

In-line monitoring of (MR) fluid properties

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ABSTRACT

Proper functionality of devices and processes based on (MR) fluids greatly depends, along with other factors, on stability of fluid characteristics such as concentration of magnetic particles and magnetic properties of the particles. The concentration of magnetic particles may change due to evaporation or leakage of carrier fluid, as well as particle sedimentation. Magnetic properties may change due to temperature, corrosion of particles or irreversible aggregation. In-line noninvasive monitoring of particle concentration and magnetic properties allows, in one way or another, compensation for the impact of destabilizing factors and provides system stable output. Two novel methods of in-line measurement of MR fluid magnetic permeability or magnetic particle concentration are considered in this presentation. The first one is based on the principle of mutual inductance and is intended for monitoring MR fluid flowing in pipes or channels. In the second one, permeability is measured by a flash-mount sensor which reacts on changes in the reluctance of the MR fluid layer adjacent to the wall. The use of the methods for stabilization of the material removal rate in high precision finishing process employing aqueous MR fluid is discussed.

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1. Introduction

MR fluid is a liquid composition that undergoes a change in mechanical properties and converts into a plastic material in the presence of a magnetic field. Normally, MR fluids consist of ferro-magnetic particles, typically greater than 0.1 μm in diameter, dispersed within a carrier fluid. In the presence of a magnetic field, the particles become magnetized and are thereby organized into chains within the fluid. The chains of particles form a spatial structure which is responsible for the change in mechanical properties, such as the increase of the yield stress. In the absence of a magnetic field, the particles return to a disorganized or free state and the initial condition of the overall material is correspondingly restored. As a smart material, MR fluids are widely used in applications as adaptive shock absorbers for vehicles, controllable clutches and actuators etc. [2–4]. Also, MR fluid is a key element in magnetorheological finishing technology (MRF[®]) for high precision optics [5,8].

In operation such factors as sedimentation, evaporation of liquid carrier media, oxidation and agglomeration of magnetic particles may result in a change of MR fluid properties and even MR system failure. In this regard, the most vulnerable systems are those that are not sealed especially those that use water-based MR fluids. Such is the case for MRF technology where the material

removal function stability is primarily dependent on MR polishing fluid stability. Properties of the fluid and, resultant, material removal rate varies when the concentration of magnetic particles and abrasive particles changes as a result of fluid instability or in response to other factors like water evaporation that inevitably occurs during polishing. Known method of monitoring properties of MR fluid in MRF is that the concentration of solids or water content is related to slurry viscosity which, in turn can be accurately measured [6]. Controlling the MR fluid viscosity by replenishing water maintains a constant removal function. In practice, an in-line, flow-type system for viscosity measurements in MRF is implemented as a capillary viscometer. Viscosity of the pumped/circulated MR fluid is derived from the ratio of pressure drop and fluid velocity measured by pressure sensors and a flow meter. The viscometer picks up changes in the slurry concentration due to water evaporation and corresponding viscosity change, and the control system responds through a feed-back loop by injecting an appropriate amount of water into the MR fluid [6]. Since the MR fluid is a non-Newtonian, rheologically complex media, the measured viscosity is a function not only of particles concentration but the shear rate or fluid velocity. Also, the viscosity changes in time due to thixotropy. These factors may introduce significant uncertainty in measurements. An appropriate calibration may mitigate this problem to some extent. In addition, viscosity sensitivity to temperature requires maintaining a constant fluid temperature. These system weaknesses result in relatively low

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accuracy of concentration control. Among other methods of in-line monitoring of MR fluid properties it is worth to notice the technique based on measurements of concentration of magnetic particles in MR fluid by determining the inductance of a coil while fluid flows through it [1]. The method requires the impedance measurement with a relatively complex technique involving high sensitivity electric bridge circuits. A shortcoming of this technique is that resolution is relatively low.

Two different novel methods of in-line measurements of MR fluid magnetic permeability and thereby magnetic particles concentration are introduced in this work. Both methods were found to provide satisfactory measurement accuracy. In the first method, measurements are provided through the use of a flow-type sensor, which is intended for measurements of concentration of MR fluid flowing in tubes, pipe, hoses, etc. In the second method, a sensitive element is a flash-type sensor. It can be conveniently used for measurements of concentration of MR fluid flowing in narrow gaps or in other restricted configurations like small tanks, containers and so on. The efficiency of new sensors is illustrated by results of testing in the MRF machine fluid delivery system. Manufactured by QED Technologies, commercial proprietary aqueous MR polishing fluids comprising both carbonyl iron and abrasive particles as well as stabilizing additives are used in all experiments.

2. Flow-type concentration sensor

Operation of the flow-type sensor is based on the principle of mutual inductance [7]. The sensor has two electrical inductors: a primary coil and a secondary coil. The electrical inductors share the same magnetic core representing a sample of a magnetic material, such as an MR fluid (see Fig. 1).

When an *ac* voltage V_p is applied to the primary coil, an axially-directed magnetic flux is created in the core:

$$B = \mu \frac{N}{l} \frac{I_p}{\sqrt{2}}, \quad (1)$$

where μ is the magnetic permeability of the core, N is the number of primary coil turns, l is the coil's length, I_p is the current amplitude, and $I_p/\sqrt{2}$ is the root mean square current. In turn, due to the flux linkage or effect of the *mutual inductance*, the magnetic flux induces an *ac* voltage V_s in the secondary coil in phase with the source voltage:

$$V_s = 2\pi\omega NAB, \quad (2)$$

where ω is current frequency and A is the cross-sectional area of core. From Eqs. (1) and (2), it follows that the root mean square

voltage V_s generated in secondary coil is given as

$$V_s = 4.44\mu\omega \frac{N^2 A}{l} I_p. \quad (3)$$

The primary coil behaves as a load with respect to the *ac* voltage source V_p , and the secondary coil behaves as a source with respect to resistor R_s . At the same time, the magnetic permeability μ depends on magnetic properties of core. In turn, these properties are dependent on concentration of the magnetic particles φ in the sample

$$\mu = f(\varphi). \quad (4)$$

When all parameters of the system are held constant, any variation in concentration of magnetic particles in the core will result in a proportional change of *ac* voltage V_s in the secondary coil. In doing so, the system output signal follows variations in the sample magnetic particles concentration. In the general case, it can be defined as:

$$V_s = f(\varphi, k_1, k_2, \dots), \quad (5)$$

where $k_1, k_2, \dots$ are some constant parameters which depend on system geometry and system electrical parameters.

The magnitude of the output signal can be manipulated by (pre)setting different system parameters such as the number of turns and geometries of the coils, frequency and voltage of the oscillator, impedance of the components. The system may also contain a temperature sensor, such as a thermistor, and a means to compensate for thermal variation in circuit impedance and change in output signal due to variations of temperature. A quantitative relationship between the concentration and the voltage V_s in the secondary coil is determined by calibration with samples of known magnetic particles concentration. Such calibration samples are constructed in the form of resin-bond sticks made of the same magnetic particles as used in particular MR fluid. Calibration gives the general linear expression

$$\varphi = aV_s + b, \quad (6)$$

where a and b are constants defined by calibration.

Sensitivity of measurements and system resolution can be increased using differential approach as shown in Fig. 2(a).

In this case two identical sets/pair of coils are used. Whereas one pair of coils has a sample of the MR fluid to be tested, another pair has a sample of reference material (air, material with known magnetic permeability, etc.). Both primary coils are connected to the AC voltage source (oscillator) in parallel. Secondary coils are connected in series, so that currents of the coils I_{s1} and I_{s2} through resistance R_s are oppositely directed. As such, the resulting current will be equal to zero when the same samples or no samples are placed inside the coils. The schematic may contain some additional common means to accurately balance the system. Any system misbalance caused by the change in magnetic properties of one of the samples results in the proportional output signal. At the same time, any change in the circuits' impedance (current) caused by the temperature will not affect the output signal because they cancel each other.

The configuration described above can be used as a bench top instrument for measurement of the magnetic permeability of materials as well as concentration of magnetic particles in magnetic fluids such as ferrofluids and MR fluids. The example of Fig. 2(b) shows two pairs of coils encapsulated in waterproof housing. One coil is submersed in the fluid, in which the magnetic permeability or concentration of magnetic particles has to be measured, while the free reference sensor contains the sample with known magnetic permeability.

An exemplary design of the flow-type sensor is shown in Fig. 3.

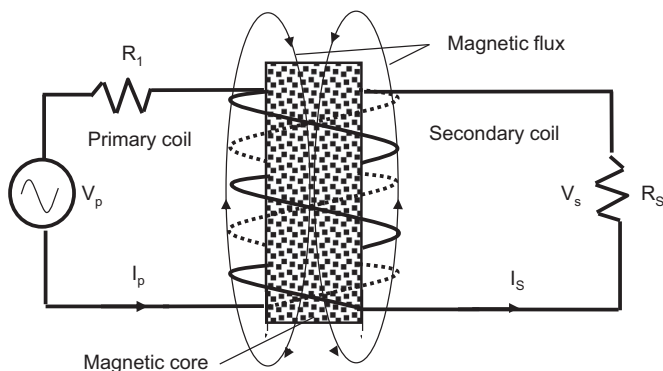


Fig. 1. Schematic of a method for magnetic particles concentration measurement based on the principle of mutual inductance.

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