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Torsional Magnetic Measuring System in Submerged Environment

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Abstract: The act of measuring the torque produced by a given machinery, or engine in operation is an important segment related to the production, maintenance and use of mechanical equipment. With the evolution of technology and the constant concern to create more modern engines that have an improved mechanical performance, the need to make measurements of the various parameters related to their operation was created, constant torque measurement is one of these parameters. The combination of this parameter with the measurement of the rotation speed allows instantaneous mechanical power to be calculated, enabling lower fuel consumption, greater operational safety, greater reliability and a lower emission rate. With the increasing use of modern machines in aquatic environments, whether in the oil segment or in the aquatic vehicle segment, this need for monitoring also expands to this environment. The development of the torque measurement technique in submerged environment using the Hall effect in addition to allowing readings in submerged environments has the benefit of being noninvasive.

Key words: Submerged torque measurement, measurement of magnetic permeability, RL (resistor-inductor) Circuit, real-time measurement, remote monitoring.

1. Introduction

No torque measurements on shafts for applications at full speed, indirect determination techniques are normally used, such as analyses performed directly on electric or thermal motors. These methods have a large margin of error and can often mask semi-static deformations or those that occur slowly.

Current measurement systems directly on the axes, use strain gauges, and must be electrically powered, and their measurement signal captured, which makes it difficult to use, as it is not possible to use wires or cables due to continuous rotation. The existing proposals are carried out in an invasive way, since the torque transducer must almost always be part of the shaft, needing to interrupt the operation of the machinery to be analyzed, in addition to occupying a lot of space for the installation of data capture systems and generally using telemetry.

When there is a need for submerged applications, whether in water or in other operating fluids, the application becomes even more complicated, and it is generally unfeasible to measure the torque directly on the shaft, mainly due to the need for electrical supply of the various methods implemented for this submerged analysis.

The proposed technique to be used [1, 2] not only eliminates the need for electrical supply to components fixed to the shaft, but also allows its full implementation in submerged environments as long as the properties of the fluid in which the system is submerged are known, so the system will work normally in submerged systems. Such systems are very useful in several areas and can be widely seen monitoring mooring loads for research buoys, monitoring dynamic loads in drill pipe, determining hydrodynamic loads in underwater cages used for fish farming, in submerged shafts, such as

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drill bits, deep sea drilling or automotive axles immersed in lubricating oils.

The technique [1, 2] uses two small magnets which are fixed to an axis, and the variation of their magnetic field, due to their relative movement as a function of torsional deformations, will be measured by a sensor based on Hall effect, while these magnets rotate along with the shaft in full rotation, which is in an environment submerged with water and/or other fluids. Due to the great dependence of the magnetic field to determine the torque used in the method [1, 2] for the submersion of this entire system, it was necessary to carry out a study on the magnetic permeability of the fluid in which the system was submerged.

Magnetic permeability is a constant of proportionality that relates the magnetic flux, which passes through the material, with the strength of the field outside the object. We can compare this property to electrical conductivity, ease of conducting electric current, but magnetic permeability is a property that represents the ease of "conducting" magnetic flux through the material in question, so this property tells us how permissive the material is to the passage of the material, magnetic flux, being therefore essential for the different studies in the areas of knowledge that involve electromagnetism. The use of magnetic liquids in the industry that use magnetic permeability concepts to perform their functions is very diverse, we can see examples of their applications in Refs. [3] and [4].

There are several existing techniques for measuring magnetic permeability, we can mention the "cavity method" created to measure the permeability of Fe_3O_4 and nano-silver powder [5]. The permeability of nanoferrite powder can be obtained by the reflection technique [6]. A differentially excited loop method was employed to measure the permeability of a magnetic thin film, with an error of less than 8% [7]. Another method proposes the measurement of the magnetic permeability of a given liquid through the application of microwaves in frequency [8], through the variation of the mutual inductance, subjecting the evaluated sample to two conditions, sample located and not located in the spaces formed by a pair of cores [9], among others. But due to the complexity and cost of the methods mentioned above, in the present work, a method of measuring and monitoring the magnetic permeability of a fluid in flow will be developed, thus allowing the reading of the torque using the method of the Hall effect sensor submerged in a fluid.

To achieve this objective, the work methodology was elaborated, which was performed and systematized in four sections, present in this thesis and organized as described below. In section II, the existing techniques necessary for the development of the method of monitoring the magnetic permeability of the fluid in which the system is immersed are presented.

In the following section, the test bench developed to simulate the submerged environment in which the system will be contained will be shown, as well as its working principle. In addition to the results of the tests performed, in section IV, the conclusions of the study will finally be presented.

2. Measurement and Monitoring of Magnetic Permeability

As previously mentioned, the method used in this study [1, 2] uses Hall effect sensors to perform the axis deformations, so the magnetic permeability of the medium in which the Hall effect sensor is inserted needs to be known. Due to this need, in this section, the development of two techniques to perform this measurement will be presented. In this same section, the particularities of each technique will be shown along with their respective results.

2.1 Inductance Measurement an RLC Resonant Circuit

Resonant circuits, also called tuned circuits, are circuits in which their voltage has its own oscillation, a characteristic oscillation that properly depends on the characteristics of the components of the circuit.

There are two types of resonant circuits, series and parallel. Both circuits consist of a capacitor, inductor and a resistor.

From the moment a voltage is applied to L and C, which are in parallel, it will result in the charging of the capacitor and subsequent discharging, thus generating a cycle of charges and discharges, giving rise to an alternating voltage signal in sinusoidal form that will oscillate with a specific frequency, the so-called resonant frequency. Each resonant circuit will have a resonant frequency that is extremely dependent on the inductance and capacitance values of the circuit components.

As shown in Ref. [10] the resonant frequency of a circuit can be obtained through the equation below:

$$F_R = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}}$$

Isolating the inductance value from the above equation, we arrive at the following equation:

$$L = \frac{1}{4 \cdot \pi^2 \cdot {F_R}^2 \cdot C}$$

As shown above, if you have the resonant frequency of the circuit and the capacitance value, you will obtain the capacitance value. The resonant frequency can be measured from the possession of the voltage sinusoidal wave over the inductor or over the capacitor. By applying a voltage pulse of 5 V, in the circuit (A) of Fig. 1, the frequency of oscillation of the sinusoidal voltage can be obtained by obtaining the time in which the sinusoidal wave remains in the positive part, as shown in (C) in Fig. 1 below.

Using the LM339 comparator IC, the positive cycle time of the wave was obtained, because as soon as the voltage in the LC circuit becomes positive, the LM339 will be floating, which will return a high level at the output. When the voltage in the LC circuit becomes negative, the LM339 will return to the low voltage output. One of the great benefits of using the LM339 IC is the great switching capacity, which is superior to the LM741 operational amplifier.

Fig. 2 below shows the circuit set up to obtain the inductance value of the test inductor through the inductance formulation (2) shown above.

From the inductance values obtained through the above arrangement, the relative permeability of the sample contained within the coil can be obtained through the mathematical relationship between the inductance of the coil with the material to be analyzed L in relation to the inductance of the coil with the core filled with air L_0, as shown in Ref. [11]. In this way, the relative permeability of the sample can be obtained and, in this way, the real permeability of the analyzed material can be obtained.

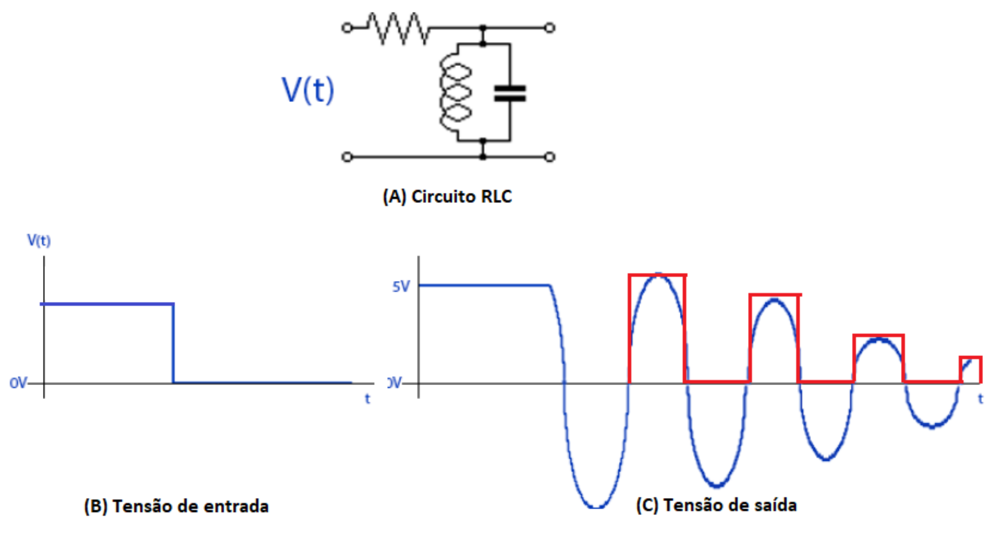

Fig. 1 (a) RLC measurement circuit diagram, (b) Circuit excitation voltage signal, (c) Voltage signal in the inductor with which the frequency is measured.

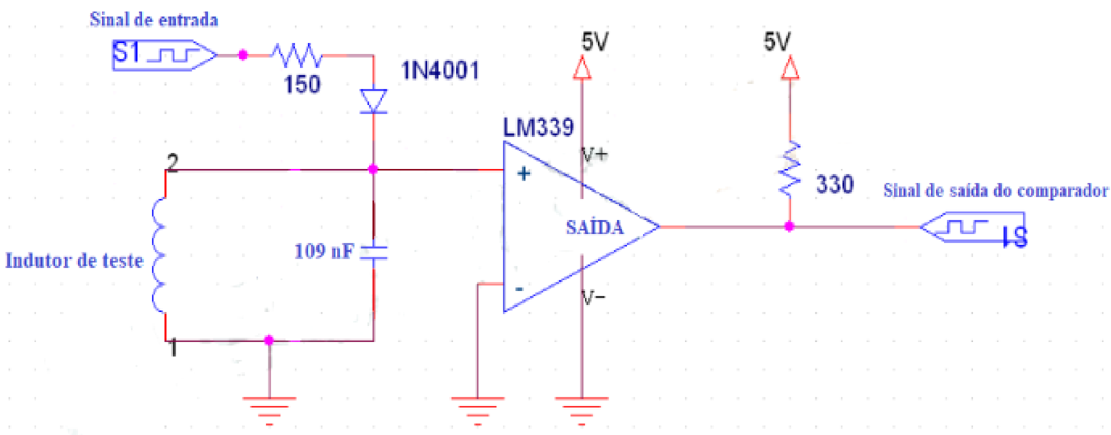

Fig. 2 Comparator circuit that obtains the inductance value as a function of the oscillation frequency.

For such a static permeability analysis, a coil with a hollow core was built through which the fluid to be analyzed will pass. To make the coil, 152 turns were made using an enameled copper wire whose diameter is 0.1 mm. In Fig 3, the coil built has an approximate diameter of 24 mm and an approximate length of 90.88 mm with a lid to contain the analyzed liquid.

3. Results

To verify the results obtained, a Minipa MXB-821 RLC bridge was used, which carried out the measurements of the winding inductance shown above with the empty core, and later with the core filled with the analyzed material, thus discovering the relative permeability of the sample, as proposed in Ref. [11]. Fig. 4 below shows the two measurements performed by the RLC bridge to certify the relative permeability of the sample.

The measurements carried out with the aid of the studied technique allowed the construction of the following graph shown below, this graph compares the results of relative permeability obtained through the aid of the RLC bridge and through the resonant circuit technique analyzed here.

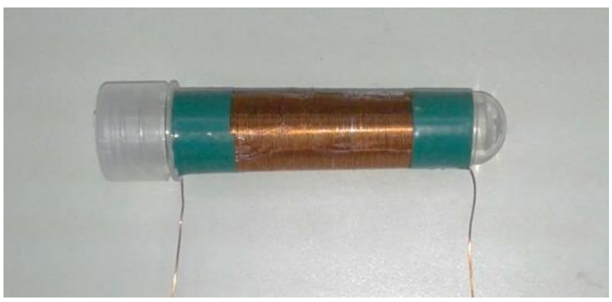

Fig. 3 Solenoid built to perform the measurements.

(1) (2)

Fig. 4 RLC bridge for measurements.

Table 1 Comparative result between the measurement made by the RLC bridge and the developed circuit.

Material analyzed	RLC bridge	Circuit resonant	Mistake percentage
Oil + 20%	1.395	1.432	2.652329749
Oil + 40%	1.923	1.95	1.404056162
Aluminum	1.0663	1.1003	3.18859608
Copper	0.7105	0.85	19.63406052
Iron material fused	2.3517	2.3889	1.581834418

The torque measurement technique used in this study works according to Fig. 1. Pairs of magnets are glued to the rotating shaft forming an angle of 45° with the horizontal axis, the plane in which the maximum shear deformations occur. A deformation suffered in the shaft will increase or decrease the distance between the magnets, which will cause an increase or decrease in the magnetic field. The stationary Hall effect sensor, positioned close to the axis, captures this variation in the field and makes the reading signal available to an acquisition unit, where the data are processed and the torque signal is provided.

The applied mechanical stress will cause the magnets to move closer together or farther apart, changing the distance *d* between them. Therefore, the distance between the magnets will become: $d \pm \Delta d$. This approximation (or departure) will influence the value of the magnetic field measured along the symmetry axis. Thus, knowing the variation in the intensity of the magnetic field, it is possible to determine the deformation suffered by the part, and consequently the applied tension, be it torsion, tension or compression. This technique uses N48 magnets, which were fixed along the axis with an inclination of 45°, as illustrated in Fig. 5, and the magnetic field meter was positioned just above the magnets, as shown in the Fig 5 and Fig 6:

This shaft deformation measurement technique presented in Refs. [1, 2] uses a Hall sensor, a 2nd order active filter and an instrumentation amplifier. The signal is sent to a 16-bit AD converter, NI MyDAQ, with a sampling rate of 200 KS/s, with more information available in Ref. [12]. The interface in Labview calculates the torque value from the variation of the magnetic field due to the relative distance between the magnets. For the redundant measurement of torque, the mechanical testing machine CME-150Nm was used, which is shown in Fig. 7 below with the glass bowl in which the shaft will be submerged.

To carry out measurements in an underwater environment using a bench, both static and dynamic, it was necessary to develop a tank to contain the water, shown in Fig. 8 below, which was inserted in the region between the mandrels, so that the specimen, together with the magnets and the sensors, remain submerged in the fluid, also submerging the data capture system.

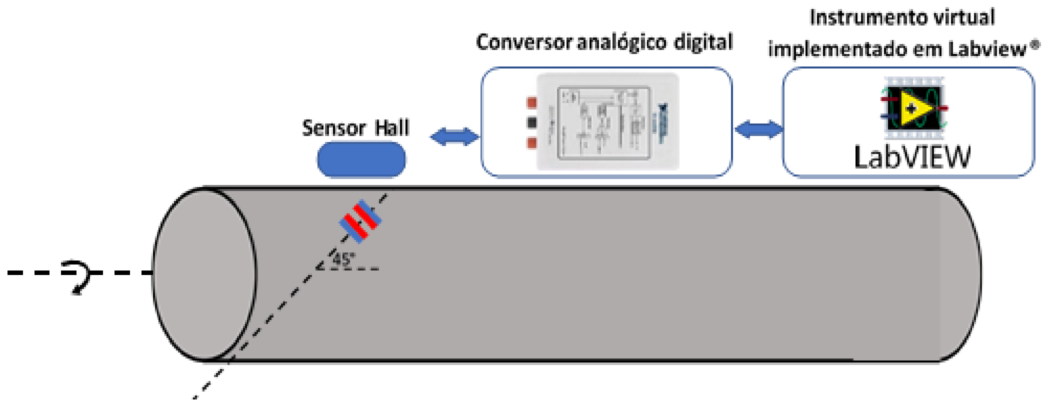

Fig. 5 Description of torque measurement system.

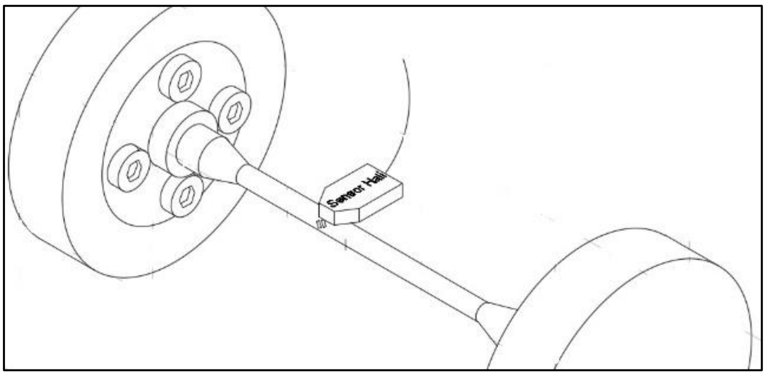

Fig. 6 Hall effect sensor installed next to magnets.

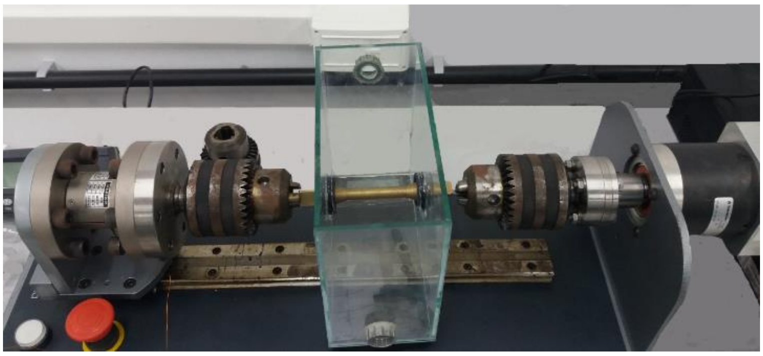

Fig. 7 Torque measurement bench.

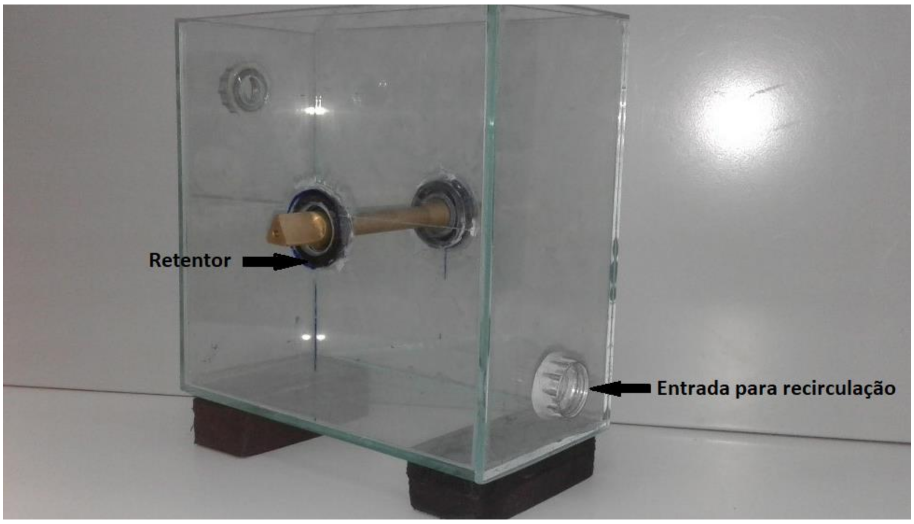

Fig. 8 Cuba developed for system immersion.

The aforementioned vat was developed in glass material with dimensions of 180 mm × 200 mm, length; width and height respectively. On the front face, two axial holes were drilled through which the shaft will pass. Retainers were placed in the holes allowing the shaft that passes through them to rotate without leaking the liquid stored in the vat.

Two holes were drilled on the side faces in order to recirculate the contained fluid in order to simulate a current, bringing the test even closer to a real scenario of use. Such water recirculation will be done with the aid of a pump which will pump water into the box through the lower side hole and remove the water pumped through the other upper side hole. Various

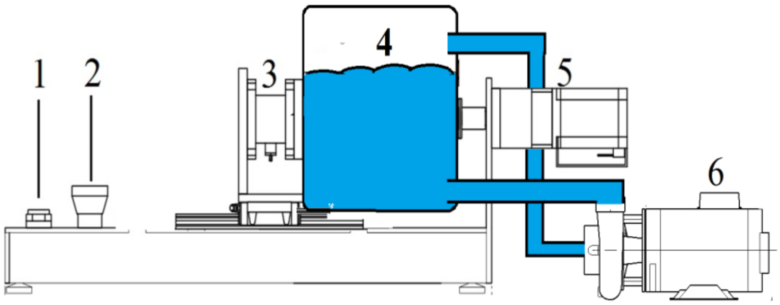

Fig. 9 Scheme of the bench used to perform the submerged measurements.

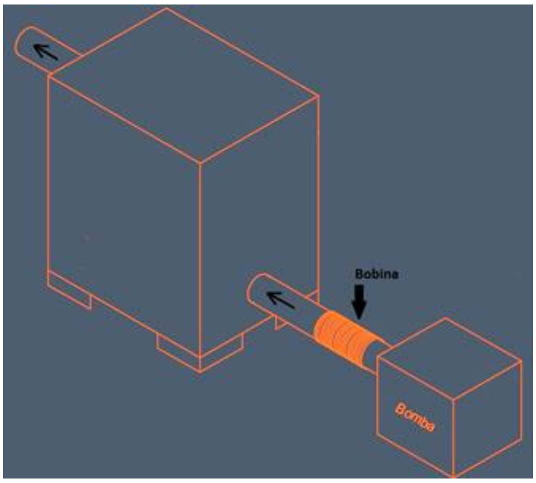

Fig. 10 Positioning of the instantaneous magnetic permeability measuring coil.

fluids will be tested, from mineral water, sea water, mineral oils and finally, flammable liquids, with the necessary safety adaptations. Fig. 9 below illustrates a frontal view of what the system would look like: (1) Activation button; (2) emergency stop; (3) torquemeter ; (4) fluid bowl; 50 Stepper motor and reduction box and (6) motor-pump system.

Fig. 10 illustrates the installation of the winding responsible for reading and analyzing the magnetic permeability of the recirculated fluid in the tank, as illustrated, the inductor will be located at the entrance of the tank and will analyze the magnetic permeability of the recirculating fluid, allowing a correct reading of the shaft deformation by the of the Hall effect sensor.

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