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Contactless flow detection with magnetostrictive bilayers

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Abstract

The paper concerns the contactless detection of an airflow through a tube by the use of a magnetostrictive bilayer strip as a sensor element. A bilayer mounted in the tube is magnetized by an exterior excitation coil. Due to its non-linear behavior, the bilayer generates a field exhibiting higher order harmonics which are detected by an exterior induction coil. The airflow yields bending of the bilayer and thus changed harmonic response, as a basis of signal establishment. For flow dynamics of 10 Hz, effective results are presented for different induction coil positions allowing flexible adjustments to individual geometric conditions. Furthermore, the shielding effect of conductive tube material (such as aluminum, copper and non-magnetic steel) was analyzed, the results indicating the need of low magnetization frequency. Finally, the significance of bilayer length was studied, increasing values yields high sensitivity, however, linked with decreasing mechanical resonance which is relevant in cases of high dynamic of airflow.

Keywords: Contactless signal detection; Flow measurement; Multifunctional sensors; Magnetostrictive material

1. Introduction

Magnetostrictive bilayer (BL) materials, sensitive to bending or temperature changes, provide the possibility to detect different measurement quantities such as displacement, curvature [1], temperature, etc. [2–7]. The strip-like BLs consists of a soft magnetic magnetostrictive layer (ML) and a non-magnetic counter layer (CL). Typical ML materials are amorphous alloys that exhibit excellent soft magnetic and mechanical properties which make them ideally suitable for sensor applications [8,9]. Depending on the material parameters such as Young's modulus and thickness of the ML and the CL, respectively, BL bending causes a strong change of the mechanical stress in the ML. As a result of the well-known magneto-elastic effect, the susceptibility χ changes by $\Delta\chi$. Signal establishment can be based on the detection of higher order harmonics which are generated by the ML in response to a magnetic excitation field [10].

This study presents a non-contact BL sensor system for the detection of bidirectional airflow in a tube representing an extended version of a previous paper [11]. The target is to detect dynamic variations of flow without any electric connections through the tube wall, advantages being given with respect to simplicity and non-destructive design. As a novelty, a one-component version of the sensor is described. Further the influence of shielding plates simulating a tube of conductive material and the BL length has been analyzed.

2. Basic principles

The basic performance of the here applied bilayers with respect to magnetic, hysteretic, mechanical and thermal characteristics of ML and CL, respectively, has been described in the above listed papers [1–5], among many others. Thus, the following is restricted to specific aspects of the here applied higher order harmonics signal detection system. Schematically, its principle is shown in Fig. 1a. It consists of an excitation coil and an induction coil which are magnetically coupled by co-axial arrangement. As known from similar devices, the geometrical dimensions of the system depend on the signal detection range.

A frequency generator and an amplifier produce a sinusoidal current I of frequency f_e. The excitation coil yields the field:

$$H_{ex}(t) = H_{ac}(t) + H_{dc} = A\cos(2\pi f_e t + \varphi) + H_{dc} \quad (1)$$

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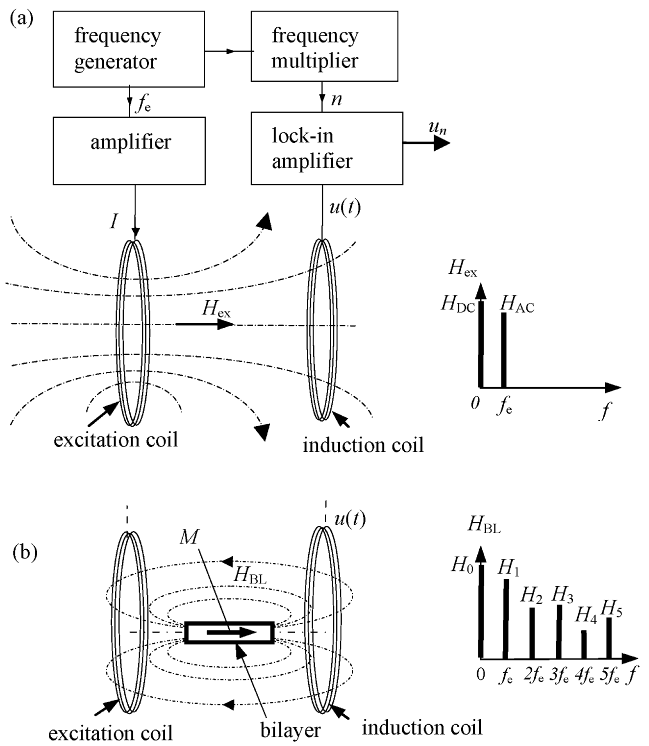

Fig. 1. (a) Measurement system and excitation field H_{ex}. (b) Bilayer field H_{BL} produced by the magnetization M.

consisting of an ac component H_{ac} of the amplitude A and phase angle φ and a dc component H_{dc}. This yields a frequency spectrum according to Fig. 1a. Of course, the magnetic field varies locally in both, magnitude and direction.

If the BL is placed within the excitation field, the ML will be magnetized with $M(H, t) = \chi(H)H_{ex}(t)$. Since the susceptibility $\chi(H)$ is non-linear, $M(H,t)$ will be non-sinusoidal. The magnetized BL will cause a magnetic field:

$$H_{BL}(t) = H_0 + \sum_{n=1}^{\infty} H_n \cos(n2\pi f_e t + \varphi_n) \qquad (2)$$

with a constant part H_0 and an alternating part that shows n harmonics of amplitude H_n and phase angle φ_n. Fig. 1b shows schematically the spectrum for the first five harmonics. The value of $H_{BL}(t)$ depends on mechanical stress due to the magnetoelastic effect, thus the values of H_n reflect the BL bending.

At the detection coil, both fields $H_{ex}(t)$ and $H_{BL}(t)$ superimpose, yielding the total magnetic flux:

$$\Phi_D(t) = \mu_0 \int_{A_D} (H_{ex}(t) + H_{BL}(t))\, dA \qquad (3)$$

where A_D is the cross-section area of the detection coil and μ_0 is the magnetic permeability in air. The voltage $u(t) = -N\dot{\Phi}_D(t)$ is induced in the detection coil of N windings. Eqs. (1)–(3) yield:

$$u(t) = N\mu_0 2\pi f_e \int_{A_D} [A \sin(2\pi f_e t + \varphi) + \sum_{n=1}^{\infty} nH_n \sin(n2\pi f_e t + \varphi_n)]\, dA \qquad (4)$$

where the first term is given by the excitation field and the second by the field of the magnetized BL. Eq. (4) can be summarized in the form:

$$u(t) = \sum_{n=1}^{\infty} U_n \sin(n2\pi f_e t + \varphi_n) \qquad (5)$$

where U_n are the voltage amplitudes of the harmonics.

3. Experimental

According to Eqs. (3)–(5), the resulting amplitudes U_n are proportional to the harmonics of $H_{BL}(t)$ thus representing a measure for BL bending. As shown in Fig. 1a, U_n represent the amplitudes measured at the detection coil by means of a lock-in amplifier, the reference signal of which is derived from the generator signal by the help of a frequency multiplier.

The experimental setup of the flow sensor is shown in Fig. 2. An airflow with a frequency of 8–10 Hz was produced by means of a loudspeaker in a 1 m long acoustic chamber with a cross-section of 25 mm and 85 mm.

The BL was produced by means of agglutination (Uhu Endfest 300, Young's module at the used mixing ratio of 100:100 E = 400–500 MPa, thermical expansion coefficient κ = 60 ppm/K) with a layer thickness of some micrometers (higher thickness offering increased bending sensitivity, however linked with also increased BL-stiffness). The BL consisted of amorphous Fe-based Vitrovac 7505 (E = 150 GPa and κ = 8 ppm/K) as the ML and non-magnetic steel as the CL (E = 180 GPa and κ = 16 ppm/K). It showed typical dimensions of 45 mm × 5 mm × 0.07 mm. However, variations in length were used for simulating different conditions. As shown in Fig. 2, an excitation coil of 25 mm diameter and 100 windings was placed behind the BL in a distance of 5 mm. The value of f_e was set to 6.5 kHz for investigation of position effects. According to Fig. 2, four different positions of the induction coil (diameter 25 mm and 100 windings) were tested, either oppositely or parallel to the excitation coil and on top of the tube either parallel or normal to the bilayer axis. One BL end was

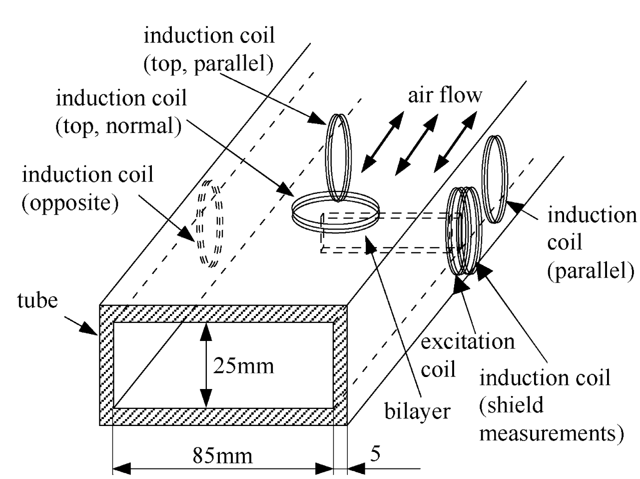

Fig. 2. Flow sensor arrangement showing five alternative positions of the induction coil.