Sensorless detection of DC motor rotation direction for automotive fuel pump fault diagnosis

GREPL[1], R., VEJLUPEK[1], J., MATEJASKO[1], M., ZOUHAR[2],F.
[1]Mechatronics Laboratory (MechLab),
Faculty of Mechanical Engineering,
Brno University of Technology,
Technicka 2, 616 69, Brno,
CZECH REPUBLIC
[2]UNIS, Mechatronic systems,
Jundrovska 33, 624 00, Brno,
CZECH REPUBLIC

grepl@fme.vutbr.cz http://www.mechlab.cz

Abstract: - This paper deals with the fault diagnosis of a brushed DC motor used as a pump in an automotive fuel module. The jamming, direction of the rotation and the angular velocity are indirectly measured without access to the rotor. Two implemented approaches are presented. The first method uses the FFT analysis of the measured current for the estimation of angular velocity together with the load of the pump using suction. The developed test lasts min. 6 sec. and reliably detects the direction of the rotation. The second method uses a magnetic field sensor for the detection of the rotation direction. Although it provides a simpler setup and a shorter measurement time, it is also more sensitive to noise and the precise positioning of the sensor.

Key-Words: - DC motor diagnosis, automotive production, sensorless motion measurement, application of magnetic field sensor.

1 Introduction

The production of mechatronics parts for the automotive industry is extremely sensitive to faults. The quality goals are defined as several fault pieces per million products with the trend towards a zero-fault strategy.

The modern car consists of dozens of electromechanical actuators, typically brushed or brushless DC motors. Although BLDC are used in some applications [7], brushed DC motors are still much more frequent mainly due to lower cost (of both the power electronics as well as the motor itself) and easier control (especially for position control applications) [5, 8, 9, 10].

This paper deals with the fault diagnosis of the automotive fuel pump with brushed DC motor. The motor is mounted inside the plastic fuel pump module (nr. 23 in Fig. 1) and there is no direct visual or mechanical access to the moving rotor. Due to strict pricing constraints, no velocity and/or position sensor is available.

The aim of the diagnosis is to detect and isolate these main faults at the end of the production process:

- non-rotating (jammed) pump (e.g. piece of material in pump turbine),
- incorrect connection wires soldering (mistake made by human operator)
- damage to the commutator and/or bearings leading to small angular velocity of the motor.

The applicable methods and approaches are limited by requirements such as: low maximal voltage during test, low maximal available time of the test, dry test only and high infallibility of the test. Other important factors are the weight of the complete fuel module which determines the usability of testing using inertial sensors, the material properties and the overall construction of the fuel module.

2 Overview of methods for brushed DC motor movement detection

This section briefly describes the principles of several methods for motion analysis applicable to a DC motor. Next, the following Sec. 3 deals with the implementation of the selected methods into the functional test bench.

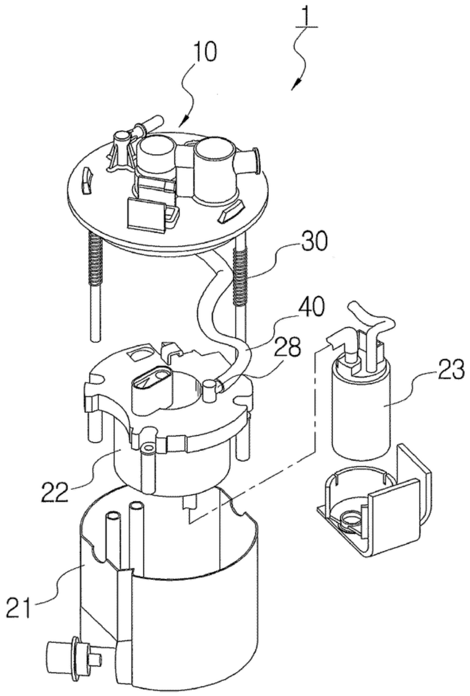

Fig. 1.: Schematics of fuel pump in the module [4]

2.1 Detection of brushed DC motor jamming

The detection of motor rotation can be easily done using just the current sensor.

The standard model of a brushed DC motor consists of two coupled equations (electrical and mechanical):

$$u = L\frac{\mathrm{d}i}{\mathrm{d}t} + Ri + k_{emf}\omega \tag{1}$$

$$J\dot{\omega} = k_{emf}i - b\omega \tag{2}$$

where u is supply voltage, i is electrical current, L is inductance, R is resistance, k_{emf} is speed const., ω is angular velocity, J is inertia of the rotor and b is viscous friction.

Neglecting L, we obtain the static electrical eq.:

$$i = \frac{1}{R}(u - k_{emf}\omega)\,. \tag{3}$$

Obviously, the starting current is equal to $i = u / R$ and thus is higher than the current in steady state rotation of the motor (3) when $\omega>0$. This starting current peak can be easily used for the detection of jamming of the motor.

The influence of the inductance neglected in (3) compared to (1) is shown in Fig. 2.

2.2 Speed measurement using current ripples

During the rotation of a brushed DC motor the commutator switches between the individual coils. This switching causes rippling of the armature current which can be used for speed measurement. Fig. 3 shows an example of typical current ripples measured by hall sensor LEM LTS6NP and the relevant frequency spectrum. The most significant peak at approximately 400Hz corresponds to motor rotational speed multiplied by the number of commutator sections.

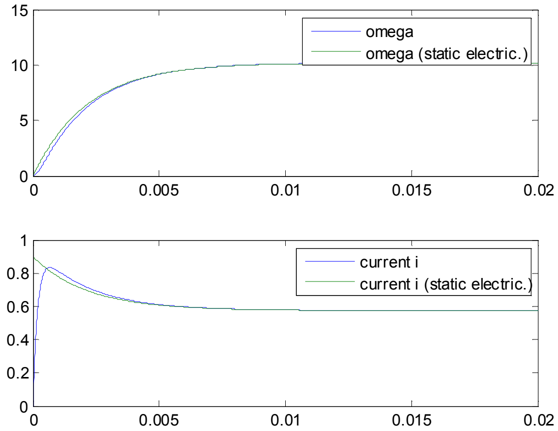

Fig. 2.: Comparison of static and dynamic models of the DC motor (simulation results)

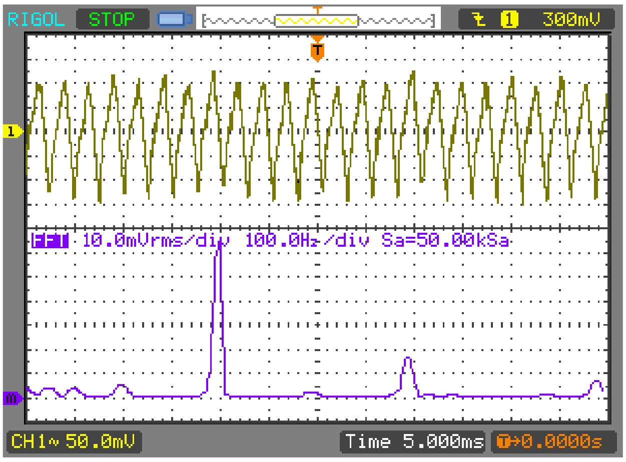

Fig. 3.: Current ripples measured on running fuel pump (Top: 50mV corresponds to approximately 152mA; Bottom: frequency spectrum).

There are many different methods for the estimation of the motor speed based on the measured current [1, 2, 3, 6].

For an offline analysis one of the possible and most straightforward approaches is FFT analysis.

2.3 Pump loading using suction

The rotation direction could be easily detected using the wet test with the fuel or another suitable liquid. However, in production the dry test is usually required. Therefore only compressed air can be used for loading the pump.

The fuel module is equipped with a return valve and thus only the negative pressure (suction) can be used for real testing. The electronically controlled ejector with sufficient capacity can be used for practical implementation.

The air flow generated by the ejector (320 l/min at 5 bars) cannot provide enough power to directly move the rotor of the turbine due to the mechanical friction in the bearings and at the commutator. However, the significant influence of the angular velocity of the motor supplied by constant voltage can be measured.

2.4 Direction detection using hall sensors

Another approach to determine the direction of the DC motor is to measure changes in the magnetic field outside the motor. As these changes are really small (units or tenths of units µT measured at a distance of 20 mm outside the outer diameter of the DC motor pump), a precise analogue hall sensor has to be used.

Such sensors are available as 3-axis magnetometers, usually used as an electronic compass i.e. for mobile devices. Linear hall sensors have already been used as rotary position sensors [11,12,13]. However these sensors usually have lower sensitivity, which makes them almost impossible to use to reliably detect the changes in the magnetic field outside the brushed DC motor.

The MAG3110 high accuracy 3-D magnetometer has been used in the presented experiments.

Fig. 4.: shows six pairs of changes in the magnetic field. Zero is the relative value taken before starting the motor. The slight differences between the values in the same directions are due to the sensor magnetisation induced by the magnetic field of the motor.

The difference between the vector orientation of DIR- and DIR+ is significant enough to determine the direction of the motor.

3 Implementation and results

The implementation of two different approaches for the detection of direction is presented in this section. Both were implemented using Rapid Control Prototyping techniques with the use of a dsPIC microcontroller [5].

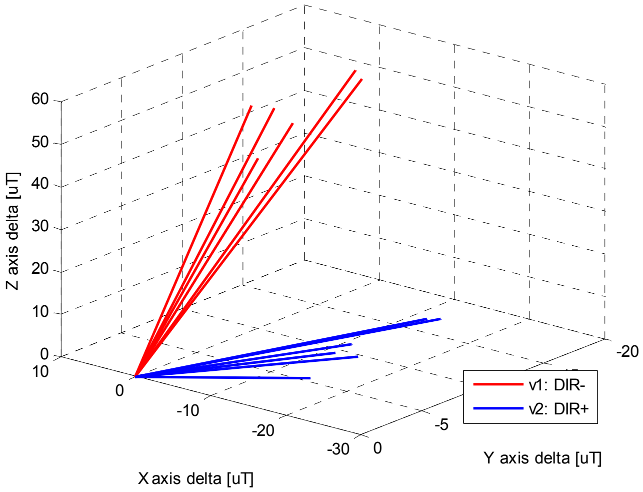

Fig. 4.: Changes in the magnetic field: six different measurement runs; each run goes in both directions

3.1 Speed measurement with suction

The first approach combines speed estimation using FFT analysis of the measured current (Sec. 2.2) with the load of the pump using negative pressure (Sec. 2.3).

Because of the requirement of a dry test, the duration of the test must be minimized and also the applied voltage must be as low as possible to avoid damage to the pump under testing. Furthermore, the supply voltage should be switched using relays with optical isolation for the minimization of switching losses.

The test consists of the following steps:

1) Activation of the ejector – the setting of stable negative pressure requires about 2 sec.
2) Rotation one direction (1 sec.).
3) Rotation with reverse direction (1 sec.).
4) Deactivation of the ejector (pressure returns to zero immediately).
5) Rotation both directions without neg. pressure.

The corresponding measurement of the armature current is shown in Fig. 5.

Next, the analysis of the data is performed in these steps:

- detection of the jamming (see Sec. 2.1)
- FFT analysis of four parts of the measured signal and determination of the velocity

- comparison of the four velocities – there are several options how to construct the logical condition for direction detection, after some experiments the following form is used: $(v1>v3)$ & $(v4>v2)$.

The resulting implementation was tested on several different fuel pump modules with very satisfactory results.

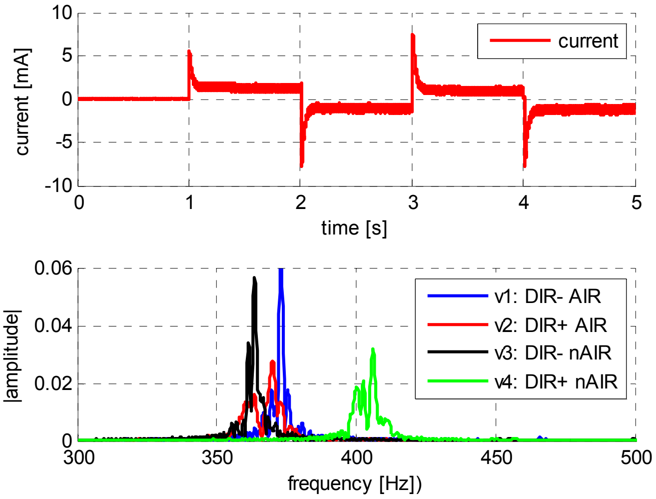

Fig. 5.: Top: Current signal; Bottom: Frequency spectrum of the current ripples.

3.2 Detection of rotation direction using hall sensor

The second approach uses the hall sensors only (Sec. 2.4).

The hall sensor is connected to the dsPIC microcontroller via an I2C bus. Data from the magnetometer is acquired at the rate of 80Hz in all three axes and sent to a PC via a UART-to-USB converter.

The test consists of the followings steps:

1) Sensor activation, steady state measurement. (t = 0..1s)
2) Rotation in one direction. (t = 1..2s)
3) Pause. (t = 2..3s)
4) Rotation in opposite direction. (t = 3..4s)
5) Data analysis.

An example of the measured data is shown in Fig. 6. Note that the values in step 3) are not equal to the initial step 1) due to magnetization of the sensor and motor housing.

This clearly demonstrates that only a relative change of the magnetic field can be used for the detection of the rotation direction.

Therefore the analysis of the measured data compares only the peaks after the start of the motor.

For the correct rotation direction, the following condition must be met:
$(p1X > pX0)$ & $(p3X < pX0)$,
where pX0 is the threshold value for the peak detection and p1X, p3X are peak values in $t=1/3$ sec.

Similar conditions can be found for the Y and Z axis and combined together according to the actual positioning of the sensor.

The final implementation was tested on several different fuel pump modules and has proven to be reliable.

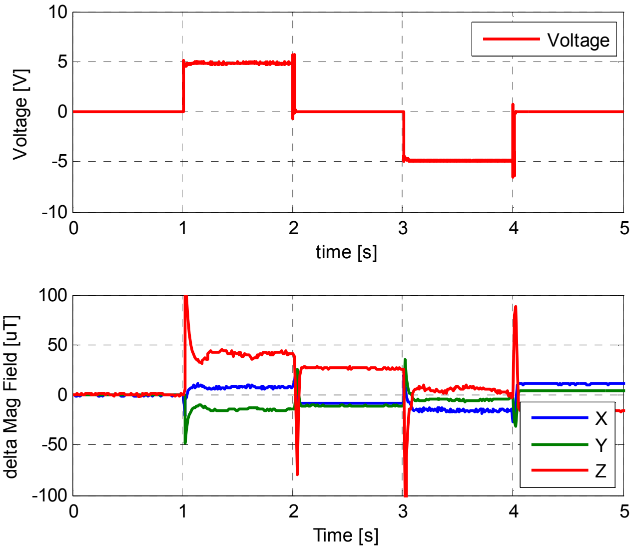

Fig. 6.: Changes in the magnetic field: TOP: motor voltage; BOTTOM: magnetic field components.

4 Conclusion

Two approaches for the detection of the rotation direction of a brushed DC motor are presented in this paper. Both were practically implemented and verified on a test bench using RCP techniques.

The first one requires a source of compressed air and needs at least 6 sec. of pump running and measurement.

The second approach allows a significant decrease in the measurement time but is more sensitive to electromagnetic disturbances, measurement noise and also the positioning of the sensor relative to DC motor.

The combination of the two presented techniques can lead to a more robust and reliable solution for a brushed DC pump fault diagnosis.

Acknowledgement:
This work was supported by the BUT grant FSI-S-11-15 "Design, testing and implementation of control algorithms with use of nonlinear models of mechatronics systems" and project ESPOSA, NO. ACP1-GA-2011-284859.

References:

[1] Schneider, P. K., Canales, S. A., System and method for determining position or speed of a commutated DC motor with error correction, U.S. patent nr.: 20090254300

[2] Ramli, R.M.; Mikami, N.; Takahashi, H.; , "Adaptive filters for rotational speed estimation of a sensorless DC motor with brushes," Information Sciences Signal Processing and their Applications (ISSPA), 2010 10th International Conference on , vol., no., pp.562-565, 10-13 May 2010,
doi:10.1109/ISSPA.2010.5605587

[3] Vazquez-Sanchez, E.; Gomez-Gil, J.; Gamazo-Real, J.C.; Diez-Higuera, J.F.; , "A New Method for Sensorless Estimation of the Speed and Position in Brushed DC Motors Using Support Vector Machines," Industrial Electronics, IEEE Transactions on , vol.59, no.3, pp.1397-1408, March 2012
doi: 10.1109/TIE.2011.2161651

[4] Lim, J.K., Sohn, I.S., Kim, O.S., Kim, J.S., Fuel Pump Module, patent app. nr. 20110168134,
http://www.faqs.org/patents/app/20110168134

[5] Grepl, R. Real-Time Control Prototyping in MATLAB/Simulink: review of tools for research and education in mechatronics IEEE International Conference on Mechatronics (ICM 2011-13-15 April, 2011, Istanbul), 2011

[6] Glowacz, Z.; Zdrojewski, A.; , "Diagnostics of Commutator DC Motor Basing on Spectral Analysis of Signals," Diagnostics for Electric Machines, Power Electronics and Drives, 2007. SDEMPED 2007. IEEE International Symposium on , vol., no., pp.497-500, 6-8 Sept. 2007,
doi:10.1109/DEMPED.2007.4393144

[7] Jianwen Shao; Nolan, D.; Teissier, M.; Swanson, D.; , "A novel sensorless brushless DC (BLDC) motor drive for automotive fuel pumps," Power Electronics in Transportation, 2002 , vol., no., pp.53-59, 24-25 Oct. 2002
doi: 10.1109/PET.2002.1185550

[8] Grepl, R., Lee, B., Modeling, parameter estimation and nonlinear control of automotive electronic throttle using a Rapid-Control Prototyping technique, *Int. J. of Automotive Technology,* 2010, Volume 11, Number 4, pp. 601-610

[9] Grepl, R., Composite Controller for Electronic Automotive Throttle with Self-Tuning Friction Compensator, Recent Advances in Mechatronics, 2011, Springer

[10] Grepl, R., Adaptive Composite Control of ET using Local Learning Method, IEEE International Symposium on Industrial Electronics, Bari, Italy, 2010

[11] Wegener, R.; Senicar, F.; Junge, C.; Soter, S.; , "Low Cost Position Sensor for Permanent Magnet Linear Drive," Power Electronics and Drive Systems, 2007. PEDS '07. 7th International Conference on , vol., no., pp.1367-1371, 27-30 Nov. 2007
doi:10.1109/PEDS.2007.4487882

[12] Racz, R.; Schott, C.; Huber, S.; , "Electronic compass sensor," Sensors, 2004. Proceedings of IEEE , vol., no., pp. 1446- 1449 vol.3, 24-27 Oct. 2004
doi: 10.1109/ICSENS.2004.1426458

[13] Jianhui Hu; Jibin Zou; Fei Xu; Yong Li; Yanchao Fu; , "An Improved PMSM Rotor Position Sensor Based on Linear Hall Sensors," Magnetics, IEEE Transactions on , vol.48, no.11, pp.3591-3594, Nov. 2012
doi: 10.1109/TMAG.2012.2202279