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Real-Time Measurement of Eccentric Motion with Capacitive Sensor for Hydraulic Pumps

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Abstract— **Cylindrical capacitive sensors have been developed and applied to various rotating machinery applications in the past two decades. In the hydraulic industry, capacitive sensors can also be used to measure various properties of hydraulic systems due to the change of its dielectric permittivity. Compared with competing optical, inductive, and piezoresistive transducers, capacitive sensors have many advantages, such as low cost and power usage, and good stability, resolution, and speed, etc. In this paper, a new approach that measures the eccentric motions of a hydraulic pump by using a cylindrical capacitive sensor is presented.**

I. Introduction

THE primary advantage of hydraulic actuators compared to other mechanical and electric systems is that larger forces and torques can be developed with comparatively compact motors without the need of gearboxes. Very accurate motion and pressure controls are also possible by using sophisticated servo valves. With those advantages, hydraulic actuators have been widely used in various industrial applications, such as hydraulic lift, power units in machine tool, and power construction equipment, etc. As the demand of automation in hydraulic industry increases rapidly, the monitoring devices for the widely used hydraulic systems have also become more and more important.

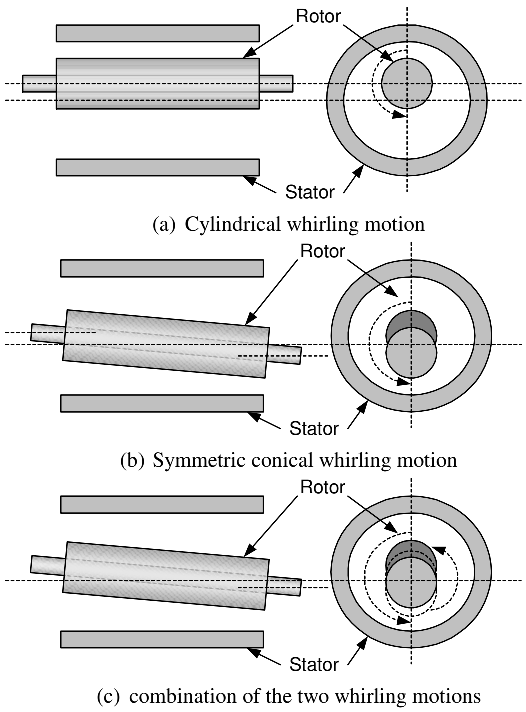
Hydraulic systems employed in automated application require strict control of pressure, level, and flow. Most of the monitoring of those sorts of properties relies on fluid transducers. Fluid transducers are divided into several groups according to the property being measured. Traditionally, those kinds of transducers are mechanical components with electrical outputs. A fundamental property of mechanical transducers is that they convert mechanical energy into an electrical signal. The major disadvantages of mechanical transducers are the slow response and the expensive price. As widely used applications, the needs of fast response and low cost sensors are paramount in the industry of hydraulics.

To overcome the disadvantages, capacitive sensors are one of the alternative choices. Compared with competing mechanical transducers, capacitive sensors have many advantages, such as low cost, lower power usage, mass producible, and faster response. Capacitive sensors can directly sense a variety of properties – motion, chemical composition, electric field – and, indirectly, sense many other variables that can be converted into motion or dielectric constant, such as pressure, acceleration, fluid level, and fluid composition. They are built with conductive sensing electrodes in a dielectric, with excitation voltages and detection circuits that turn a capacitance variation into a voltage, frequency, or pulse width variation.

Applications of capacitive sensors are numerous and vary widely. One of the general applications nowadays is the position measurement in micrometer or nanometer scale [1-3]. Some other applications include measuring the chemical properties wherein the material is inserted as the dielectric of the capacitor [4, 5], wiring system of a power system [6], and tactile sensor in robotics [7]. Each application involves the capacitance measurement of a test capacitor. Thus, the measured capacitance is correlated to various system parameters depending on the application. There are also many other characteristics that are associated with capacitance measurement in other researches [8, 9]. The capacitance of the sensor is often measured indirectly but rather represented by an intermediate measurement, such as a voltage in a bridge circuit or the signal period in a timer circuit. The measured signal is then correlated to the property desired. Various researchers [10, 11] have also proposed to measure the capacitance with different techniques.

Capacitive sensors have also been used to measure mechanical movements of rotating devices. Different techniques that measure radial and axial movements [12] and angular position with a full circle measurement [13] have been proposed by different researchers. However, due to the manufacturing defect, eccentricity and other geometric errors occur in rotating devices. As the shaft rotates, the effective radii and the capacitance of the sensor vary from position to position. In this paper, we will use a cylindrical capacitive sensor to measure the eccentric motions of a pump.

The eccentric motions of a rigid rotor are divided into the two basic modes: 1) cylindrical whirling motion and 2) symmetric conical whirling motion [14]. The cylindrical whirling motion of the rotor means that the rotor remains aligned with the stator but the geometrical centerline of the rotor travels around the geometrical centerline of the stator in a circular orbit. The symmetric conical whirling motion of the rotor means that the whirling radius at each end of the rotor is equal but in opposite directions. Fig. 1 shows the configuration of the possible eccentricity between the inner and the outer cylinders. The eccentric motions of the rotor can be almost whatever motions, in which the centerline of the rotor deviates from the centerline of the stator, at least, at



(a) Cylindrical whirling motion

(b) Symmetric conical whirling motion

(c) combination of the two whirling motions

Fig. 1. Different modes of eccentric motions.

some time instant. Conventionally the electromagnetic forces acting between the rotor and stator have been studied analytically [15]. Most of these studies focused on two special cases of the whirling motion, i.e. static and dynamic eccentricity. In this paper, we will use an oscillator circuit to measure the variation of the capacitance of a cylindrical capacitive pickup device attached to a rotating device. To simplify the task, the present work focuses on the whirling motion of the rotor. Also, for simplicity, only the rigid rotor motions are considered i.e. the bending of the rotor is neglected. The measured capacitance is then converted to the corresponding eccentricity in real-time.

The organization of the paper is as follows. In the second section, we will discuss the analytical model of the capacitive sensor. In section III, we will discuss the validity of the analytical model and the experimental setup. This section also demonstrates a readout interface with indirect measurement. The real-time measurements of eccentric motion of a hydraulic pump are demonstrated in section IV. Summary and conclusions are given in the last section.

II. Analytical Model of Cylindrical Capacitive Sensor

Instead of measuring the geometric properties, the method used in this paper measures the capacitance of a cylindrical capacitive pickup device and then converts the measurement back to the property of geometric defects. Various researchers have proposed different analytical models for the cylindrical capacitive sensor [16, 17]. In this section, we will take a more deterministic view of the cylindrical capacitor and propose a feasible way to measure the capacitance of the cylindrical capacitive sensor.

A. Structure of Cylindrical Capacitive Sensor

The components of a hydraulic system are analogous to a simple capacitor that includes two conductors. The pump shaft, swash plate, and pistons are electrically connected and can be thought as the first conductor. Insulated from this conductor is the external housing that acts as the second conductor. Insulating these two conductors is the insulating material that acts as the dielectric medium. The configuration is illustrated in Fig. 2. The lengths of the inner and outer cylinders are both L, and the individual radii are R_A and R_B. As the pump starts to rotate, the capacitance of the pump is modulated due to the fluid pumping mechanisms, which is a function of the changing internal geometry.

B. Analytical Model

Assume that the profiles of both inner and outer cylinders do not have any manufacturing defects, and the cylinders have charge $+Q$ and $-Q$ on the surfaces. By applying Gauss' Law, the enclosed charge within a unit length l is

$$q_{in} = \left(\frac{Q}{L}\right) \cdot l ,$$

and the electric flux is

$$\Phi = \frac{1}{\varepsilon_0} q_{in} ,$$

where ε_0 is the dielectric constant of the capacitor, and

$$\Phi = \oint \vec{E} \cdot d\vec{A} = E \cdot A .$$

Solving for E, then the electric field is

$$E = \frac{\Phi}{A} = \frac{\frac{1}{\varepsilon_0}\left(\frac{Q}{L} \cdot l\right)}{2\pi r l} = \frac{Q}{2\pi\varepsilon_0 r L} .$$

The voltage between the inner and outer cylinder is

$$\begin{aligned}\Delta V &= -\int \vec{E} \cdot d\vec{S} = -\int_{R_A}^{R_B} \frac{Q}{2\pi\varepsilon_0 L} \cdot \frac{1}{r} dr \\ &= -\frac{Q}{2\pi\varepsilon_0 L}\left[\ln R_A - \ln R_B\right]\end{aligned} ,$$

and

$$C = \frac{|Q|}{|\Delta V|} = \frac{2\pi\varepsilon_0 L}{|\ln R_A - \ln R_B|} = \frac{2\pi\varepsilon_0 L}{\left|\ln\left(R_A / R_B\right)\right|} , \quad (1)$$

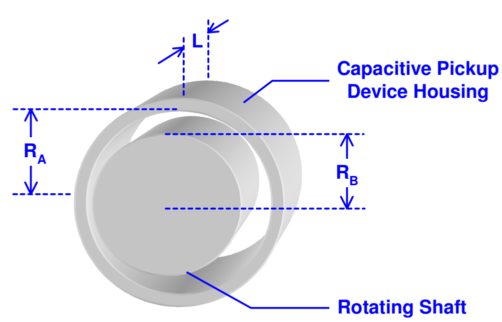


Fig. 2. Configuration of concentric cylinders of the capacitor.

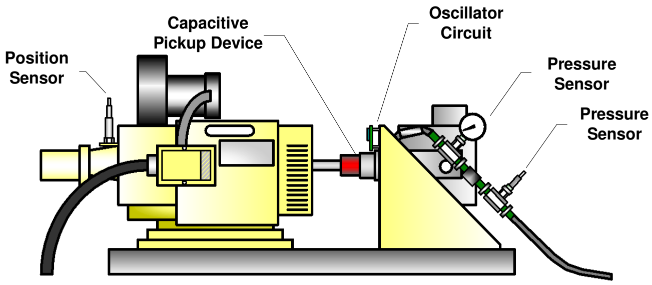


Fig. 3. Schematic of the testing facility.

where R_A and R_B are the radii of the inner and outer cylinders. When the operating status achieves its steady state, $2\pi\varepsilon_0 L$ remains as a constant. The equation with respect to the ratio of the radii of the inner and outer cylinders R_A/R_B shows that if the two cylinders are in very close proximity to one another, the capacitance becomes very sensitive to the ratio.

However, for an actual cylindrical capacitive sensor, the geometric shapes of the inner shaft and the outer sheath are not perfect circles, and the effective radii are different from position to position. Eq. (1) is only a model to explain the mechanism of capacitance change, but this is not a dynamic model as the sensor starts to rotate. To derive the precise value of capacitance of the sensor, an experimental measurement is required.

III. Experimental Setup

A. *Testing Facility of the Hydraulic System*

The testing facility of the experiment setup is a hydraulic system, which includes a pump, a cylindrical capacitive pickup device, an oscillator circuit, a data acquisition device, a position sensor, a needle valve, and sensors of various properties. The schematic setup of the hydraulic system is shown in Fig. 3. The hydraulic pump is driven by a DC motor that is controlled by a speed oriented controller. After cranking the pump speed to the desired speed, it would take 30~90 seconds to achieve steady-state. As the pump operates, hydraulic fluid is forced through a needle valve, resulting in a static pressure drop. In this manner, the load of the hydraulic circuit can be simulated by changing the opening of the inlet needle valve. The pump of this testing facility is a Mannesmann-Rexroth, model AA4VSO. Nine pistons are attached to the swash plate of this 39.04 kg pump, and the swash plate angle can be swept from about 5° to its maximum value 15°. It is a variable displacement pump with a maximum displacement of 38 cc/rev. The electric motor which drives the pump is a 12.68 kW Reliance Model 258ATZ. The pump and the motor are coupled via an insulated coupling. This insures that the pump is electrically isolated from the motor. The pump housing is earth grounded. The fluid reservoir, which contains the fluid of the hydraulic circuit, holds 120 liters of Texaco Rando HD-100 hydraulic fluid.

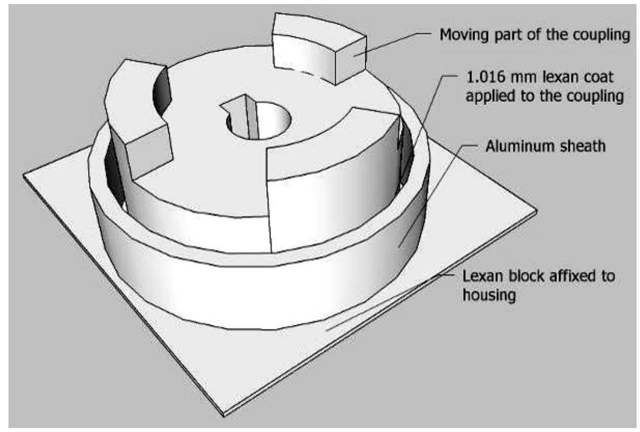


Fig. 4. The solid model of the adopted capacitive pickup device.

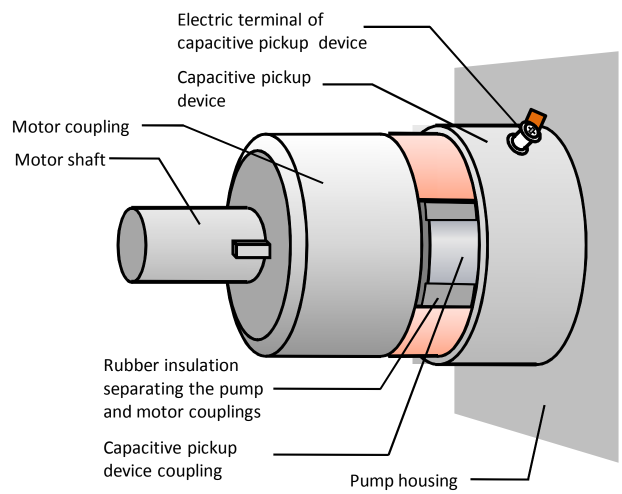


Fig. 5. Physical setup of capacitive pickup device and the couplings.

As to the dimensional parameters of the coupler, the radii of the inner cylinder and outer cylinder are 42.23 mm and 44.45 mm, respectively. The rotating speed of the experiments was controlled within 400 to 1200 RPM.

B. *Capacitive pickup Device*

To sense the capacitance of the pump, a terminal must be connected to each of the pump conducting surfaces, namely the housing and the shaft. Since the shaft of the pump is rotating while in operation, it is not easily accessible. This problem is solved through the use of a capacitive pickup device.

The motor and pump shafts are connected by an insulated coupling. The pickup device consists of an aluminum cylindrical sheath, called the capacitive pickup device that encircles a modified coupling placed on the end of the pump shaft, external to the pump. The sheath is mechanically fixed to the pump but electrically insulated. The coupling is turned down on a lathe and coated with a smooth insulator, lexan. This coated is also turned such that its outer diameter is smaller than the inner diameter of the sheath, forming an air gap less than 1.016 mm, nominally. A solid model of this device is shown in Fig. 4. The lexan coat is not shown making the air gap more visible.

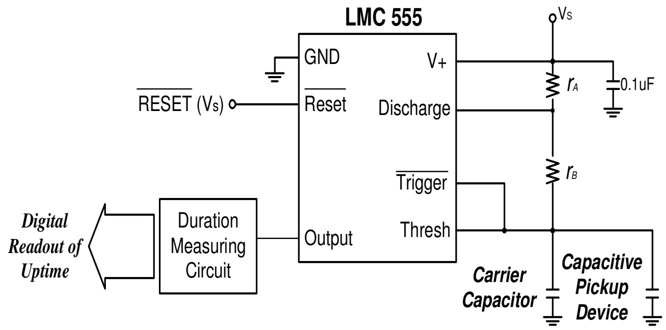


Fig. 6. Configuration of the oscillator circuit.

Together, the sheath and key form a concentric cylindrical capacitor whose dielectric is the lexan coat and air gap. The measured capacitance is an electrical series combination of the pump capacitance and the fixed cylindrical capacitor. Fig. 5 demonstrates how the capacitive pickup device connects to the hydraulic pump. As the motor starts to rotate, the capacitance of the capacitive pickup device also changes. The capacitance is then picked up by a oscillator circuit.

C. Hardware Setup of Capacitance Measurement

To obtain accurate measurements of the capacitance, an oscillator circuit is used. Instead of measuring the capacitance directly, the oscillator circuit converts the varying capacitance into a pulse chain with different durations. By measuring the duration of individual pulses, the value of the capacitance can be obtained accordingly. However, if the only capacitance existing in the oscillator circuit is from the sensor, the capacitance would be too small to yield an extremely short duration of pulses, which is difficult to measure and can easily be perturbed by electrical noises. To avoid this situation, a carrier capacitor is adopted to increase the duration of pulses.

In addition to the capacitive sensor and the carrier capacitor, there is one other capacitance existing in the circuit which can be significant. In practice, the capacitance due to the wiring of the connections would need to be taken into consideration if the capacitance of the sensor is too small. The overall capacitance of the carrier capacitor, the wiring, and the sensor is an electrical parallel combination.

The oscillator circuit employed is a CMOS 555 timer with the astable type of circuit configuration as shown in Fig. 6. The circuit triggers itself and free runs as a multivibrator. In this mode of operation, the capacitor charges and discharges between 1/3 and 2/3 supply voltage. As in the triggered mode, the frequency is independent of the supply voltage. For the capacitance of the pump system is small, it generates an extremely high frequency signal while connecting to a timer circuit directly. This signal can be interfered easily by exogenous perturbations existing in the wiring. To avoid the disturbance, a 4 kHz modulated frequency is used to record the variance of capacitance of the pump system. A mechanical encoder is equipped at the end of the motor shaft to detect the angular position. The resolution of this position sensor is 60 counts per revolution.

Once the capacitance of the pump system is inserted, the output signal pulse duration modulates the carrier capacitance with the time-varying capacitance of the pump system. The duty cycle of the oscillator circuit is set to be 50%, and the pulse duration can be measured from either the *uptime* (charge time) or the *downtime* (discharge time). To avoid the noise at 0 volt, the uptime at 5 volt is used to measure the pulse width. A duration measuring circuit, which converts the pulse chain into a 16-bit digital readout, is used to measure the length of the uptime signal. This add-on circuit was synthesized with a programmable logic device (ispLSI2032E) manufactured by Lattice Semiconductor. With a 16 MHz sample rate, the duration measuring circuit is capable to measure the uptime-duration from 0.0625 μs to 4.096 ms. In this application, the quantization levels of the uptime-duration measurement are between 100 μs to 150 μs depending on the modulated capacitance. This add-on circuit is also in charge of measuring the angular position of the pump shaft with a resolution of 6°. The acquired information of duration and angular position is then sent back to a host PC with MATLAB and dSPACE installed.

Based on the configuration of the oscillator circuit designed, the uptime-duration t_{uptime} is represented as

$$t_{uptime} = 0.693 \cdot \left(r_A + r_B\right) \cdot C_{coupled}, \tag{2}$$

where r_A and r_B are the values of the resistors in the circuit, and $C_{coupled}$ is the coupled capacitance of the carrier capacitor $C_{carrier}$ and the capacitive sensor C, which can be represented as

$$C_{coupled} = C + C_{carrier}. \tag{3}$$

Replace the term $C_{coupled}$ in Eq. (2) with Eq. (3) and embed the value C derived from Eq. (1) into Eq. (2), the measurement of the uptime can be rewritten as

$$\begin{aligned} t_{uptime} &= 0.693 \cdot \left(r_A + r_B\right) \cdot \left(C + C_{carrier}\right) \\ &= 0.693 \cdot \left(r_A + r_B\right) \cdot \left(\frac{2\pi\varepsilon_0 L}{\left|\ln\left(R_A / R_B \right)\right|} + C_{carrier} \right). \end{aligned} \tag{4}$$

Thus, the ratio of the effective radii R_A/R_B, which is a position based function, can be estimated indirectly from uptime-duration measurement. However, there is a condition that this equation cannot be applied to detect the eccentric motion – if the eccentric motion only contains cylindrical whirling motion.

IV. Experimental Results

To observe the eccentric motions, the uptime-duration of the oscillator circuit needs to be recorded from position to position. The resolution of the equipped angular position sensor is 60 counts per revolution. The maximum rated rotating speed of the hydraulic pump is 1600 RPM. Therefore, the least required sample time of data acquisition device is

$$1600\text{RPM} \times \frac{1}{60} \cdot \frac{\text{sec}}{\text{min}} \times 60 \frac{\text{counts}}{\text{rev}} = 1600 \frac{\text{samples}}{\text{sec}} .$$

The time interval between each sample is around 625 μs, which is long enough for the add-on circuit to record a complete uptime-duration. With Eq. (4), uptime measurement can further be divided into two parts: the uptime- duration generated by the carrier capacitor and the fluctuation caused by the geometric variation of the capacitive pickup device. Therefore, the uptime fluctuation can be represented as

$$t_f = \frac{1.386 \pi \varepsilon_0 L \cdot (r_A + r_B)}{\ln(R_A / R_B)} ,$$

where t_f denotes the fluctuation of uptime measurement caused by the varying ratio of R_A/R_B. Thus, with uptime-duration measurement, the geometric variation can be derived. That is

$$\frac{R_A}{R_B} = e^{\frac{1.386 \pi \varepsilon_0 L \cdot (r_A + r_B)}{t_f}} . \tag{5}$$

By subtracting the nominal uptime from the measurements, the ratio R_A/R_B between the inner radius of the sheath and the radius of pump shaft can be derived indirectly. Thus, if the eccentric motion contains conical whirling motion, the variation of this ratio can then be obtained.

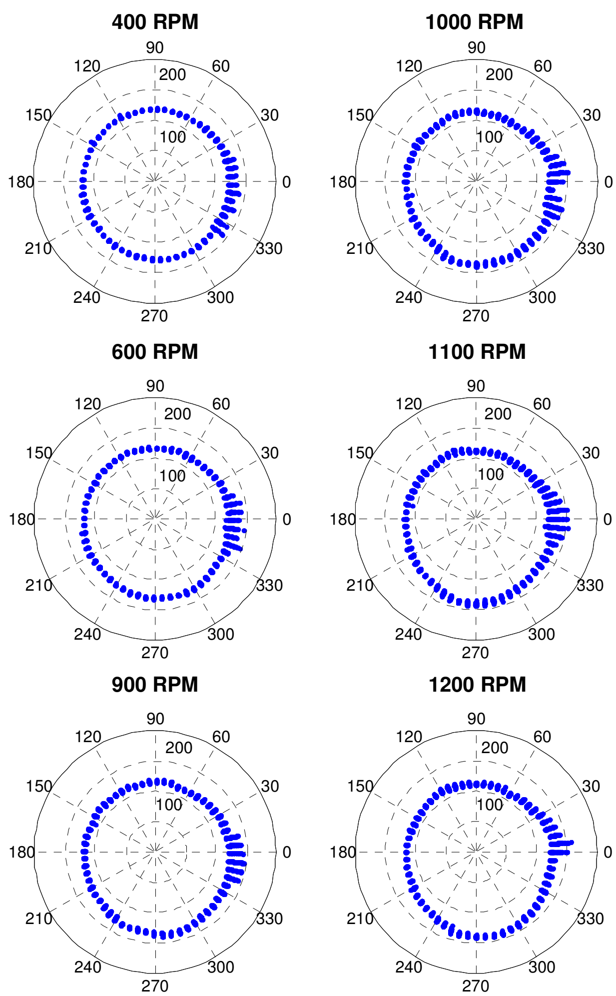


Fig. 7. Uptime-duration measurements of the hydraulic pump.

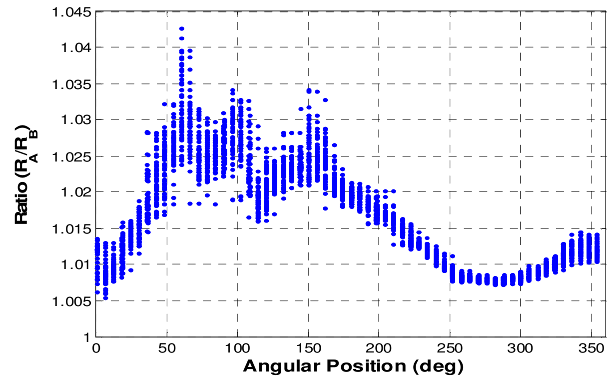


Fig. 8. Estimated ratio between R_A and R_B at 1200 RPM.

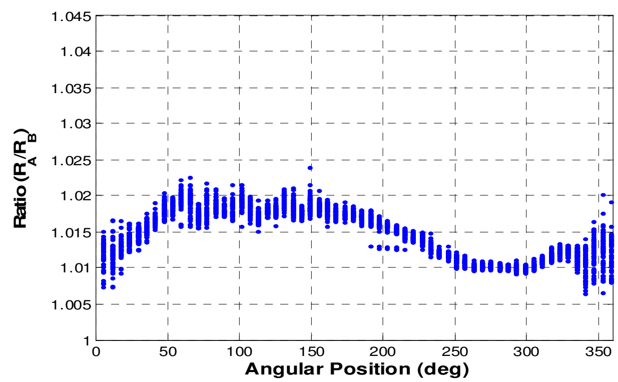


Fig. 9. Estimated ratio between R_A and R_B at 600 RPM.

In the experimental setup, the nominal uptime-duration generated by the carrier capacitance is designed to be 100 μs with 50% duty cycle. The controlled rotating speed was set to be ranged between 400 RPM and 1200 RPM. As the rotating speed of the pump achieves ~850 RPM, the pump starts to experience large vibrations and generate noises. With the measurement of the capacitive pickup device, this phenomenon can also be observed. Fig. 7 illustrates the uptime measurements of the oscillator circuit when the pump is operated under different rotating speeds. The blue dots, which the unit is μs, in each polar plot indicate the uptime of the circuit at its corresponding angular position. From the experimental results, it is clear that variation of uptime-duration measurement is relatively smaller at lower rotating speeds. As the speed becomes faster, the uptime-duration measurement starts to fluctuate. It can be observed that the uptime is less in the range between 30° and 210°, and the uptime becomes longer as the shaft rotates to the range between 210° and 30°.

With eq. (5), the estimated ratio between the inner radius of the sheath and the radius of pump shaft can be generated in real-time to monitor the eccentric motion variation at different rotating speeds. Fig. 8 and Fig. 9 illustrate the calculated ratio of R_A/R_B at rotating speeds of 600 RPM and 1200 RPM. To derive the table of operation signatures of the

Table 1. Signature profiles of R_A/R_B at different rotating speeds.

	600 RPM		900 RPM		1200 RPM	
	max	min	max	min	max	Min
0°	1.015	1.007	1.016	1.003	1.014	1.006
30°	1.018	1.014	1.017	1.012	1.019	1.012
60°	1.023	1.015	1.028	1.019	1.043	1.023
90°	1.020	1.017	1.023	1.016	1.032	1.022
120°	1.020	1.017	1.026	1.017	1.030	1.016
150°	1.024	1.017	1.025	1.016	1.035	1.020
180°	1.018	1.016	1.021	1.016	1.022	1.018
210°	1.016	1.012	1.013	1.009	1.020	1.013
240°	1.013	1.012	1.014	1.010	1.013	1.009
270°	1.011	1.009	1.010	1.008	1.008	1.007
300°	1.010	1.009	1.010	1.008	1.009	1.007
330°	1.014	1.009	1.013	1.009	1.013	1.009

rotary motion of the experimental setup at different rotating speeds, this equation can be used to determine the motion profile. Table 1 lists the profiles of the ratio at different rotating speeds (600 RPM, 900 RPM, and 1200 RPM). This table can be used for diagnosing the health condition of the hydraulic pump later.

V. CONCLUSION

In this paper, we have applied a well known mathematical model of cylindrical capacitive sensor and an oscillator circuit to acquire eccentricity measurement of rotary devices. The proposed method makes explicit the relationship between the eccentricity and the measured capacitance. With the low cost acquisition device, the eccentric motion of a rotating device can be obtained in real-time easily. This measurement device can also serve as a diagnosis tool of rotary motion once the table of signature profiles is obtained.

ACKNOWLEDGMENT

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