Inductance position sensor for pneumatic cylinder

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Inductance position sensor for pneumatic cylinder

Pavel Ripka,[a] Andrey Chirtsov, Mehran Mirzaei, and Jan Vyhnanek
Faculty of Electrical Engineering, Czech Technical University, Prague 166 27, Czech Republic

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The position of the piston in pneumatic cylinder with aluminum wall can be measured by external inductance sensor without modifications of the aluminum piston and massive iron piston rod. For frequencies below 20 Hz the inductance is increasing with inserting rod due to the rod permeability. This mode has disadvantage of slow response to piston movement and also high temperature sensitivity. At the frequency of 45 Hz the inductance is position independent, as the permeability effect is compensated by the eddy current effect. At higher frequencies eddy current effects in the rod prevail, the inductance is decreasing with inserting rod. In this mode the sensitivity is smaller but the sensor response is fast and temperature stability is better. We show that FEM simulation of this sensor using measured material properties gives accurate results, which is important for the sensor optimization such as designing the winding geometry for the best linearity. https://doi.org/10.1063/1.4993559

I. INTRODUCTION

Measurement of the piston position is required for precise control. Inserting sensors into the piston rod[1] is expensive and brings mechanical problems. Inserting sensors inside the piston brings problem with reliability.[2] The same problem applies for the optical sensors.[2–5] Magnetic scale on the piston rod is only incremental sensor.[6]

External position monitoring is simple and cheap, but the existing solutions are limited to non-magnetic cylinders. For cylinders with composite shell inductance displacement sensor was reported in Ref. 7. For aluminum shell (which is typical for pneumatic cylinders) magnetic sensors are used together with permanent magnet attached to the piston. The position of this permanent magnet is traditionally measured by a linear array of magnetic sensors. More elegant solution is to use magnetostrictive delay line[8] outside the cylinder to precisely measure the magnet attached to the piston. Using the magnetostrictive delay line, position can be measured with extreme precision of 10 µm.[9] However, sensors with permanent magnet have two drawbacks. The first drawback is that sensors with permanent magnet use expensive stainless steel piston rod, which is non-magnetic and does not distort the field from the magnet. Compensating these effects for ferromagnetic rod would be very complex.[10] The second drawback is that the permanent magnet cannot be easily mounded on the piston of existing cylinders.

Using piston remanence instead of permanent magnets[11] is also not a practical solution, as it leads to problems with long-term stability and we do not recommend such approach, as remanence of soft iron changes with time, temperature and magnetic history. The problem with AC methods is that the frequency should be small so that the magnetic field penetrates through the conductive wall. This in general brings problems with the sensor response to fast movements. We recently developed AC contactless piston position transducer with axial excitation and detection of radial magnetic field associated with the end of rod made of magnetically soft iron.[12] The disadvantage of this sensor is its short linear stroke which leads to the necessity of using linear sensor array, making the device rather complicated.

[a]Corresponding author: ripka@fel.cvut.cz

In this paper we return to the simple concept of variable inductance sensor and we show that such sensor can be used to measure position of the piston in pneumatic cylinder with aluminum shell, if position accuracy of 1 mm is acceptable, which is the case for many industrial devices. The inductance of the solenoid wound on top of the cylinder is changing with piston position even though the cylinder is made of conducting material, which partly shields the AC field. While at low frequencies the inductance is increased by inserting the ferromagnetic rod, at high frequencies the effect of eddy currents in the solid rod prevails and the inductance is decreasing. We have studied these dependencies by FEM modelling and verified the simulations by measurement. We also studied the temperature dependence of the sensor output and an influence of the temperature dependence of permeability and conductivity.

II. THE MODEL CYLINDER

The 500 mm model cylinder has 60 mm diameter with 2 mm thick aluminum wall. The aluminum piston is 10 mm thick and it is moved by 20 mm diameter iron piston rod, which is 700 mm long, so that with the piston at the end position still 20 cm of the rod is outside the cylinder. The single-layer solenoid coil has 808 turns is wound directly on top of the cylinder. Its 5 mH inductance at 20 Hz increases with inserted rod by 6 mH. The device is shown in FIG. 1 together with potentiometric positions sensor which was used as position standard for the verification measurements. FIG. 2 shows the rod and piston.

FEM model of the cylinder was built by FEMM software. Due to the rotational symmetry the problem is only two-dimensional and analysis is simple and fast. For the FEM model we measured material characteristics of the used components. The results are in Table I. Electrical conductivity was measured using 4-terminal method with the measuring current of 50 A. The voltage terminals were positioned in the region of homogeneous current density, which was verified by measuring potential at several positions. The effective permeability was measured using the same excitation solenoid: the rod flux Φ_{rod} was measured using 10-turn coil wound on the rod surface. After that the air flux Φ_{air} was measured in the same coil when the rod was removed. The voltages V_{rod} and V_{air} induced into the coil were measured by SR830 Lock-in amplifier using tracking filter setting. The effective permeability was calculated as

$$\mu_{\mathrm{eff}} = \Phi_{\mathrm{rod}}/\Phi_{\mathrm{air}} = V_{\mathrm{rod}}/V_{\mathrm{air}} = 51$$

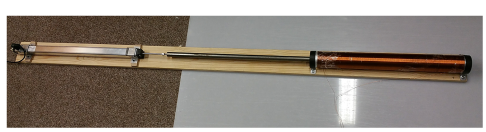

FIG. 1. Model cylinder attached to standard position sensor.

FIG. 2. Piston and piston rod of the model cylinder.

TABLE I. Material parameters for the FEM, model.

rod effective permeability	measured	(-)	51
rod relative permeability	estimated by FEM	(-)	77.5
rod conductivity	measured	(MS/m)	4.45
cylinder conductivity	measured	(MS/m)	30

at 10 Hz. This value is lower than material permeability estimated by FEM, which was 77.5. There are two reasons for this difference: 1. demagnetisation effect, 2. eddy current effect in the solid bar even at the low frequency of 10 Hz.

III. ATTENUATION OF THE EXCITATION FIELD

In order to observe the shielding effect for the excitation field we measured the field in the middle of the cylinder without the piston. The measurement was made using DRV425 microfluxgate sensor manufactured by Texas Instruments. The field versus excitation frequency measured for constant source voltage of 10 V as a function of frequency is shown in FIG. 3. The excitation current is shown in the same figure. It is clear that the 2 mm thick aluminum cylinder barrel has only small attenuation for the frequencies below 100 Hz, where the attenuation is 150/180 = 0.83.

Next step was observation of the effect of eddy currents inside the piston rod. We fully inserted the piston and rod inside the barrel and measured the field inside the rod using induced voltage into the 10-turn coil around the rod. The measured results are shown in FIG. 4 again for constant source voltage of 10 V. Magnetic field inside the bar decreases with frequency much faster than the field in

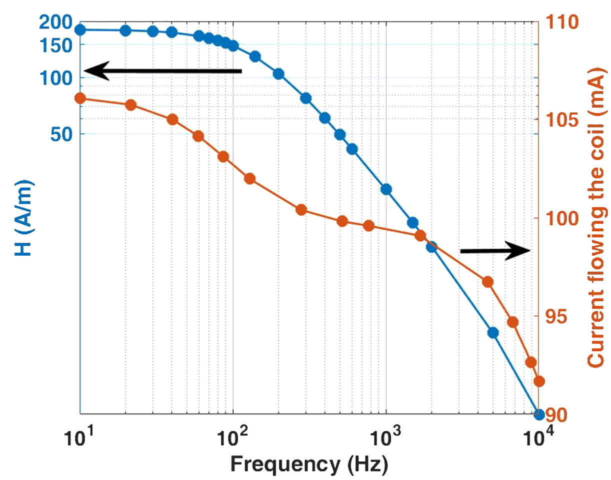

FIG. 3. Field in the center of the cylinder without rod for constant source voltage of 10 V as a function of frequency. Measured values. The DC field was 180.8 A/m.

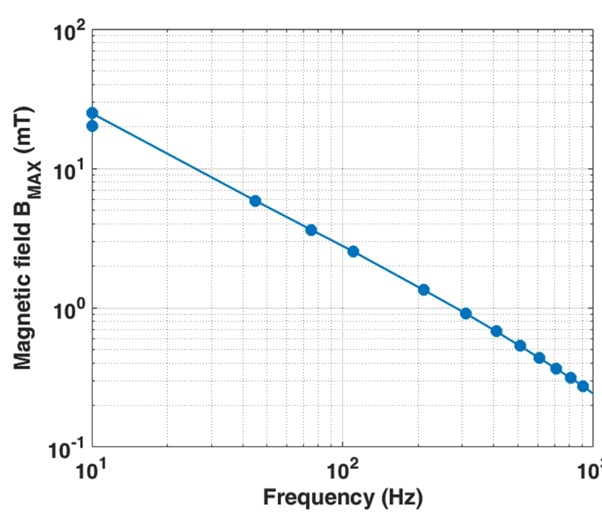

FIG. 4. Field inside the iron rod positioned in the center of the cylinder for constant source voltage of 10 V as a function of frequency. Measured values. The DC field was 180.8 A/m.

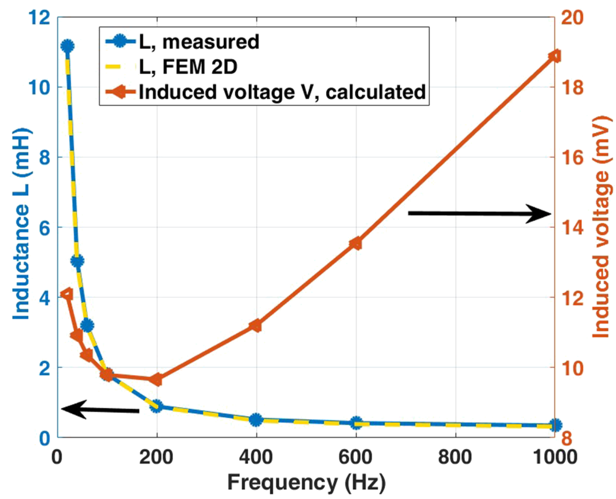

FIG. 5. Piston is completely inside. Dependence of the inductance (measured value) and induced voltage on the excitation frequency for maximum value of the excitation frequency I_m= 8.61 mA.

the air - this shows that the eddy current effect inside the massive rod is much significant than the effect of the eddy currents inside the barrel wall.

Next measurement was the inductance of the coil with fully inserted rod with piston as a function of frequency and amplitude of the measuring current. Rapid inductance decrease with frequency (FIG. 5) is caused by eddy currents in the rod, piston and cylinder wall. However, inductance is not the parameter best describing the performance of the future sensor. The sensor output can be the imaginary part of the voltage across the excitation coil, or voltage induced into the separate sensing winding. The frequency dependence of the induced voltage $2\pi fLI$ drops with frequency less rapidly, as shown in the same FIG. 5. At higher frequencies the induced voltage is even increasing with frequency. This shows that finding optimum excitation parameters is complex task which cannot be solved using just engineering intuition and higher frequencies cannot be taken from the considerations.

IV. VERIFICATION OF THE FEM MODEL

FEM model is relatively simple and it can help in the sensor design. Complicated tasks such as design of non-uniform winding density in order to optimize the sensor linearity cannot be solved experimentally without FEM modelling. FIG. 6 shows frequency dependence of the coil inductance with fully inserted piston. For FEM modelling we used the measured values of conductivity of iron and aluminum. We also found the permeability value of 77.5 giving the best fit between inductance modelling and measurement. This permeability corresponds well with the previously measured value.

We extended the FEM model also to calculate temperature effects. First of all we measured conductivity as a function of frequency and used these values to estimate inductance. TAB. II shows comparison between experimental results and FEM results, which shows well excellent fit (in one piston position).

V. RESPONSE TO MOVING PISTON

The inductance response to piston movement was calculated by FEM at different frequencies and later verified by measurements. Calculated values for low frequencies are shown in FIG. 7 and for the higher frequencies in FIG. 8. Using low frequency brings high sensitivity, but also high temperature dependence and slow response to fast moving piston. At the frequency of 20 Hz the inductance is increasing with piston position towards the end (fully inserted) position.

At the frequency of 45 Hz the inductance is position independent, as the permeability effect is compensated by eddy current effect. At higher frequencies eddy current effects prevail, the

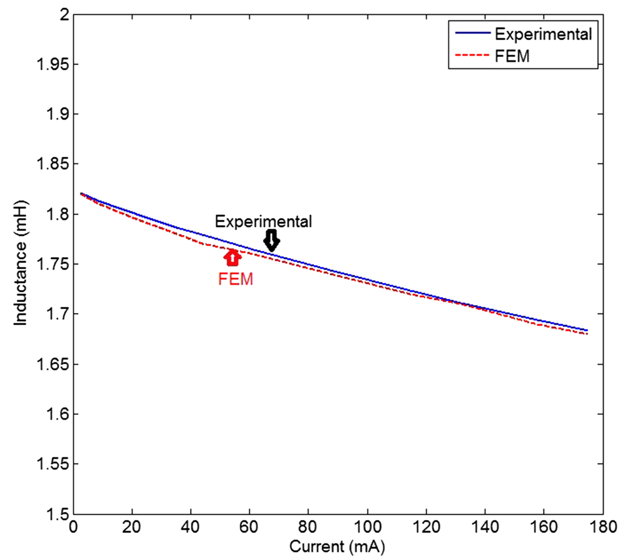

FIG. 6. Piston is completely inside, dependence the inductance on the amplitude of the excitation current through the coil at 100 Hz. The measured and FEM modelled values give the best fit for permeability value of 77.5.

TABLE II. Comparison between experimental results and FEM results for inductances.

		Frequency (Hz)			
		20	60	100	200
Exp.	Room temp.	10.934 (mH)	3.156 (mH)	1.826 (mH)	0.912 (mH)
	47 ^{o}C	11.455 (mH)	3.206 (mH)	1.833 (mH)	0.914 (mH)
FEM	Room temp.	10.780 (mH)	3.163 (mH)	1.814 (mH)	0.890 (mH)
	47 ^{o}C	11.312 (mH)	3.303 (mH)	1.892 (mH)	0.919 (mH)

sensitivity is smaller, but temperature stability is better. For f=100 Hz the inductance decreasing almost linearly with inserting rod. As already mentioned the induced voltages are large enough for precise measurement.

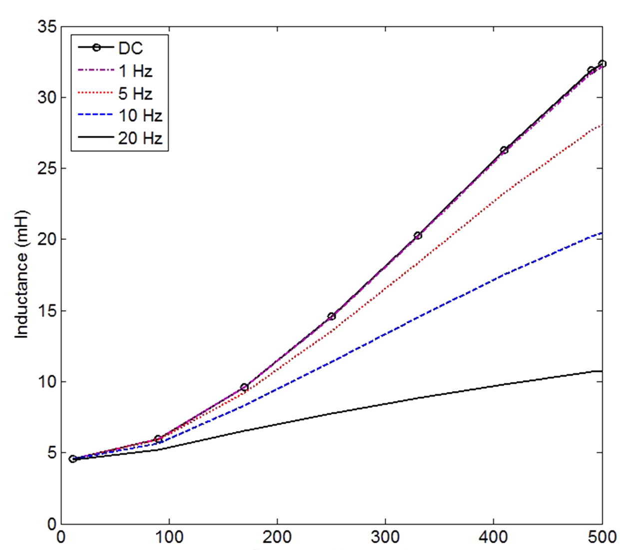

FIG. 7. Inductance vs position for low frequencies - FEM simulation.

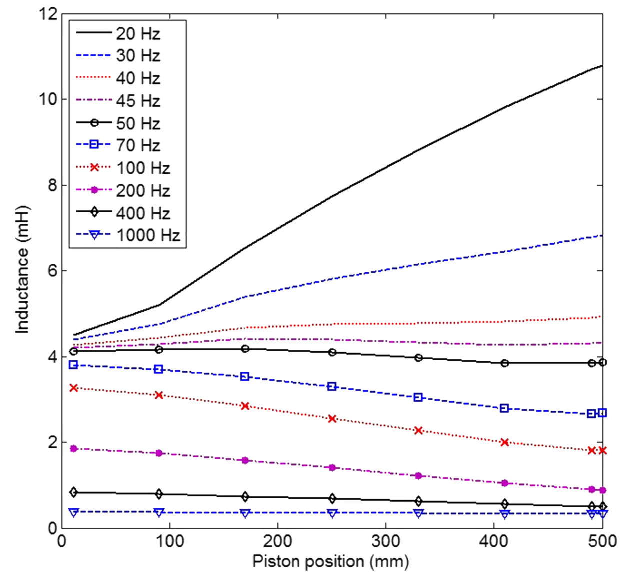

FIG. 8. Inductance vs position for high frequencies – FEM simulation.

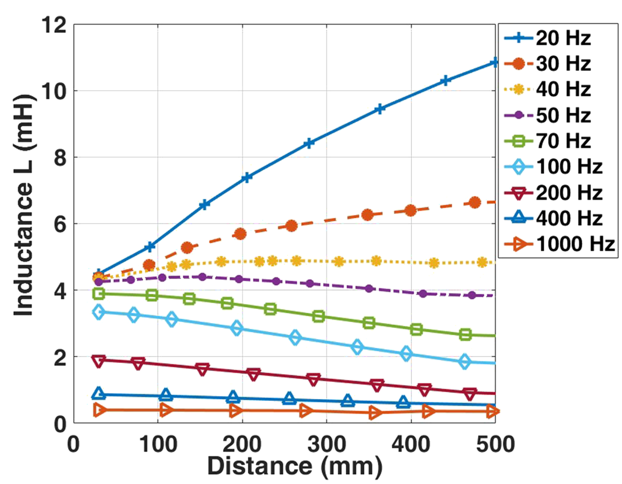

FIG. 9. Measured inductance of the coil (Ls) as the function of the piston position.

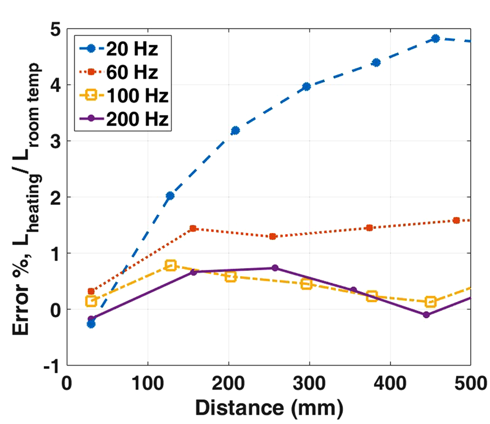

FIG. 10. Error (%) in comparing the coil inductance at a high temperature (47°C) with respect to the usual temperature. L_heating/L_room_temp.

The simulated values shown in FIGs. 7 and 8 predict well the measured characteristics shown in FIG. 9. FIG. 10 shows the results of the preliminary tests at elevated temperature. The best temperature stability (0.02%/K to 0.03%/K depending on the position) was found ad 70 Hz, where the inductance change with position is still 1.5 mH.

VI. CONCLUSIONS

We have developed position sensor for pneumatic cylinder with aluminum wall using solenoid coil on top of the cylinder barrel. For frequencies below 45 Hz the coil inductance is increasing with inserting rod due to the rod permeability. This mode has disadvantage of slow response to piston movement and also high temperature sensitivity. At the frequency of 45 Hz the inductance is position independent, as the permeability effect is compensated by the eddy current effect. At higher frequencies eddy current effects in the rod prevail, the inductance is decreasing with inserting rod. In this mode the sensitivity is smaller but the sensor response is fast and temperature stability is better. We show that simple FEM simulation of this sensor gives excellent fit with the measured results, if we use measured conductivity and estimated permeability. This will allow to use FEM simulation for the optimization of the sensor geometry to improve the linearity and also find ways how to compensate for the temperature dependence. The best temperature stability of 0.03%/K was found at 70 Hz, where the inductance change with position 1.5 mH is still high. We also show that the parameter important for the performance is induced voltage rather than inductance.

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