulations of the device behavior. A laboratory prototype and experimental results assessing the suitability of the developed sensing strategy are also illustrated.

1. Introduction

Flow measurement is an important issue in several application contexts and several kinds of sensors are used on the basis of specific needs [1]. Main sensing principles adopted are electromagnetic [2], ultrasonic [3], turbine [4], thermal [5], differential pressure [6,7] and vortex flowmeters [8].

In electromagnetic flow meters, which exploit the induction Faraday's law, the magnetic field is generated by external coils while the liquid serves as the conductor. The voltage produced by the liquid movement is directly proportional to the flow rate. This method can be used only with conductive liquids. Ultrasonic flow meters measure the velocity of a liquid or a gas by averaging transit times between ultrasound pulses propagating into or against the flow direction. Turbine based devices exploit the effect of the flow on a turbine spin rate to estimate the target flow. The thermal approach is mainly used in case of flow measurements with low amount of fluid and it is based on conducted heat measurements. In differential pressure drop devices the flow is estimated by measuring the pressure drop over an obstruction in the flow channel. Vortex flowmeters measurement involves placing a body in the path of the fluid. As the fluid passes this body, vortices are created. The frequency at which these vortices alternate sides is essentially proportional to the flow rate of the fluid.

In this paper a novel and low cost approach to implement a flow sensor is presented [9]. The proposed methodology exploits a ferrofluid mass dispersed in water to convert the static (slow varying) flow rate into the mass displacement which is then measured by an inductive readout strategy.

The sensing methodology, the device behavioral model, the developed prototype and experimental results are discussed in Sections 2 and 3. In the following, the use of ferrofluids in transducers is discussed as a premise to claim advantages of the proposed sensing approach.

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 [10]. In the presence of a magnetic field the ferrofluid modifies its physical properties such as density. Actually, a magnetic field applied to a ferrofluidic volume and the consequent magnetic force cause the alignment of the ferrofluidic particles in the direction of the field. Moreover, under particular conditions, a ferrofluid volume subjected to a magnetic force can behave like a mass connected to tunable equivalent spring whose properties can be controlled by modulating the magnetic field [11].

In literature, actuators and sensors using magnetic fluids are available. In [12] a rotating micro-pump implemented through a ring tube with inner and outer sections is described. Fluid sampling is accomplished by two caps of ferrofluid created by two external permanent magnets managed by a DC motor. In [13] an innovative gyroscope based on an oscillating mass of ferrofluid is addressed.

The pump described in [14] is based on a pipe filled with water and one cap of ferrofluid which moves the fluid from the inlet section to the outlet section. Five sinusoidal signals, opportunely out

* Corresponding author at: DIEEI, University of Catania, V.le A. Doria, 6, 95125, Catania, Italy. Tel.: +39 095 7382601; fax: +39 0957387965.
E-mail address: bruno.ando@dieei.unict.it (B. Andò).

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http://dx.doi.org/10.1016/j.sna.2012.09.026

of phase each other, drive an array of coils which control the cap movement. In particular, a model describing the device behavior is proposed along with experimental results confirming the suitability of the proposed methodology.

In [11] the architecture of an innovative inclinometer based on the movement of a drop of ferrofluid inside a glass pipe filled with water is presented. External coils wounded around the glass pipe are used to retain the drop of ferrofluid and to measure its displacement due to the applied tilt.

When dealing with magnetic fluids attention must be paid also to adhesion problems. An approach to prevent adhesion is implemented in the tilt device presented in [15]. In particular, two actuation coils have been used to move the ferrofluid mass around the equilibrium position thus preventing its adhesion to the glass pipe and reducing the static friction.

Focusing on the flow sensor presented in this paper requires also a brief introduction about the possible instability of ferrofluids in magnetic fields [16]. In fact, under particular conditions magnetic fluids show interesting patterns coming from ferrohydrodynamic instabilities which can be exploited to implement suitable sensing strategies overcoming drawbacks related to static friction and wall adhesion. As an example, the inertial sensor presented in [17] is based on the exploitation of the Rosensweig instability which consists in the formation of ferrofluid spikes due to high magnetic pressure gradient in the ferrofluid surface [16]. In particular, the latter instability occurs when the free surface of a ferrofluid is subjected to a vertical magnetic field. Over a certain intensity of the field peaks appear at the fluid surface which typically form a static hexagonal pattern. Moreover, nonlinear oscillations can be achieved by superimposing a static magnetic field to oscillating external (magnetic) forces [16].

The device in [17] consists on a glass plate filled with water and a spike shaped drop of ferrofluid. An external stimulus applied to the system, e.g. an acceleration, is transferred to the ferrofluid mass thus producing perturbation of spikes around their equilibrium position. Two planar coils in differential configuration have been used to monitor the spikes position.

The flow sensor presented through this paper exploits a suitable magnetic field configuration to produce a single spike of ferrofluid inside a pipe filled with water [9]. The governing mechanism conferring the ferrofluid the desired spiked shape is based on the Rosensweig effect. A liquid media flowing inside the pipe produces a movement of the spike free-end which is then detected via a dedicated inductive readout strategy.

An important outcome of this paper is the experimental validation of the proposed methodology which exploits the relationship between the target flow to be measured and the behavior of the ferrofluid mass then converted in the output signal by the readout electronics.

In the following sections, mechanisms ruling the device behavior and a model of the flow sensor are presented along with experimental results assessing the model capability to predict static behaviors of the device. The latter is mandatory for the sake of the device design as evidenced in Section 2.

Details on both the device architecture, the conditioning electronics and the adopted characterization procedure are also given.

Above traditional advantages coming from the use of a magnetic fluid, as the active mass of inertial sensors such as the possibility to fix the device specifications (operating range and responsivity) by tuning the applied magnetic field intensity and high robustness against mechanical shocks, specific claims for the novel proposed flow sensing methodology are summarized in the following.

Compared to traditional solutions (such as thermal, electromagnetic and differential pressure flow sensors) the proposed methodology allows for implementing the flow measurement in a section of pre-existing channel without damaging the original structure. The approach developed only requires to fix a mass of ferrofluid in a channel section and to clamp the external control and reading units.

Moreover, conversely to traditional approaches, the proposed ferrofluidic flow sensor guarantees the electric insulation between the device electronics and the liquid media and the physical decoupling between the device structure and the readout system. The latter feature is strategic to implement flow measurement in hostile contexts involving invasive liquid media and requiring the substitution of the liquid housing (e.g. the pipe). It must be considered that the disposable part of the device (the pipe) is very cheap while the external electronics implementing the readout strategy can be re-used.

Above the already mentioned advantages, it must be highlighted that the proposed sensor can also operate with non conductive liquids.

As evincible from the device architecture, the proposed sensing methodology is suitable for scalability, use in miniaturized channels and, and as highlighted by experimental results in Section 3, it can be used to measure low flow rate [18,19].

Above statements confirm the suitability of the proposed methodology to develop low-cost flow sensors fixing drawbacks above discussed. The proposed strategy can be implemented in pre-existing channels, with diameters ranging from centimeters to microns, and it allows the insulation between electric parts and the liquid media.

Mentioned features encourage the use of the proposed methodology in several real contexts from bio-medical systems, requiring low flow rate measurements, small channel sections and a variety of fluids, to applications requiring non invasive flow measurements of liquids in pre-existing channels.

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. Design and implementation of the flow sensor

2.1. The sensing methodology

The ferrofluidic flow sensor consists of a glass pipe filled with water and a drop of ferrofluid while external parts are used to confer a spike shape to the ferrofluid mass. In particular, the shaping system, exploiting the Rosensweig effect, is composed by two permanent magnets placed on the top and on the bottom of the pipe. The permanent magnet on the top of the pipe is used to implement a retaining magnetic force acting on the mass of ferrofluid.

As it will be described in Section 2.3, the magnetic force acting on the ferrofluid mass resembles an equivalent elastic force (or equivalent spring) which maintains the ferrofluid drop in a compliant position [11]. Moreover, the distance between the top magnet and the ferrofluid defines the magnetic pressure acting on the ferrofluid and hence its physical properties such as viscosity and density. As it will be clearly stated and demonstrated in the following, this mechanism will allow for modifying the device performances (e.g. responsivity and operating range) which are strictly related to the value of the equivalent spring constant.

The magnet on the bottom side is used to shape the ferrofluid mass as a single spike. A schematization of the sensor is shown in Fig. 1a.

It can be affirmed that magnets size and position will define the retaining force acting on the ferrofluid mass which also depends on the physical properties of the magnetic fluid, as discussed in Section 2.3 (see Eq. (5)).