SENSORS FOR MAGNETIC BEARINGS

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Abstract— **A variety of distance sensors suitable for the application to magnetic levitation is examined. The characteristics of the sensors regarding the phase shift between in- and outgoing signals, frequency response, dc-stability, stability to emf interference, resolution and temperature stability are analysed. A simple eddy-current sensor applicable to levitation is presented and the effects of its non-linear signal upon the system's performance are considered.**

I. Introduction

Magnetic bearings consist of an actuator and a levitated object which can be either a rotor or any other ferromagnetic body. In order to provide stable support, the actuator needs accurate information about the position of the levitated body which must be given by a sensor. Due to their contactless, low friction characteristics, magnetic bearings can be utilized in extreme environments and for very high rotational speeds. It is therefore important to know the response of the sensor to the temperature changes and its phase behaviour with regard to the frequency response. The phase shift associated with frequency is rarely quoted in suppliers documentation; it is, however, an important figure to know since the actuator has to respond to position changes of the object immediately at potentially high frequencies. Rotating shafts may run at speeds of 1000 Hz, often with a cutting tool at one of their ends. This tool can have, say, four cutting edges and the rotor would, therefore, experience a vibration of 4000 Hz. The majority of sensor types are designed to give a linear output with distance to the measured object. Since linearization is an added complication which, potentially, introduces errors (phase shifts, thermal drifts) into the levitation system, it should therefore be avoided, if possible. Magnetic levitation devices can, via the Proportional-Integral-Differential (PID) control, cope with non-linear sensor signals as long as the sensitivity is large enough for stable levitation. However, linear sensors should be used in applications where both the levitation process and the knowledge of the exact position of the levitated object is desired.

II. The Different Types of Transducers and their Characteristics

The types of sensors that will be examined here are eddy current, inductive, Hall element, capacitive, optical and ultrasonic sensors.

A. The eddy current sensor

A sensor which is widely used for magnetic levitation, mainly for small air gaps, is the eddy current sensor. It is a special type of an inductive sensor and it consists of a wire coil (plus conditioning electronics) that oscillates at a high, constant frequency, f, typically between 0.5 - 2 MHz, and is thus surrounded by an electromagnetic field. The amplitude of oscillation is also kept constant. An electrically conductive material close to this coil carries induced eddy currents which in turn change the impedance of the coil. Hence information regarding the coil distance is gained. This sensor responds to any conductive material. Its output is usually linearized. Eddy current sensors exhibit excellent frequency response (of a vibrating object) with very little phase shift. The phase shift ($\Delta\Phi = 2\pi f \Delta t$, where Δt is the time difference between the deviation of the suspended object and its registration by the sensor) has to be kept low in order to obtain stable levitation. Fig.1 shows the simulated phase shift of a linear output eddy current sensor [1] that is rated for frequencies of up to 100 kHz. This frequency is too high for magnetically suspended objects and our own measurements have been restricted to 3 kHz. The phase shift of the commercial eddy current sensor is $\leq 5°$ for oscillations below 3kHz. Long term drift (dc-stability) is better than 0.1% of full scale sensor output, which means that for a sensor of 4mm measuring range, the drift per month is $< 4\mu$m [1].

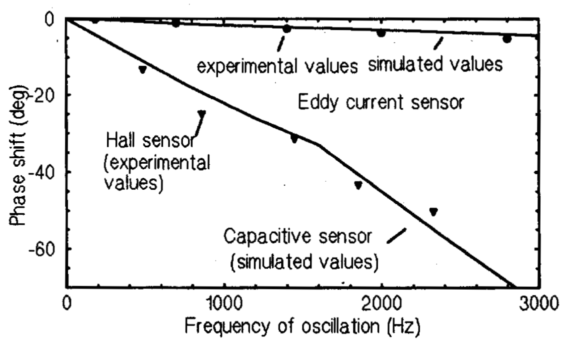

Figure 1: Phase shift vs frequency of eddy current, non-linear inductive, Hall type and capacitive sensor

A.1 A non-linear eddy current sensor

This in-house built sensor consists of an oscillating coil which forms a part of a Colpitts oscillator, oscillating at approximately 0.8 MHz and, as linearizing circuitry has not been used, the number of electronic components has been kept to a minimum. Upon approach to a conductive material the amplitude and the frequency of the oscillator change due to the change of inductance. Thus this sensor type is generally referred to as the inductive sensor. For the purpose of this paper, the change in amplitude has been used for the determination of distance between sensor and target. The experimental values of the phase response of this nonlinear eddy current sensor are included in Fig.1. The sensor signal was compared to an optically triggered signal which was assumed to give an immediate response [2]. The nonlinear probe showed a phase shift of 5° at 2800 Hz (Fig.1). The nonlinearity and the sensitivity of this transducer (coil diameter 19mm), measured against an aluminium target and a mild steel target, is shown in Fig.2. The 19mm sensor is capable of resolving distances of $\leq 10\mu$m against these targets. As can also be seen in Fig.2, ferromagnetic materials produce different results than solely conductive materials. This is due to the additional changes of the coil inductance caused by the

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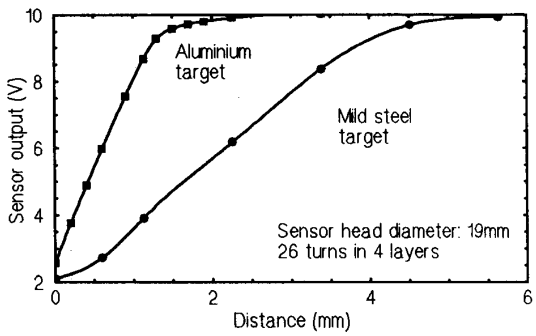

Figure 2: Output voltage and sensitivity vs distance (targets: Al, Mild steel)

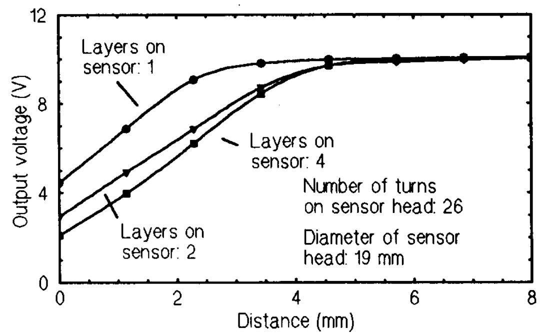

Figure 3: Output voltages vs distance to sensor (target: Steel) for three geometries of sensor heads

ferromagnetic material. The sensitivity of the sensor against the steel target is: 2.4 V/mm at 1mm, 1.9 V/mm at 2mm, 2 V/mm at 3mm and 1 V/mm at 4mm distance with a slow decline for larger distances. The measuring range is approx. 4 mm. Against the aluminium target the sensitivity is 5.9 V/mm at 0 mm and 4 V/mm at 1.2 mm distance, deteriorating quickly for larger distances. The measuring range is here reduced to below 1.3 mm. This different behaviour for different materials is almost absent for true eddy current sensors. Since the stiffness of a bearing is directly related to the sensitivity of the transducer, a variable bearing stiffness can be expected from this kind of nonlinear sensor via the relationship $dV/dx \propto AdI/dx$ (V: sensor voltage output, x: amplitude of oscillation of the suspended object, A: effect of PID-control and amplifier gain, I: current in the stator of the bearing). However, the rotors of magnetic bearings are rarely designed to oscillate by more than 100 or 200 μm and for such displacements the sensitivity varies only slightly. For oscillations of $\mp 100\mu$m in amplitude, at 1mm distance from the sensor, the transducer sensitivity varied by -0.8% / -3.6% for steel and by +3% / -8% for aluminium ($\pm$ indicates increased (reduced) stiffness to the stiffness at 1mm). Accurate information about the relative position of the levitated object is, without calibration for distance and material, difficult to obtain with this sensor.

Ferrite cores should not be used with inductive or eddy current sensors, because stray fields of the magnetic bearing itself influence or even saturate such cores and reliable measurements are no longer possible. A sensor head, consisting of a wire coil of 12 mm diameter, screened by an aluminium case so as to avoid a change in sensor output caused by the magnet pole pieces, has been exposed to a magnetic flux of 0.44T. When the sensor was without a ferrite core, and the field was applied, no change in the output signal could be detected. A ferrite core caused the same sensor to be more sensitive, though over a smaller range, however the field application caused the sensor output to change by a voltage equivalent to 135 μm. Since magnetic bearings are often used in hostile environments with large temperature changes, the temperature response of sensors is important. Eddy current probes have a temperature stability of approximately 0.01 μm/K to 100 μm/K; these values depend on the size of the sensor and whether the manufacturer quotes for the sensor head only or for the entire transducer including conditioning electronics. The above mentioned nonlinear sensor exhibited a sensor head temperature stability of approximately 0.01 μm/K. The dc-drift is such that a sensor with a head diameter of 19mm would report an erroneous position change of less than $\pm$ 5 μm over 24 hours.

A.2 Influences of sensor head geometry on sensor characteristics

The above treated non-linear inductive sensor had a wire coil consisting of 26 turns as a transducer . The turns were arranged on a central plastic former in 1, 2 or 4 layers with a respective reduction of the axial dimensions of the transducer windings. The winding thickness to winding height ratio produced the following sensor outputs: The peak sensitivities, for a steel target, were 2.08 V/mm for the 4-layered, 1.75 V/mm for the 2-layered and 2.18 V/mm for the mono-layered sensor head. The higher sensitivity in the last case has to be put against the shorter reach of this sensor when compared with the 4-layered sensor. The physical sizes of eddy current and inductive sensors are small. For unscreened (i.e. no metal case around the sensor coil) sensors, with measuring range between 1 and 4mm, the ratio of transducer diameter to measuring range is between 2 and 5, for screened sensors this ratio is between 4 and 8 [1, 3, 4].

B. The capacitive sensor

The simulated phase delay of a capacitive sensor [1] is shown in Fig.1. The capacitive probe works on the principle of an ideal plate capacitor whose reactance changes linearly with distance between the two capacitor plates, one of which can be the levitated body [1, 6]. The capacitive sensor shows, like the Hall sensor, a high value of phase shift (approx. 50° at 2500 Hz) and may be best employed for slow running machinery. Capacitive probes show low values of temperature drift, typically between 0.03 and 0.17 μm/K [1], depending on the size of the transducer. These values should be very much lower for the probe head alone since thermally induced changes in the conductivity of the target material are of no consequence. The ratio of transducer diameter to measuring range for capacitive sensors is approximately 10 for sensors of range 1 to 3mm [1]. The sensor's dc-stability is quoted to be $\leq$ 0.02% per month [1] which is, for a 4mm range sensor, better than 0.8μm per month.

C. The Hall sensor

Also shown in Fig.1 is the measured phase response of a Hall type sensor (approx. 50° at 2500 Hz). The Hall element can either be activated by a permanent magnet situated on the levitated object or it can be embedded in the flux path of the stator [5]. The temperature dependence of Hall elements is well known. Magnetic bearings, which potentially can become hot either by environmental influences or simply by the power dissipation in its coils require therefore the use of temperature compensated Hall transducers. Even so, measurements on a

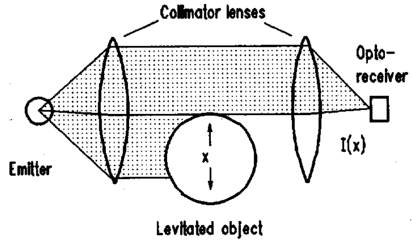

Figure 4: Obscuration method for optical sensor; the levitated object influences by its position the intensity of light that the receiver registers

temperature compensated Hall sensor revealed a shift in the voltage output with increasing temperature. The chosen temperature range was from 21.6 °C to 101.4 °C. Over this 79.8 °C temperature change the voltage output of the transducer varied from 5.95 V to 5.85 V, i.e. a difference of 0.1 V. The sensitivity of this transducer, at constant room temperature, was found to be 0.1826 mV/μm. A 0.1 V shift over the 79.8 °C temperature change would, therefore, result in a shift of 0.55mm in the location of the suspended body. Typical radial bearing clearances are of the order of 0.5 - 1 mm, that means that Hall sensors should be avoided if a substantial temperature rise is expected during the operation of the bearing.

D. *The optical sensor*

A simple yet efficient sensor that is widely used for laboratory magnetic levitation is the analog opto-sensor based on obscuration [7]. The levitated object is positioned between two collimating lenses (Fig.4) where it influences the intensity of incident light on the opto-receiver (a high speed photodiode). In order to reduce the effect of ambient light the wavelength of the sensor radiation is in the infrared or is pulsed. Laser light is also being used [7]. The photodiode enables the sensor to be very fast acting, typically 0.05μs. The transmittance of the space between emitter and receiver has to remain, however, very constant which precludes this sensor from many applications. Another drawback is the necessity of the sensor parts being located on a tangent to the levitated object, thus posing large space demands. The deviation from linearity of a opto-sensor containing two 25mm lens and using IR emitter and receiver was measured to be 6% of the full scale sensor output.

D.1 Laser sensors

Another optical sensor is the laser displacement sensor, based on the triangulation of a light beam. A laser beam is emitted from a laser diode and this beam is reflected diffusely by the levitated object. A linear position sensor element is focussed onto this point and, depending at what location on this element the reflected light hits the sensor, a distance-dependent signal is obtained [1]. This signal is usually linearized. This sensor type is sensitive to the reflectivity of the levitated object. Surface changes (colour, roughness, pollution) of this object influence its accuracy. The size of the laser sensor is typically between $50 \times 50 \times 20$ mm^3 to $100 \times 50 \times 30$ mm^3 [1, 8]. It has a large measuring range of up to 100 mm. This large range could make it a candidate for levitation in, for instance, windtunnels or other applications, where the space between stator and rotor is large. The frequency response is from 250 Hz up to 16 kHz, depending on the sensor electronics, and the resolution is from 0.2 (for small sensors) to 60 μm. The temperature stability of the sensor head is between 0.5 μm/°C and 30 μm/°C, depending again on the size of the sensor.

E. *The ultrasonic sensor*

This sensor type has the advantage of a very long range (0.7 to 3.5m [1]) but it suffers from its poor resolution (approx. 1cm).

F. *Sensor susceptibility to electromagnetic noise*

Preliminary investigations as to the susceptibility of different transducers to electromagnetic noise revealed that the Hall sensor, the eddy current sensor, both the commercial linear sensor and the in-house made non-linear sensor, and the opto-probe all detected the presence of a piezoelectric discharge (via delta-peaks on the oscilloscope). The discharge happened approximately at a distance of 5 mm to the transducer. The Hall probe was most influenced by the discharge. A levitated shaft, utilizing the non-linear eddy current probe, however did not react to the piezoelectric discharge. Neither was the shaft position influenced by an electricity discharge of 30V, 2A, obtained from a short-circuited power supply.

III. Discussion

It is obvious from the above that the most versatile sensor type in the short measuring range is the eddy current sensor. It combines small physical size with high resolution, excellent temperature stability, small phase shift and high dc-stability. Capacitive sensors show a higher resolution and even better temperature- and dc-stability; they are, however, bigger in size and might suffer from environmental changes. Opto-sensors are very fast acting but large in dimension and are influenced by outside interference. Hall type sensors are small in size but suffer from temperature instability and, like capacitive sensors, they have a slow response. Ultrasonic sensors will have only limited application due to their poor resolution. Although levitation with non-linear sensors is possible, linear output sensor provide information on relative distances and assure constant suspension stiffnesses of suspended objects.

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