Contactless Piston Position Transducer with Axial Excitation

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Existing piston position sensors require either drilling precise hole into the piston bar or mounting permanent magnets or measuring device inside the pressurized cylinder. We present a new solution for aluminum pneumatic cylinders, which uses the ferromagnetic bar inside the solenoid as a marker and linear array of fluxgate sensors as a scale. Instead of relying on DC remanence we use active AC excitation; the reading is resistant against external fields, both DC and AC. Using sensor array allows to compensate for temperature effects. The linear stroke of the individual sensor is 40 mm, so that array density should be about 30 mm. 1 mm position resolution is achievable. The weak point of the new transducer is the response time: for fast moving pistons the excitation frequency should be high, which leads to weaker signal and lower resolution.

***Index Terms*—About four key words or phrases in alphabetical order, separated by commas.**

I. Introduction

PISTON POSITION TRANSDUCERS for hydraulic and pneumatic cylinders are more demanded by industry, as they are necessary for fine control.

Position sensor for hydraulic cylinders are usually in a shape of a long probe which is inserted into the deep narrow blind hole in the cylinder rod [1]. Non-contact sensors based on magnetostrictive principle (using toroidal permanent magnet in the piston) or variable inductance replace potentiometer sensors, which are cheap but have limited lifetime due to friction. The disadvantage of this type of sensors are the cost and reliability issues associated with the necessity of the long “gun drilled” hole in the rod and necessary fitting for the sensor, which resides inside the cylinder. Similar disadvantages exist for the microwave position sensors [2]. Vision-based sensors [3] and incremental optical piston position sensors [4, 5] were also developed, but they did not found industrial applications due to the reliability issues. Some systems use magnetic scale of a piston rod together with Hall sensors [6].

External monitoring of the hydraulic piston position is a challenge, as the walls of hydraulic cylinders are usually made of carbon steel which is ferromagnetic. The field of permanent magnet embedded in the piston is therefore shielded by the ferromagnetic barrel wall and distorted by both the wall and rod. Precision better than 5 mm is therefore hardly achievable. Some special hydraulic cylinders such as those used in water hydraulic systems have composite shell. For these cylinders inductive displacement sensor can be built using a coil winding in the shell of the cylinder [7].

Pneumatic cylinders usually have aluminum wall which is transparent for permanent magnet and therefore ideal for external sensors. Thanks to the simplicity and non-contact non-invasive capability these sensors are reliable and cost effective. The sensors being used for this application are mainly Hall and AMR, rarely GMR.

However, permanent-magnet based piston position sensors have several disadvantages:

1. They are influenced by external magnetic fields including those induced by DC currents
2. They require non-magnetic stainless steel piston rod, which is expensive. Aluminum cannot be used for this part because of strength requirements
3. Sensor cannot be mounted on existing cylinders if they are not equipped by magnet. Usually the complete cylinder should be exchanged, which is difficult and expensive especially in the case of large machinery.

The distance between the permanent magnet and sensors is nonlinear function of the measured magnetic field. If the ferromagnetic objects are present in the close vicinity, the mentioned function is very complex. Non-linear observer methods has been employed to accurately estimate the piston position in real time [8].

External DC magnetic sensors has been used also for the measurement of a piston position inside the cylinder of free piston engine [9]. The disadvantage of such DC systems without permanent magnet is that they rely on the remanence of ferromagnetic parts which may easily change with time and temperature.

In this paper we introduce novel eddy-current external position sensor for pneumatic cylinders. It uses AC magnetic field excitation and detection by integrated fluxgate sensors.

II. New Sensor Design

In this paper we suggest new AC piston position transducer using axial coil directly wound on the cylinder surface as a field source. The 2 or 3 mm thick electrically conducting cylinder wall has large attenuation, however we show that at low frequencies the field inside the cylinder is still strong

Manuscript received April 1, 2015; revised May 15, 2015 and June 1, 2015; accepted July 1, 2015. Date of publication July 10, 2015; date of current version July 31, 2015. Corresponding author: F. A. Author (e-mail: f.author@nist.gov. Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier (inserted by IEEE).

enough so that the cylinder movement can be observed by external fluxgate sensor.

For the verification of this principle we built a physical model of the pneumatic cylinder using 60 mm diameter barrel pipe made of 2 mm thick aluminum, 10 mm thick aluminum piston and 20 mm diameter steel piston rod. On top of the cylinder we wound single-layer axial coil with parameters in Tab 1.

TABLE 1 HERE

The coil was supplied from the function generator with 50 Ω internal resistance, so that the rms excitation current of 90 mA at low frequencies was decreasing with frequency to 70 mA at 100 Hz. The maximum generated field in the center of the cylinder was 156 A/m at 10 Hz and it was reduced mainly by the shielding effect of the aluminum cylinder to one half at 250 Hz. The field at the end of the cylinder was 128 A/m@10 Hz. The frequency dependence of the internal field measured in the middle of the cylinder is shown in the Fig. 1. The field at the end decreases to 50 % at DC as theoretically predicted. This decrease is smaller for AC excitation as a consequence of the eddy currents; at 10 Hz the decrease is only 20 %.

FIG. 1 HERE

In order to optimize the direction and position of the fluxgate sensors and also to find the optimum excitation frequency we made extensive simulations based on FEM analysis. For the material properties we have used the following values: for the iron rod relative permeability $\mu = 50$ and conductivity $S = 10 \cdot 10^6$ S/m, for the aluminum cylinder and piston conductivity $S = 38 \cdot 10^6$ S/m Fig. 2 shows an example of the simulations: radial and axial field component calculated for four positions of the piston. The simulation shows that the field maximum is about 20 mm from the end of the bar and this distance is smaller at the limit position where the bar is completely out of the coil.

FIG. 2 HERE

The simulated reading of the sensors in positions A to D as the function of the piston position is shown in Fig. 3 for the frequencies from 2 Hz to 128 Hz.

The sensitivity decrease with frequency is caused by two effects:

1. eddy currents in the aluminum cylinder: the field from the excitation coil is attenuated by the shielding effect as shown in Fig. 1, and the response from the rod is attenuated again before it reaches the sensors. These two shielding factors are not the same, as in the first case the attenuated field is in the axial direction, while in the second case it is in the radial direction.

2. Eddy currents in the piston bar. They are also the main source of phase shifts.

The simulation show that the eddy currents in the aluminum piston give negligible contribution to the measured signal.

FIG. 3 HERE

The simulations were verified by measurement. An array of integrated fluxgate magnetic sensors was mounted in radial direction which is perpendicular to the primary field of the excitation coil. This was possible only because the used sensor has low crossfield error [10]. We have used integrated fluxgates DRV425 manufactured by Texas Instruments [11, 12]. The sensors were fixed in the plastic holders manufactured by 3-D printing. The experimental stand is shown in Fig. 4. The piston position was monitored by resistive transducer with 0.1 mm accuracy. The output voltage of the fluxgate sensors was measured by SR865 DSP Lock-in amplifier. The reference signal was derived from the coil current.

FIG. 4 HERE

In our case we used DRV425EVM modules with 0.5 mT range. However, using maximum range of 2 mT would allow to increase the excitation current by the factor of 10. In such case the noise limit would drop below 0.1 mm. The measured characteristics shown in Fig. 4. fits with the simulations. The sensitivity drops to one half at 20 Hz which is similar to the value predicted by simulations.

FIG. 5 HERE

Fig. 5 shows that the sensitivity in the radial direction is twice than the axial sensitivity. The axial field response is linear in the vicinity of the sensor location, which can be aslo used for the position sensing. The field in the axial direction was only 1.6 A/m. At 32 Hz the phase shift is large which makes modulus measurement of axial component useless. Regardless of using radial or axial field component. Sensor array should be used to cover strokes higher than 4 cm.

FIG. 6 HERE

III. Conclusion

Position of the piston in pneumatic cylinder can be measured by AC magnetic method. Using axial field excitation and an array of radially oriented fluxgate sensors on the cylinder surface an accuracy of 1 mm and resolution of 0.1 mm is achievable. The sensor linear range is 4 cm. For longer strokes linear array of sensors spaced 2 to 3 cm should be used. The main advantages of the new method are:

1. it can be used on existing cylinders, both the coil and sensors are mounted outside the cylinder.
2. no influence of external magnetic fields
3. no need for expensive non-magnetic stainless steel piston rod.
4. resistance to the rod geometrical and magnetic imperfections (verified by measurement with several rods, some of them with a curvature and some of them exposed to mechanical shocks)

The disadvantage of the axial transducer is that the excitation frequency should be kept low, which limits the dynamic response of the transducer.

Acknowledgment

Andrey Chirtsov was supported by Texas Instrument.

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TABLE I
PARAMETERS OF THE EXCITATION COIL

Coil length (mm)	480		
Number of turns	808		
	DC	100 Hz	1 kHz
L (mH)	-	3,5	0,4
R (Ω)	14.1	15	18

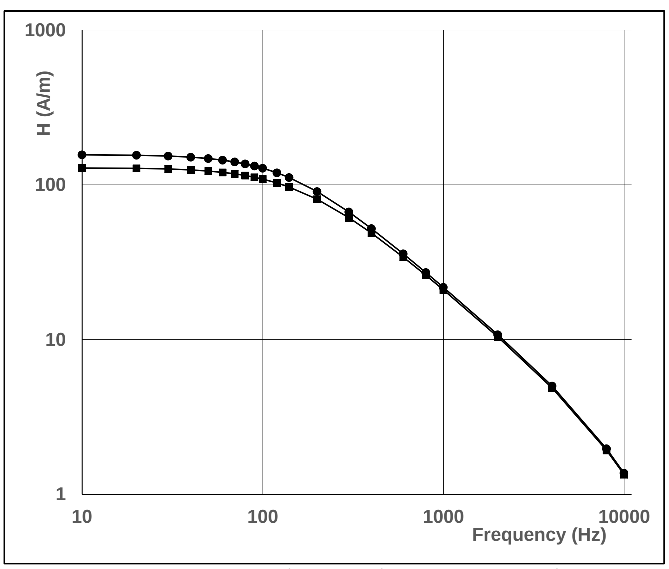

Fig. 1. Frequency dependence of the axial field in the middle of the cylinder (•) and at its ends (x)

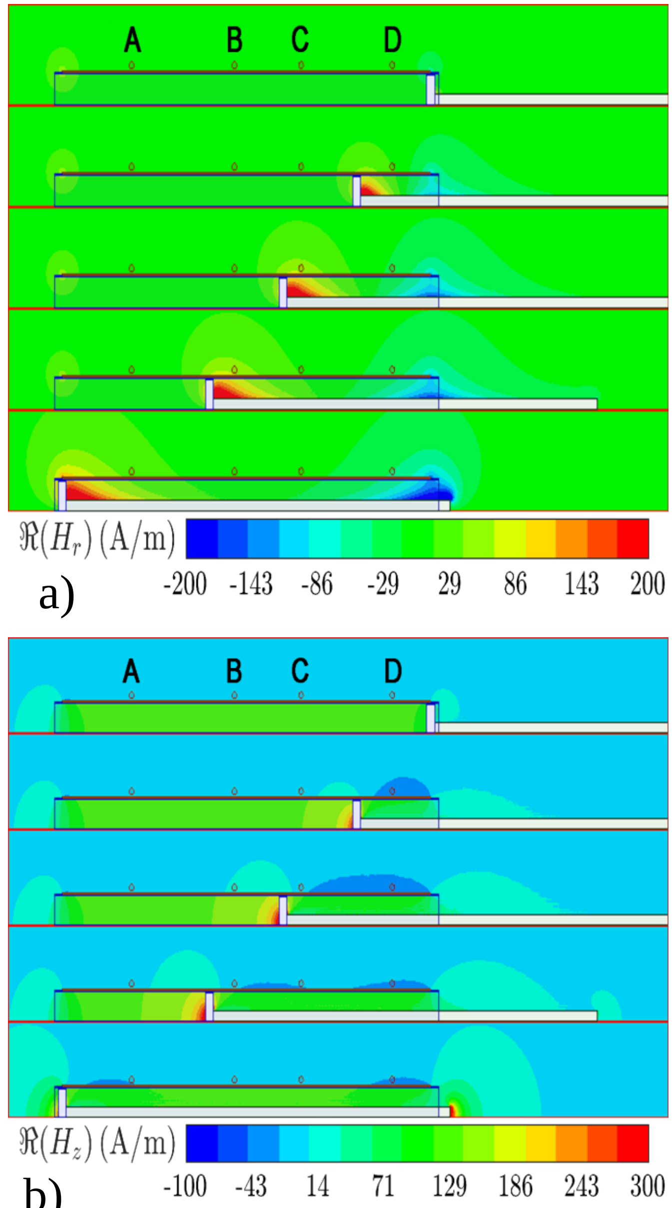

Fig. 2. FEM simulated field for several positions of the piston: a) radial component and b) axial component. The excitation frequency was 2 Hz. The location of the sensors is marked A to D.

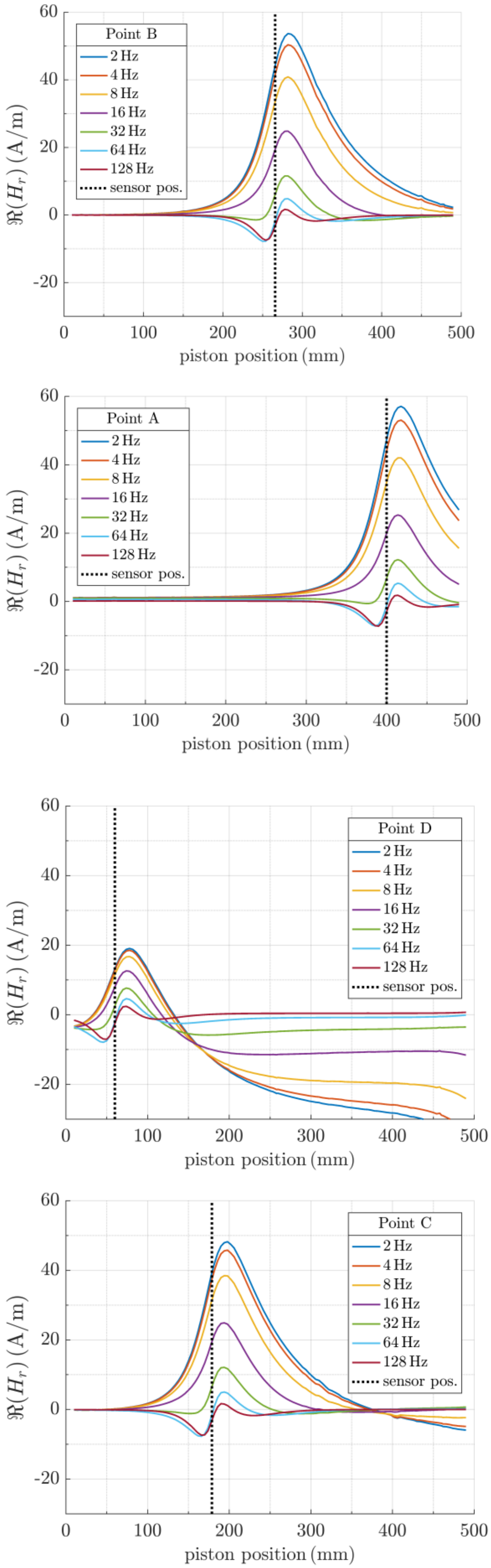

Fig. 3. : The reading of the sensors in positions A, C and D as the function of the piston position (FEM simulation)

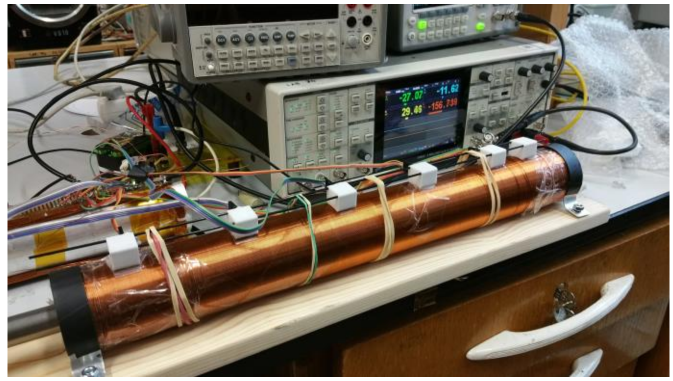

Fig. 4. : The reading of the sensors in positions B and C as the function of the piston position (measured X component)

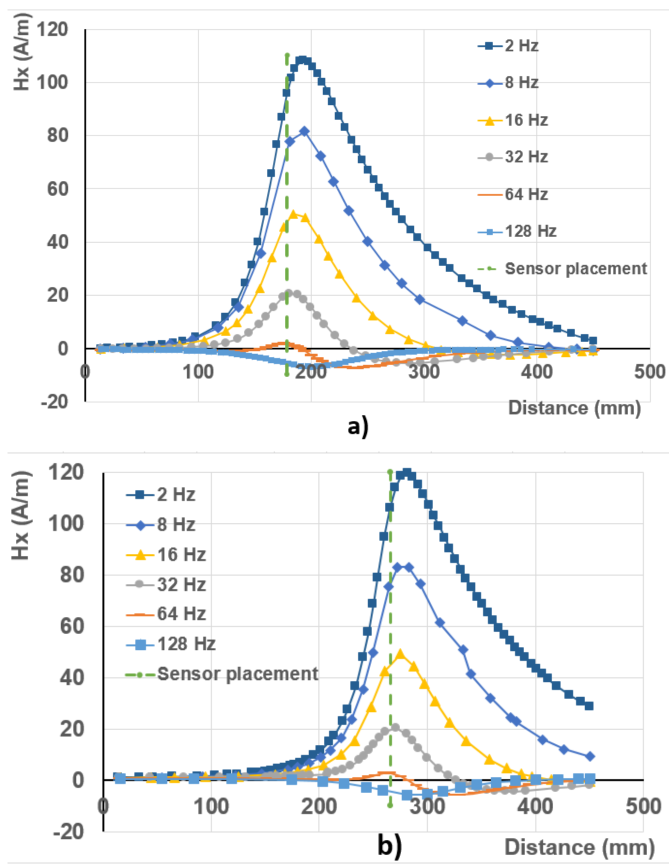

Fig. 5. : The reading of the sensors in positions B and C as the function of the piston position (measured X component)

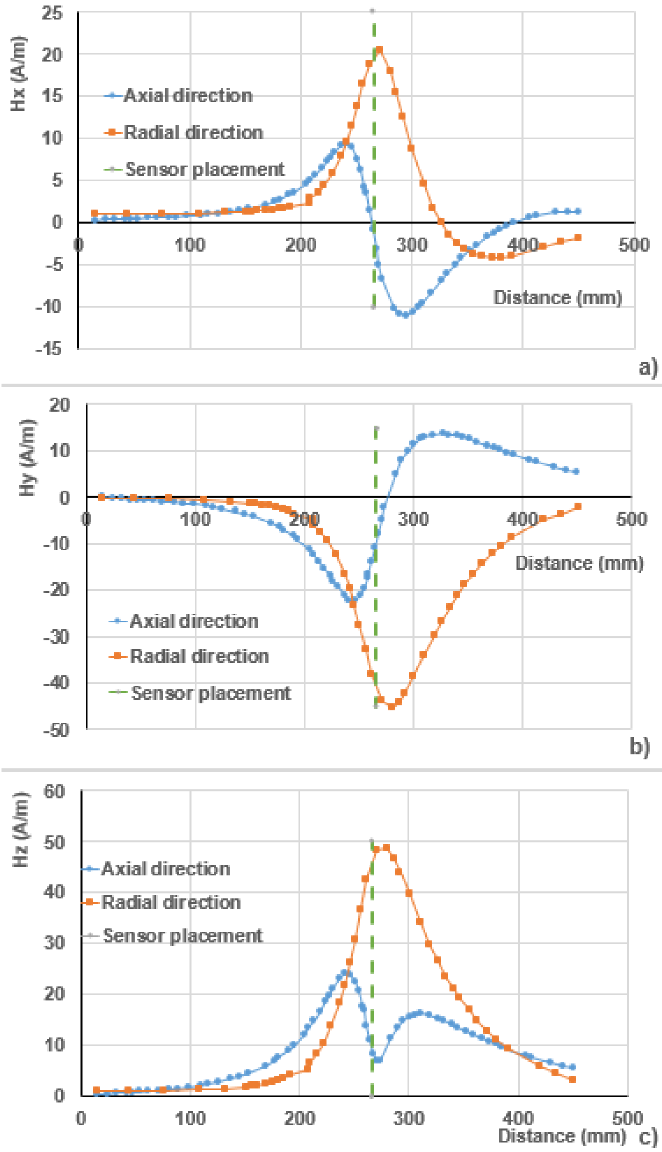

Fig. 6: Axial and radial field for 32 Hz excitation frequency a) X component (in-phase with current), b) Y component, c) modulus