Automotive fuel pump fault detection based on current ripple FFT and changes in magnetic field

Vejlupek J., Grepl R., Matejasko M., Zouhar F.

Abstract— This paper presents the approach for the testing of the automotive fuel pump with DC motor. Several faults such as pump jamming, incorrect soldering and/or damage to the commutator can occur due to incorrect manufacture processes. The proposed methods are based on current and magnetic field measurements and subsequent signal processing. The range checking, FFT analysis of the current ripples and change detection are combined to reach the correct and robust fault detection. During the test, the pump is optionally loaded using air suction applied to pump outlet. The implementation of developed algorithms suitable for the production line is also presented.

Keywords— application of magnetic field sensor, automotive production, DC motor diagnosis, sensorless motion measurement.

I. Introduction

THE production of mechatronics parts for the automotive industry is extremely sensitive to faults [14, 15, 18]. 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, 20].

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:

1. non-rotating (jammed) pump (e.g. piece of material in pump turbine)
2. incorrect connection wires soldering (mistake made by human operator)
3. 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.

II. 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 Chapter III deals with the implementation of the selected methods into the functional test bench.

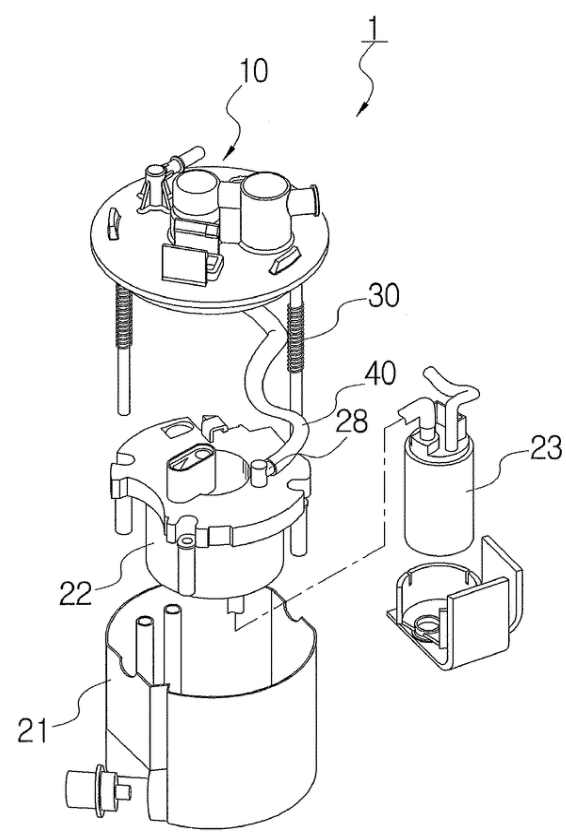

Fig. 1.: Schematics of fuel pump in the module [4]

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A. *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):

$$u = L\frac{\mathrm{d}i}{\mathrm{d}t} + Ri + k_{emf}\,\omega \qquad (1)$$

$$J\dot{\omega} = k_{emf}\,i - b\omega \qquad (2)$$

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.:

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

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 ω>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.

B. *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.

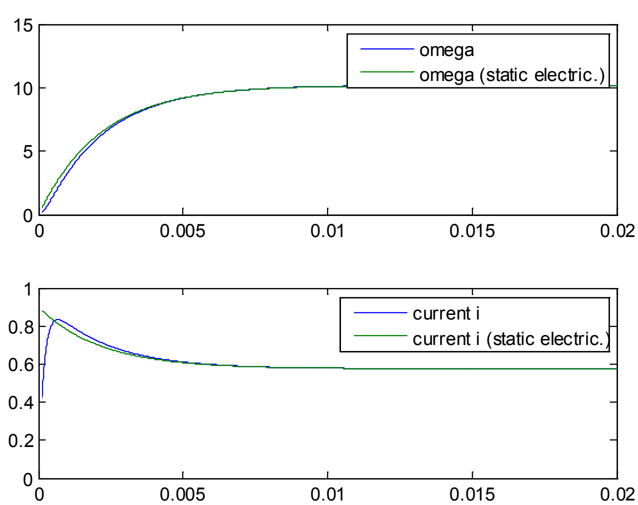

Fig. 2.: Comparison of static and dynamic models of the DC motor (simulation results)

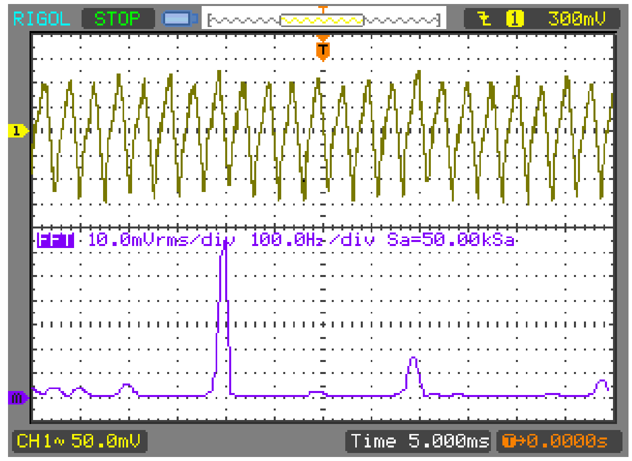

Fig. 3.: Current ripples measured on running fuel pump (Top: 50mV corresponds to approximately 152mA; Bottom: frequency spectrum).

(3) 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.

C. *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.

D. *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 [11,12,13,16,17]. 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 magnetization 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.

Sensor	Sensitivity	Range
HAL401	48.5 mV/mT	+-100 mT
SS496A	1 mV/mT	+- 75 mT
A1301	2.5 mV/mT	+- 80 mT
A1302	13 mV/mT	+-150 mT
ML90215	5-140mV/mT	+-450 mT
ML91207	15-40mV/mT	+-450 mT
MAG3110	10 bit/µT (digital res.)	+- 1000 µT

TABLE I. – MAGNETIC FIELD SENSORS – COMPARISON

TABLE I. shows comparison of several hall-effect based sensors available on the market. There are basically two categories: linear (intensity output), and threshold (on/off). To measure the magnetic field, we need linear sensor. But the initial experiments with HAL401 shown, that the changes are really small, we have searched further for more sensitive device, which we found as an electronic compass. This device is usually found in UAV navigation modules, smartphones etc. To compare the sensitivity, we can take the HAL401 and assume 10V 16-bit ADC, which would give us resolution about 152 µV/bit. Dividing the HAL401 sensitivity 48.5 mV/mT by the ADC resolution 0.152 mV/bit we get the overall resolution of about 0.319 bit/µT. That is about 3 to 4 orders lower resolution compared to electronic compass MAG3110. For illustration, the total intensity of Earth magnetic field above surface ranges from 20 to 70 micro Tesla.

III. 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].

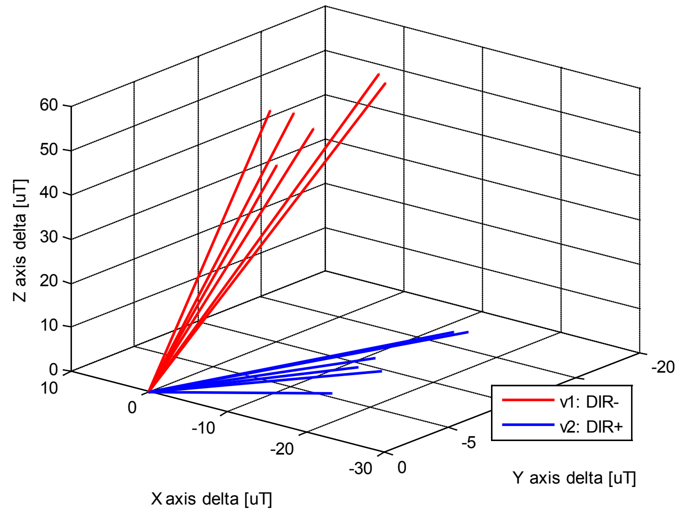

Fig. 4.: Changes in the magnetic field: six different measurement runs; each run goes in both directions

A. 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:

1. detection of the jamming (see Sec. 2.1)
2. FFT analysis of four parts of the measured signal and determination of the velocity
3. 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).

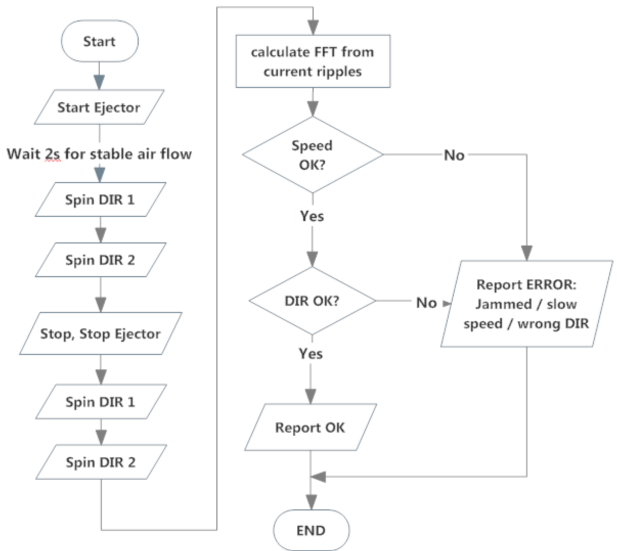

Fig. 5.: Algorithm functional diagram

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

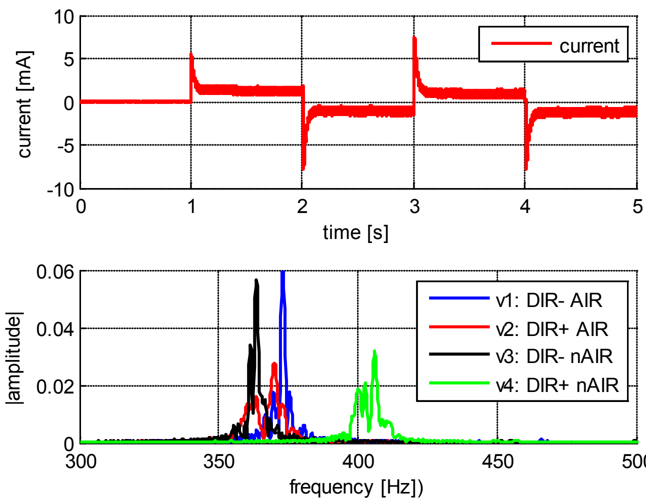

Fig. 6.: Top: Current signal; Bottom: Frequency spectrum of the current ripples.

At the moment, this application is implemented on PC using LabView and USB NI-6351 for the data acquisition and HW control. Custom electronic was designed and manufactured.

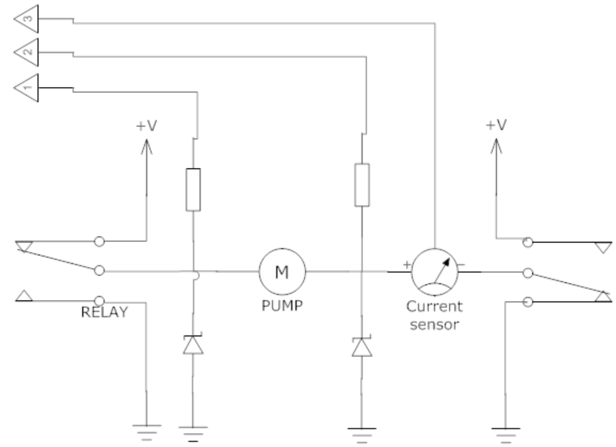

Fig. 7.: Schematics for the testing device

Fig. 8. shows the schematic for the testing device: In the middle, there is the DC motor – PUMP. Instead of using H-bridge, we are using relays. We are also measuring the voltage on the motor as we had an idea to use the voltage generated from spin-down with and without air loading to determine the direction of rotation, but this does not work as the dry pump stopping time after power down is very short and the difference is negligible, variable and therefore unreliable. Current is being measured by current transducer LEM LST-6NP with analogue voltage output. The whole system scheme is shown in Fig. 9.

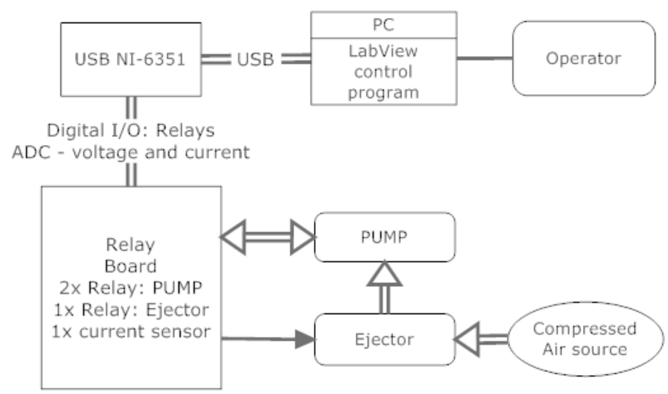

Fig. 8.: Schematics of the device used for testing the jamming and direction of rotation based on the current ripples FFT combined with air suction loading.

B. 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.

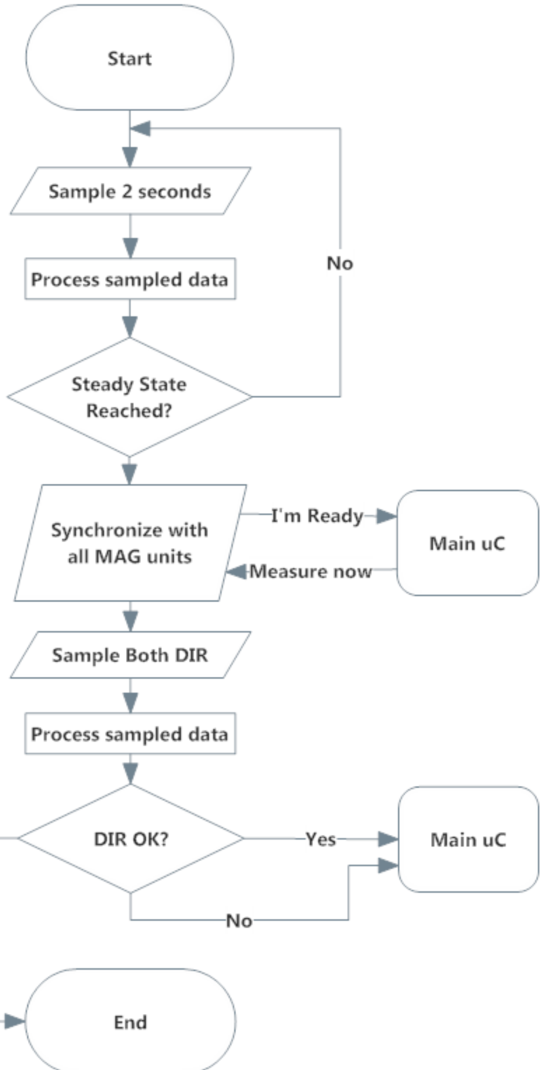

Fig. 9.: Diagram describing implementation of algorithm for direction detection using the electronic compass (MAG3110)

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.

Block diagram of the algorithm is shown in Fig. 10. (There is synchronization with Main uC, which applies to the multi-sensor arrangement presented below in III-C).

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.

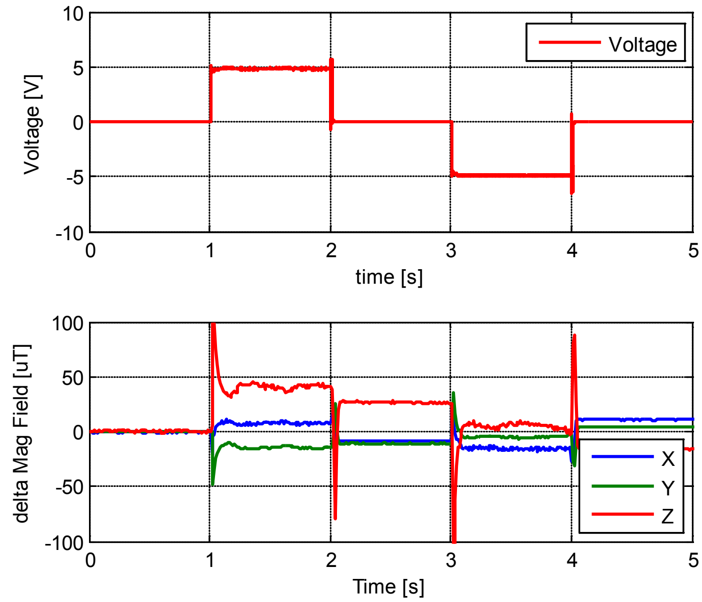

Fig. 10.: Changes in the magnetic field: TOP: motor voltage; BOTTOM: magnetic field components.

C. Embedded implementation of the method using suction and FFT

Current high level implementation was done in LabView, which is very convenient way to rapid control prototyping, as it is very fast and easy to produce, however it requires a PC. This is suitable for quality test lab, but not for the production line. For this reason, the next step is embedded device, which may be inserted simply into the production line to test all manufactured pieces. We have proposed an embedded solution based on microcontroller, which basically replaces the PC with NI-6351. Algorithm is being implemented using RCP [5] in MATLAB Simulink together with Kerhuels Blockset.

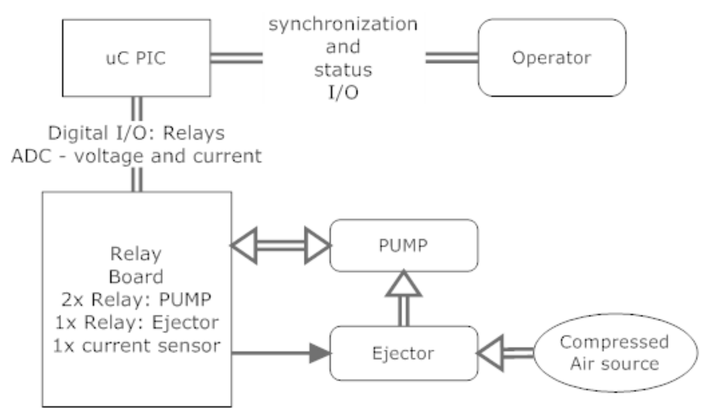

Fig. 11.: Schematics of the proposed embedded device for the suction loading / FFT method

Schematics of the proposed embedded device are shown in Fig. 16., device is embedded, but it still need some configuration from line operator to determine the acceptable performance parameters for the type of pump under test.

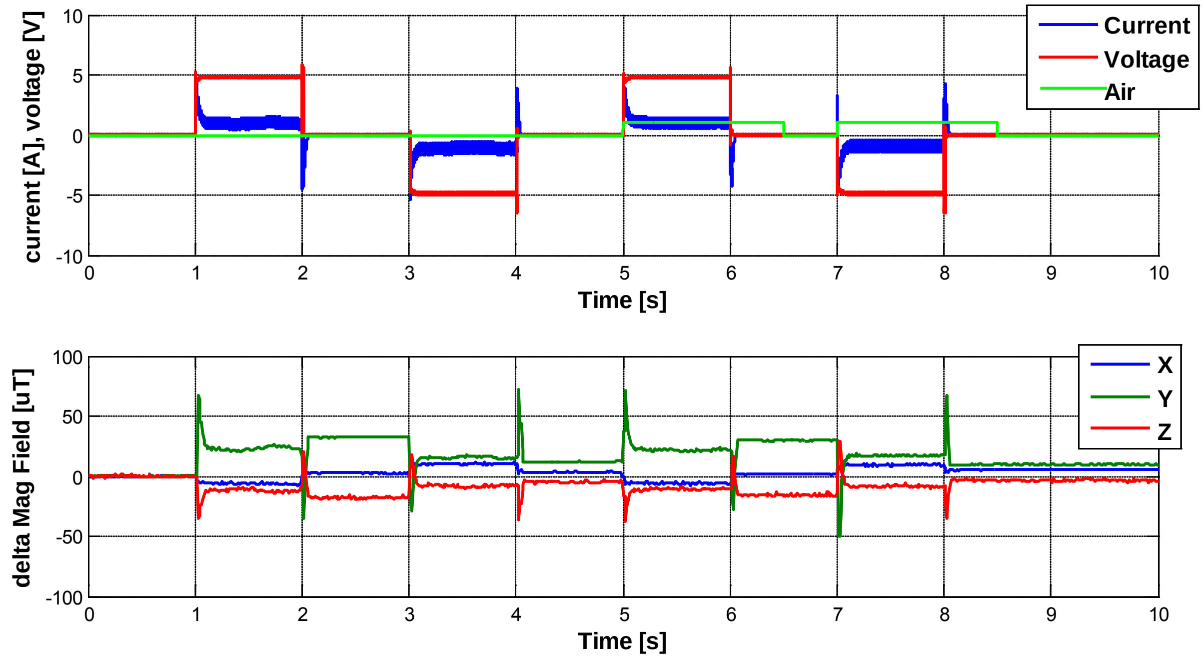

Fig. 12.: Changes in magnetic field and relation to the current

Fig. 13.: Completed device used for FFT / Air load tests

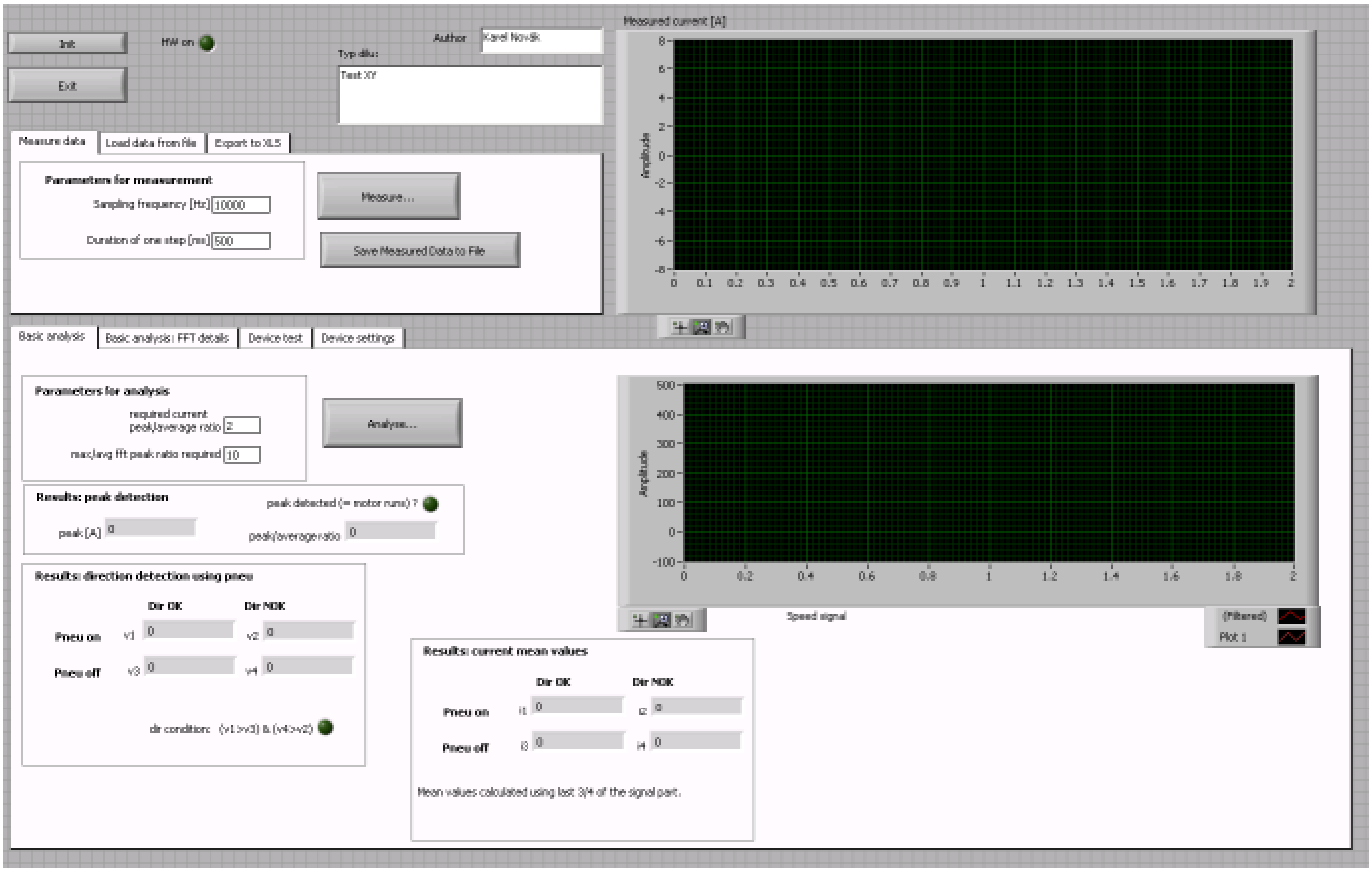

Fig. 14.: LabView application for FFT / Air load tests front panel

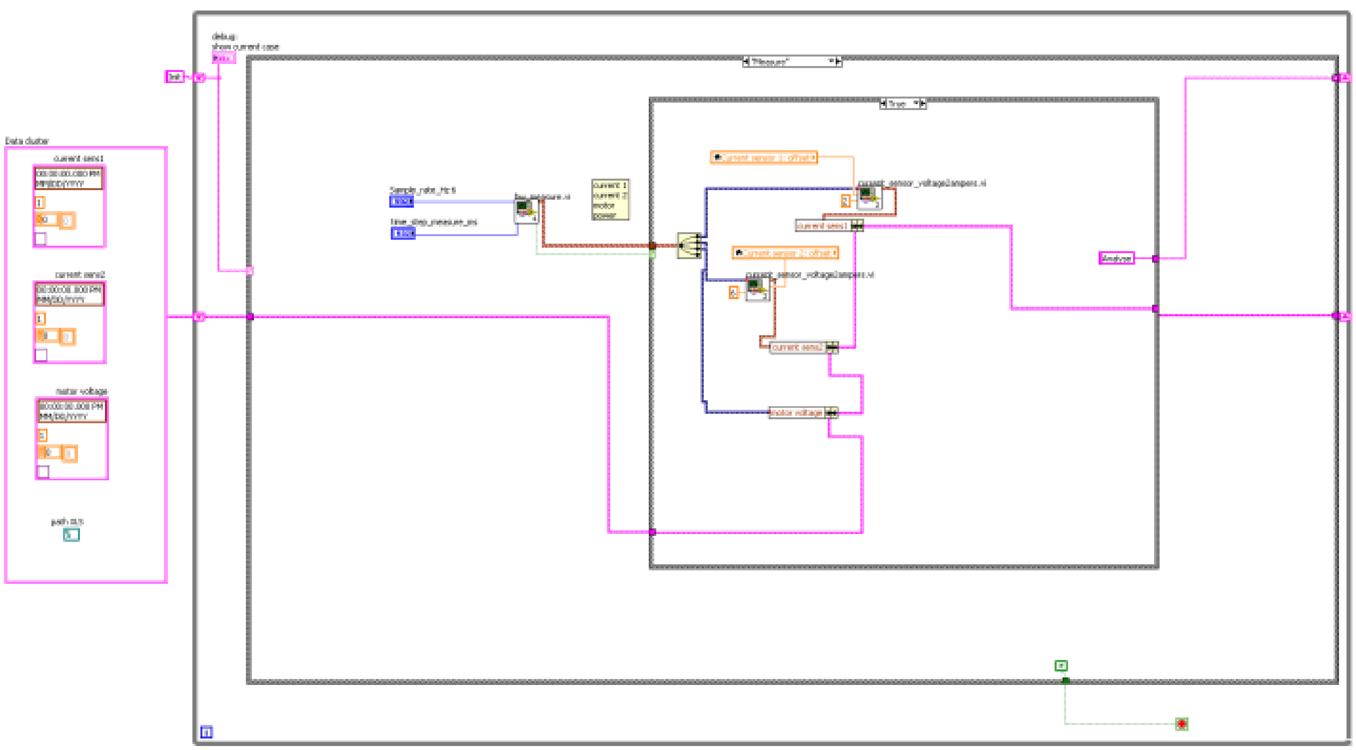

Fig. 15.: LabView application for FFT / Air load tests block diagram – Measure state (program is implemented as a state machine)

Also the line worker will be still required to connect and disconnect the pump to air ejector and Relay Board pump connector.

A. *Robust embedded implementation of the method using hall sensor*

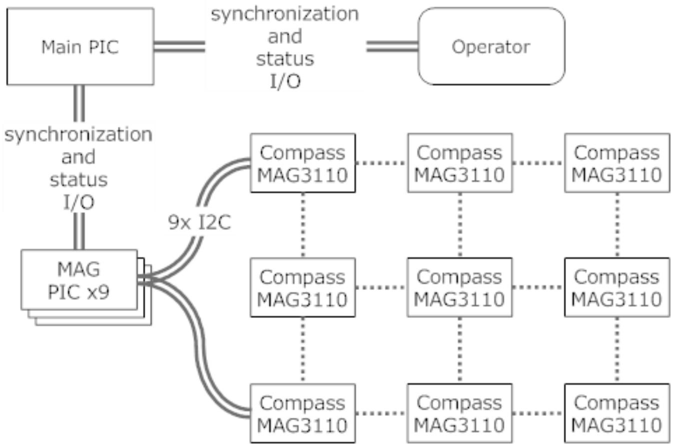

Fig. 16.: Schematics of the proposed device used for testing the direction of rotation based on changes in magnetic field

As the method proposed in section III-B has proven to be working, there is a request from our automotive partner to implement this method into embedded device and to make it more robust by using multiple sensors placed in matrix. As there are no electronic compasses with programmable I2C bus addresses, we had to use separate I2C busses and therefore we have decided to build the device with multiple microcontrollers, where one is in charge of synchronization and operator / line interaction, and other nine microcontrollers are just for I2C communication with electronic compass and data processing. As this may seem to be wasteful solution in terms of resources, its main merits are: easiness of implementation, scalability and variability. Algorithm presented in Fig. 10. still applies, and it is implemented on each of the nine “MAG PICs”. Synchronization signals with the main microcontroller are indicated.

Further experiments with the alignment of the sensor and pump have proven the relation between the current flowing into the pump and the changes in the magnetic field outside the pump.

In Fig. 12, relation between the current and direction of rotation is shown: most significant is the Y axes, where the change in Magnetic field is very similar to the current flowing through the pump.

IV. 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 approach 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 pumps fault diagnosis.

For both approaches, there is a proposed embedded solution. Further work will combine these two solutions in one embedded device performing both approaches.

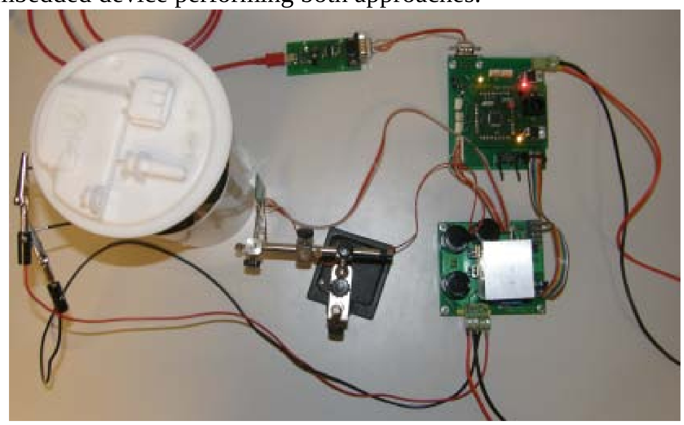

Fig. 17.: Embedded implementation prototype with one magnetometer: From the left: Fuel pump, holder with electronic compass MAG3110, Top right: microcontroller board + FTDI RS232-USB converter, bottom right: H-bridge

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