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Magnetic fluids in aerodynamic measuring devices

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Abstract

The paper presents the operating principle for inductive transducers with magnetic fluids used in aerodynamic measuring devices, as well as some of their dimensioning relations. Their performances are exemplified through several concrete applications concerning the measurement and control of: pressure distributions on aerodynamic profiles; small and very small volumetric flow rates (leakage flow); degree of porosity of casting; very small displacements using pneumatic devices. A two-axes inclinations transducer was experimentally investigated in wind turbine construction. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic fluids; Inductive transducers; Aerodynamic measuring devices

1. Introduction

The unique performances of rotating seals with magnetic fluids for gases led to some special applications for aerodynamic measuring devices.

Following the first laboratory investigations of inductive transducer for differential pressure [1] and scanning valve [2,3], the resulting improvements [4,5] allowed us to develop several generations of devices for aerodynamic quantities and inclination angle measurements. These devices, presented in the catalogue [6], use electric coils with magnetizable fluid column as a variable magnetic core. The characteristics of the sensing unit were investigated using both analytical methods [7] and numerical simulation [8].

The increasing interest towards inductive transducers with magnetic fluids resides in their simple and robust construction, as well as in the possible miniaturization.

2. The principle of differential inductive sensors

Fig. 1 presents the differential transducer for pressure in gases, as an example of inductive transducer with magnetic fluid. A U tube has its vertical arms half-filled with magnetic fluid. Each arm has an uniformly wound coil (L_1 and L_2). A pressure difference, $P_1 - P_2$, leads to a level gap Δh, and to a corresponding inductance difference $L_2 - L_1$.

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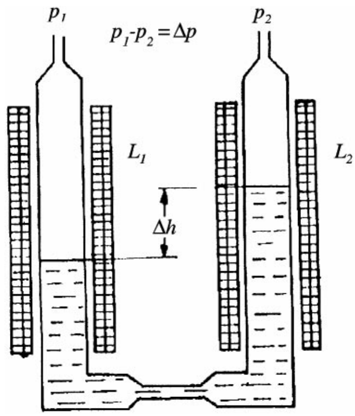

Fig. 1. Principle of differential pressure sensor.

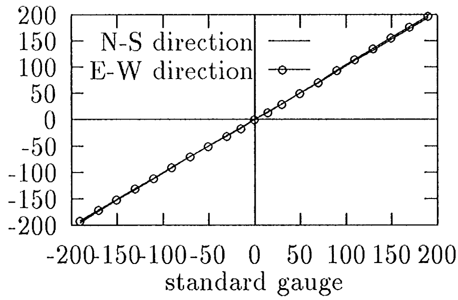

Fig. 2. Experimental results for a two-axes inclination sensor (hexadecimal minutes).

An electronic system [9] measures the difference $L_2 - L_1$, which, within certain limits, is directly proportional to the pressure difference.

For zero pressure difference, a non-zero level gap can be obtained by an inclination with respect to an axis normal to the plane of vertical arms. Fig. 2 presents the characteristics of a two - axes inclinations transducer (N–S and E–W directions are two arbitrary orthogonal axes).

3. Theoretical aspects concerning the dimensioning of the inductive sensor

In order to establish the necessary relationships for sensor dimensioning, both analytical and numerical methods were employed. The analytical approach uses the method of images to compute the magnetic field for both real and filiform coils. These calculations assume a linear magnetizable medium for the magnetic fluid because of the small value for the magnetic field intensity (H).

We consider a vertical coil of height l with filiform circular loops of radius R, immersed in magnetic fluid up to the depth x. The winding is assumed to be uniform with a single level of loops, having N^* loops per unit length.

If a constant value of the magnetic induction vector is admitted on the entire surface of a coil loop, equal to the one at the center of the circular loop, we obtain the following dependence for the inductance L function of the depth x:

$$L(x) = \frac{\mu_0 \pi R^2 N^{*2}}{2} \frac{\mu_{r2} - \mu_{r1}}{\mu_{r1} + \mu_{r2}} \Big[4\mu_{r2}\sqrt{x^2 + R^2} - 4\mu_{r1}\sqrt{(l-x)^2 + R^2} + \frac{4\mu_{r1}\mu_{r2}}{\mu_{r2} - \mu_{r1}} \times \sqrt{l^2 + R^2} - \frac{3(\mu_{r2}^2 + \mu_{r1}^2) - 2\mu_{r1}\mu_{r2}}{\mu_{r2} - \mu_{r1}} R + \mu_{r1}\sqrt{4(l-x)^2 + R^2} - \mu_{r2}\sqrt{4x^2 + R^2}\Big]. \tag{1}$$

The values of the relative magnetic permeability of air and magnetic fluid are μ_{r1} and μ_{r2} respectively, and, μ_0 is the absolute magnetic permeability of the vacuum.

In the general case of the filiform coil, when the magnetic induction vector is not constant on the entire surface of a circular filiform loop [10], one obtains

$$L(x) = \frac{RN^{*2}}{2(\mu_1 + \mu_2)} \iint_S \Bigg(\frac{(R - r\cos\varphi)}{A} \times [(\mu_2 - \mu_1)(\mu_1\sqrt{A + 4(l-x)^2} - \mu_2\sqrt{A + 4x^2}) + 4(\mu_1 - \mu_2) \times (\mu_1\sqrt{A + (l-x)^2} - \mu_2\sqrt{A + x^2}) + 4\mu_1\mu_2\sqrt{A + l^2} - (3\mu_1^2 + 3\mu_2^2 - 2\mu_1\mu_2)\sqrt{A}] \Bigg) \mathrm{d}s, \tag{2}$$

where S is the surface of a loop, r and φ are the integration variables on this surface, and $A = R^2 + r^2 - 2Rr\cos\varphi$. Fig. 3 shows the relative variation of the inductance of a coil for three different magnetic fluids.

If there is no r dependence in Eq. (2), the particular case (1) is recovered. Although the double integral in Eq. (2) can be evaluated analytically, the resulting expression is too complicated to be practical.

If real coil loops are considered [11] and the coil has m loops in magnetic fluid, n loops in air, 2ρ the coil step and $2\rho_0$ the diameter of the conductor, the final expression is a finite sum of complete elliptical integrals of the first and second species:

$$\begin{aligned} L(n,m) &= n\mu_1\psi_0 + m\mu_2\psi_0 \\ &+ 2\left(\mu_1\sum_{t=1}^{n-1}(n-t)\psi(2\rho t) + \mu_2\sum_{t=1}^{m-1}(m-t)\psi(2\rho t)\right) \\ &+ \frac{\mu_2-\mu_1}{\mu_2+\mu_1}\left(\mu_1\sum_{t=1}^{n}t\psi(2\rho t) - \mu_2\sum_{t=1}^{m}t\psi(2\rho t)\right. \\ &+ \mu_1\sum_{t=n+1}^{2n-1}(2n-t)\psi(2\rho t) \\ &\left.- \mu_2\sum_{t=m+1}^{2m-1}(2m-t)\psi(2\rho t)\right) \\ &+ 2\mu_1\mu_2\left(\sum_{t=1}^{\min(m,n)}t\psi(2\rho t) + \sum_{t=\min(m,n)+1}^{\max(m,n)}\min(m,n)\right. \\ &\left.\times\psi(2\rho t) + \sum_{t=\max(m,n)+1}^{m+n-1}(m+n-t)\psi(2\rho t)\right), \end{aligned} \tag{3}$$

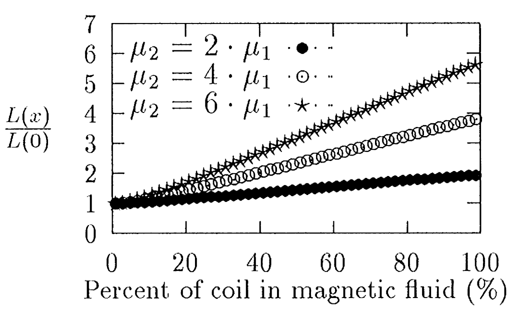

Fig. 3. The relative variation of the inductance of a coil, calculated using Eq. (2) for $R = 7$ mm, $N^* = 10\,000$ loops/m, $l = 0.1$ m.

where,

$$\psi(\rho) = R\left\{\frac{2}{k(\rho)}[F(k(\rho)) - E(k(\rho))] - k(\rho)F(k(\rho))\right\}, \tag{4}$$

$$\psi_0 = R(\ln\frac{8R}{\rho_0} - 2) \tag{5}$$

and

$$F(k) = \int_0^{\pi/2}\frac{d\beta}{\sqrt{1-k^2\sin^2\beta}}, \tag{6}$$

$$E(k) = \int_0^{\pi/2}\sqrt{1-k^2\sin^2\beta}\,d\beta \tag{7}$$

are the complete elliptical integrals of the first and second species, in normal trigonometrical form, with a modulus k,

$$k(\rho) = \sqrt{\frac{4R^2}{\rho^2+4R^2}} < 1. \tag{8}$$

If the presence of the magnetic fluid is admitted only inside the coil, the method of images cannot be used anymore and as a consequence a numerical simulation method should be employed. The finite differences method is used to solve the axial-symmetric magnetic field in a meridian half-plane [8,12].

Fig. 4 presents both the calculated and measured values for a coil of 100 mm height and for three different magnetic fluids (with relative magnetic permeability values: $\mu_{rLM1C} = 5.7$; $\mu_{rLM2C} = 4.4$; $\mu_{rLM3C} = 2.9$).

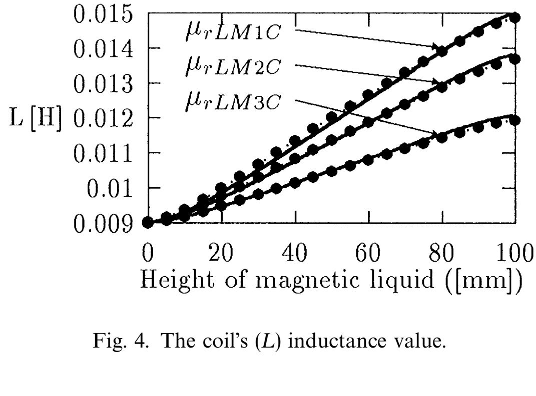

Fig. 4. The coil's (L) inductance value.

4. Magnetic fluid transducers and applications

First, we have constructed differential pressure transducers for gases [5], with a maximum pressure difference of ± 200 mm H_2O. The smallest pressure difference that can be measured is of order of the micrometers H_2O.

When using a single transducer for several pressure sources, a scanning valve [2,3] connects successively each pressure source with the transducer. The scanning valve has a magnetic fluid sealing system (Fig. 5) and has been built with 12 or 24 branches.

The ensemble of differential transducer and scanning valve driven by a step-by-step motor has been used for aerodynamic laboratory investigations [13], especially for pressure distribution measurements on aerodynamic profiles.

The transducer for differential pressure in gases with magnetic fluid, replaced some of the pressure transducers used for classical pneumatic laboratory installations, such as the high precision pneumatic comparator [14,15]. This device gives an electric signal proportional to the measured length and it is used for dimensional control. Its accuracy is of the order of micrometers. Also, on the same principle, there was constructed an experimental model of a force gauge [16].

The development of the inclination sensor with magnetic fluid [4] (Fig. 2) led to the possibility of introducing the inclination and acceleration correction, for the differential pressure transducer (Figs. 6 and 7). Therefore the applications field of the differential pressure transducer in gases has been extended [17,18].

A new group of transducers resulted for measurement of the volumetric flow of gases. It was started with the flow meter where changing the measure domain, requires changing only the transducer head (Figs. 8 and 9). The lower limit of the measured air flow, based on this principle, resulted at 50 cm^3 of air per minute (full scale) in the case of the leakage flow detector. With this transducer it was possible to measure the air flow rate through the pores of some aluminum pieces manufactured by casting [18].

Smaller air flow rates have been measured by counting the air bubbles passing through magnetic fluid [19] (Fig. 10). Using an external magnetic

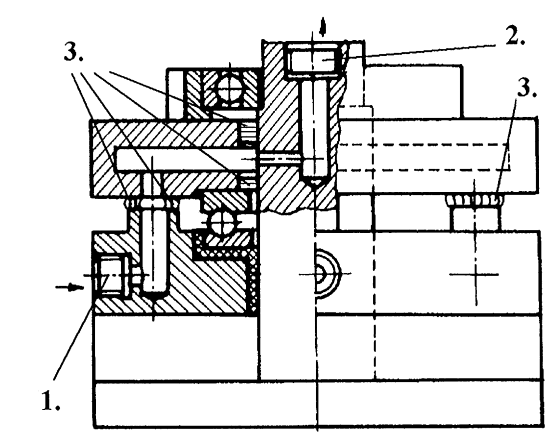

Fig. 5. Scanning valve with magnetic fluid. **1.** = input pressure; **2.** = output pressure; **3.** = magnetic fluid.

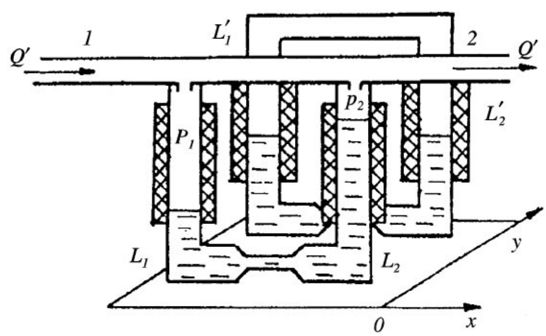

Fig. 6. Sensing unit. L_1,L_2 – differential pressure sensor; L'_1,L'_2 – inclination sensor.

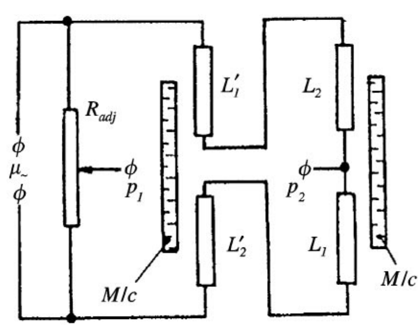

Fig. 7. Electrical connection. M_{lc} = magnetic fluid column; R_{adj} = output voltage adjustment resistor.

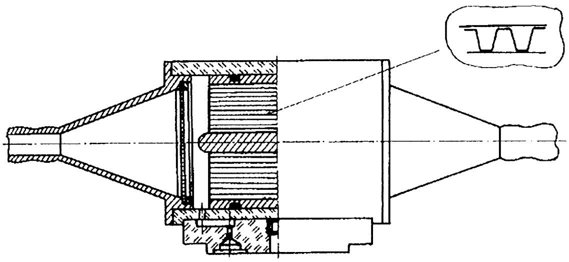

Fig. 8. Transducer head with laminarization structure for great flow rate.

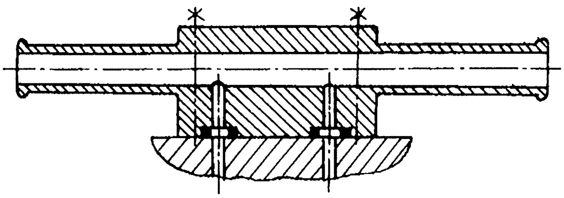

Fig. 9. Transducer head for small flow rate.

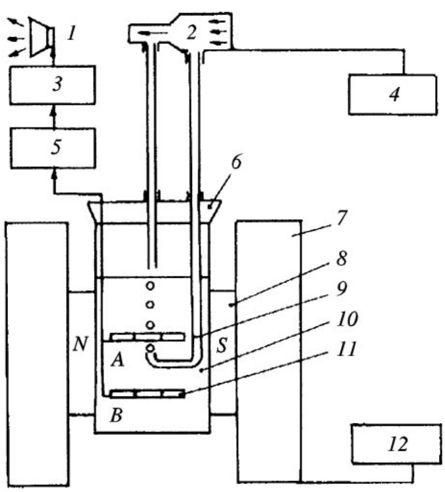

Fig. 10. The functioning principle of the gas flow sensor: 1 – loudspeaker, 2 – aerodynamic tunnel, 3 – counter and sound generator, 4 – stabilized AC power supply, 5 – AC bridge, 6 – rubber stopper, 7/8 – coil/poles of electromagnet, 9 – glass capillary, 10 – magnetic fluid, 11 – A/B coils of the sensor, 12 – stabilized DC power supply.

field, this design can be used also to control the bubbles frequency (Fig. 11).

As a straight forward application, the abovementioned transducers, giving an electric signal

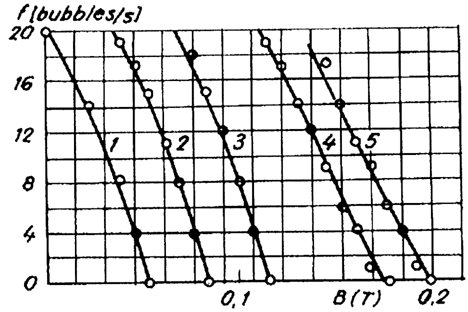

Fig. 11. Variation of emission frequency of gas bubbles with magnetic field induction B (plate pole faces, uniform field). 1 $\Delta P = 84$ mm H_2O, 2 $\Delta P = 96$ mm H_2O, 3 $\Delta P = 108$ mm H_2O, 4 $\Delta P = 136$ mm H_2O, 5 $\Delta P = 144$ mm H_2O.

proportional to the momentary volumetric flow rate (Figs. 6 and 7), conducted to the construction of a volumetric counter for gas flow measurement [17].

5. Conclusion

Magnetic fluids proved their applicative potential in the field of inductive sensors and complementary devices for the measurement of aerodynamic quantities, inclination angle and force, as well as for pneumatic dimensional control.

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