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ANALYSIS OF THE CHARACTERISTICS OF AUTOMOTIVE MASS AIR FLOW SENSORS

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ABSTRACT: *An analysis of the characteristics of automotive mass air flow sensors is made. A test system has been developed to study the sensors. The measurement data is processed with MATLAB using curve fitting.*

KEY WORDS: *Mass air flow meter, Hot film mass (HFM) sensor, Engine Control Unit (ECU), characteristic, curve fitting, polynomial, voltage.*

1. Introduction

The mass airflow sensor is designed to measure the air mass and temperature of the intake air in motor vehicles with diesel and gasoline applications. The sensor measures the actual air mass flow rate for an optimized air-fuel mixture, supporting an efficient fuel combustion, low exhaust emissions and powerful engine performance.

The standard mass airflow sensor consists of a plug-in sensor and cylindrical housing. The electronic module, with the evaluation circuit and the sensor element, is located in the plug-in sensor.

The sensor element contains a film-like heating resistor and electronic components. The sensor element protrudes into the air flow and is cooled by the air flowing past. The sensor element is supplied with a stabilized voltage of 5 V from the ECU. The temperature of the heating resistor is controlled by an electronic circuit located in the plug-in sensor and powered by the car battery (+12 V). If the sensor element is cooled, the current for the heating process increases. The evaluation electronics in the sensor converts the heating current into an analog voltage signal and sends it to the engine control unit. Some newer models of mass air flow meters use digital interface (frequency or data output) instead of analogue voltage [5]. The described construction is also known as Hot Film Mass (HFM) sensor. Only a portion of the air mass flow is registered by the sensor element. The total air mass that flows through the measuring tube is determined by means of calibration, known as the characteristic curve definition.

Hot film air mass meters are very sensitive components. The sensitive surface of the HFM is gradually destroyed by dirt particles in the air being sucked in. Due to the intake paths being partially unfavorable, the measuring surface also comes into contact with water when it rains.

Diffusing gases (from the crankshaft ventilation system) after the engine has been switched off also damage the measuring sensors [7].

HFM sensors rarely fail completely. In most cases, they measure an incorrect air mass value due to a layer of dirt on the sensor element, which inevitably leads to driving problems. Such an error is usually noticeable through poor performance, but only from a certain speed (from 2000 rpm for diesel engine).

Due to the contamination of the measuring sensors, the heating element is no longer cooled sufficiently by the air flowing past, so not much power is needed to heat it up, but it is precisely this power that is crucial for load detection: a lot of air drawn in, strong cooling, a lot of power to heat it up, a lot of power means high injection quantities are possible.

Unfortunately, little can be done against graduate HFM sensor failure.

During maintenance work, special care must be taken to ensure that air filter elements of original equipment manufacturer quality are used. All air ducts must be absolutely tight and the air filter housing is carefully cleaned with a lint-free cloth (not compressed air). If there is any suspicion that moisture is being sucked in, all air passages must also be carefully examined.

Cleaning the HFM with brake cleaner is only successful for a short time. Although some of the deposits on the sensor plate come off, the cleaner itself damages the HFM sensor and the areas on the sensor plate that are damaged by particles remain. Using compressed air to clean the sensor element also causes its damage.

In most cases HFM sensor changes its characteristics over time, but the output voltage remains within limits between 0.5 V and 4.5 V and ECU does not recognize any fault. If the voltage is outside the limits of 0.5 ÷ 4.5 V, the ECU stores a fault code in its memory, sends a command to the instrument cluster to light up the “Check Engine” light and calculates a replacement value, This “emergency function” is so well coordinated that it is difficult to recognize by changes in the running behavior of the engine.

2. Testing and measurements

The approximate condition of the sensor can be estimated by measuring its output voltage with a digital voltmeter. The voltage at so-called zero air measurement, should be between 0.98 V and 1.02 V. If this value is missed, even just a little, the meter is defective and must be replaced [7].

This measurement is only possible when the meter electronics is powered and the engine not running. Some cars do not supply power to the sensor when the engine is not running and the sensor cannot be tested on the car.

In our case the original sensor of the car BOSCH 0 281 002 461 (HFM-5) was not fully damaged and it was decided to clean it with a special Air Mass Sensor Cleaner. After the cleaning, the sensor was damaged completely and the voltage at its output was close to zero. The damaged sensor had to be replaced.

Unfortunately, the original part was no longer manufactured by BOSCH [2] and the replacement part 0 281 006 759 (HFM-7-R5) was at high price. It was decided to buy an analogue part from another manufacturer. At that time more than 10 sensors from different manufacturers were available. Most of the manufacturers offered only the sensor element without the housing and it was needed a set of 5-point “Torx” security bits to replace the element. A sensor NTK 91609 was obtained and was installed in the original housing. The result was an unsatisfying handling of the vehicle that was felt when driving. The measured output voltage of the sensor at no-air condition was at required limits 1 ±0.02 V. Later, another sensor was used (Pierburg 7.22684.18.0) with even worse results - noticeably low engine power and sometimes stalling during idling. The situation described above applies to a car with a diesel engine with electronic control produced from 2006 to 2009.

Finally, it was decided to collect different sensors, study their characteristics and find out which ones correspond to the desired characteristic.

The sensors collected are described in the following table:

Table 1. Mass airflow sensors

№	Manufacturer	Part Number	Condition	Remark
1.	BOSCH	0 281 006 759	new, aftermarket	with housing, HFM-7-R5
2.	BOSCH	0 281 002 461	used, original	with housing, HFM-5
3.	Pierburg (i2s)	7.22684.18.0	new, aftermarket	sensor only, hot film
4.	Pierburg	7.22684.18.0	new, aftermarket	sensor only, sensor element - 2 discrete thermoresistors
5.	NTK	91609	new, aftermarket	sensor only, hot film
6.	Pierburg (i2s)	7.22684.18.0	new, aftermarket	sensor only, hot film
7.	BOSCH	0 281 002 461	used, original	with housing, HFM-5

A test rig was built to investigate the characteristics of the sensors (Fig. 1).

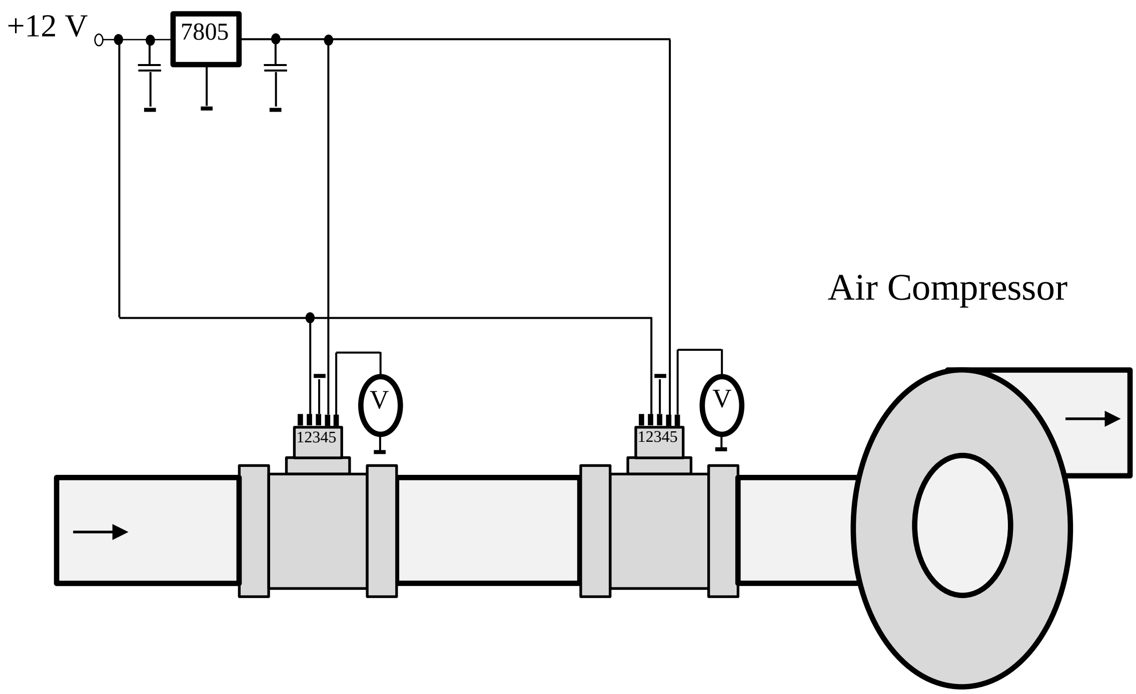

Fig. 1. The schematic of the test rig

The test rig consists of two housings, three plastic pipes with appropriate diameter, air compressor and a 7805 voltage regulator for +5 V power supply. A laboratory linear regulated power supply unit was used as a 12 V DC voltage source. The sensor output voltages were measured with two digital voltmeters with the same range and preselected with equal accuracy in the range from 0 to 4 V (UT81B) [8]. It was considered that accuracy more than 2 digits after the decimal point was not needed because the relative accuracy of sensors given by the manufacturer is within ± 3 % [1].

The sensor BOSCH 0 281 006 759 [3] was used as a reference sensor and it was placed first in the air path (left oh the Fig. 1). In the second housing (right), the remaining 6 sensors were placed in series and the voltages at the two outputs were measured simultaneously.

An 800 W blower with graduate adjustment of the motor speed was used as an air compressor. The blower was used in suction mode after the sensors because of more stable voltage readings than in the case when air was blown into the first pipe. The all measurements were made at room temperature. The results from the measurements are given in the following table.

Table 2. Voltage measurements results

Sensor №	Voltages, V					
1.	1.00	1.75	2.13	2.33	2.53	2.65
2.	1.06	1.78	2.13	2.32	2.51	2.62
1.	1.00	1.65	2.00	2.15	2.30	2.67
3.	1.01	1.66	1.95	2.09	2.25	2.60
1.	1.00	1.72	2.11	2.22	2.32	2.65
4.	0.94	1.68	1.97	2.06	2.15	2.51
1.	1.00	2.08	1.73	2.15	2.39	2.65
5.	1.01	1.67	2.05	2.18	2.45	2.67
1.	1.00	1.71	1.91	2.14	2.29	2.65
6.	1.00	1.72	1.88	2.05	2.17	2.52
1.	1 .00	1.70	2.13	2.26	2.38	2.64
7.	1.03	1.70	2.11	2.23	2.35	2.58

As can be seen from the table, the output voltages of three of the sensors (№ 2, № 4 and № 7) at zero-air flow are out of specification. While the characteristic of sensor 2 except for the initial value approaches the reference, the characteristic of sensor 4 is quite different. The voltages at zero-air of the remaining 3 sensors are within tolerance, but in other parts of their characteristics they differ from the reference. The present study could not cover the entire range of output voltages (1 ÷ 4.5 V) due to the insufficient power of the air compressor used. On the other hand, engine operation modes at high airflow values are relatively rare.

To estimate the error introduced by the differences in sensor voltages, it is not the voltages that are compared, but the amounts of air that correspond to them. This is necessary because the relationship between the output voltage of the sensor and the mass airflow is non-linear [1], [5].

Two characteristics were used to estimate the errors in the measurement of the mass airflow. One is taken from the technical specifications of the HFM-5 sensor [1] and the other was experimentally obtained from the engine control unit (ECU). Judging by the dimensions of the sensor housings, the characteristic of the tested sensors should be close to that of number 3 in the document. Although the characteristic in [1] refers to a different sensor number, as will become clear later it is quite similar to that obtained from ECU. The characteristic which is stored in the ECU's read only memory (ROM) is obtained by applying calibrated voltage to its input to which the sensor is connected and monitoring the mass air flow value through a diagnostic tool connected to the car's diagnostic interface in OBD II mode. Mass air flow in [1] is given in kg/h and the diagnostic tool gives it in g/s. The connection between two units is:

$$Qm[g/s] = Qm[kg/h]/3.6. \quad (1)$$

The following table shows the sensor characteristic data from [1] and the value 0 at a voltage of 1 V has been added to the data. The third row of the table represents the mass airflow data calculated in g/s.

Table 3. Characteristic of sensor from [1]

Voltage, V	1	1.2695	1.4060	1.7100	2.1563	2.7522	3.5070	3.9393	4.2349
Mass airflow [kg/h]	0	10	15	30	60	120	250	370	480
Mass airflow [g/s]	0	2.78	4.17	8.33	16.67	33.33	69.44	102.78	133.33

The data from the table is well approximated with a 4-th degree polynomial using MATLAB's basic fitting tool. The polynomial function describing the data from Table 3 is:

$$Qm[kg/h] = 2.9603U^4 - 17.097U^3 + 56.959U^2 - 47.24U + 4.7575. \quad (2)$$

The following table contains the data on the relationship between sensor voltage and mass airflow obtained from ECU (BOSCH EDC16U1).

Table 4. Characteristic of the sensor from ECU.

Voltage, V	1	1.1	1.4	1.5	1.7	1.8	1.9	2	2.2
Mass airflow [g/s]	0	1.33	4.44	5.66	8.36	9.8	11.36	12.97	17.11
Voltage, V	2.4	2.6	2.8	3	3.2	3.4	3.6	3.8	4
Mass airflow [g/s]	22.3	28.3	35.44	43.91	53.77	65.14	78.3	93.33	110.41

The data from the table is well approximated with a 4-th degree polynomial using MATLAB. The polynomial function representing the data from Table 4 is:

$$Qm[g/s] = -0.08048U^4 + 3.829U^3 - 12.13U^2 + 23.81U - 15.3. \quad (3)$$

Although the two polynomials look different, their graphs are quite close (Fig. 2).

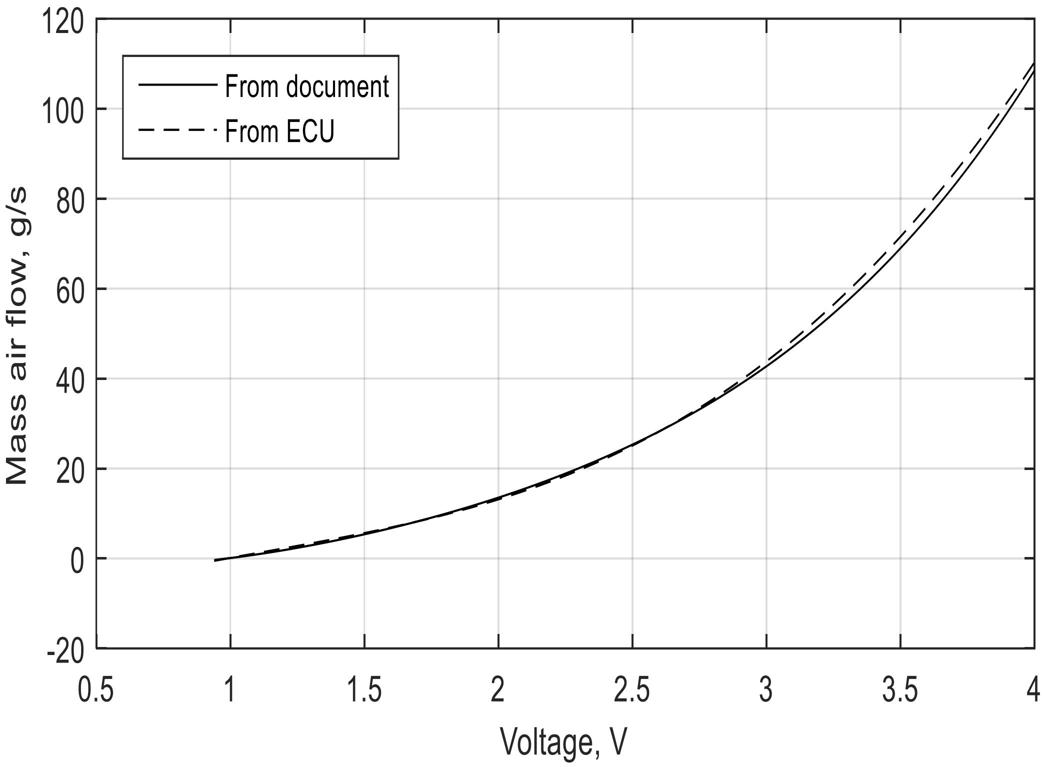

Fig. 2. Comparison of the characteristics of the MAF sensor

In fact, for voltages above 1.5 V, the relative difference between the values of the two polynomials does not exceed ± 1 %. Before being plotted in the figure, the values of the polynomial (2) are divided by 3.6 according to (1).

To compare the characteristics of the tested sensors it is assumed that the sensor № 1 from Table 1 has the same characteristic that is stored in the ECU memory.

The comparison of characteristics of the sensors in pairs using data from Table 2 was made in the following sequence:

1. The approximated with (3) mass air flow value Qm which corresponds to the voltage of the reference sensor for each of the six measurements is found.
2. The approximated with (3) value Qm of the second sensor corresponding to its voltage is found.
3. The relative difference between two sensors in these voltage points are calculated.

The relative difference is calculated according to:

$$Err_n = \frac{Q_n - Q_1}{Q_1}.100\ \%. \tag{4}$$

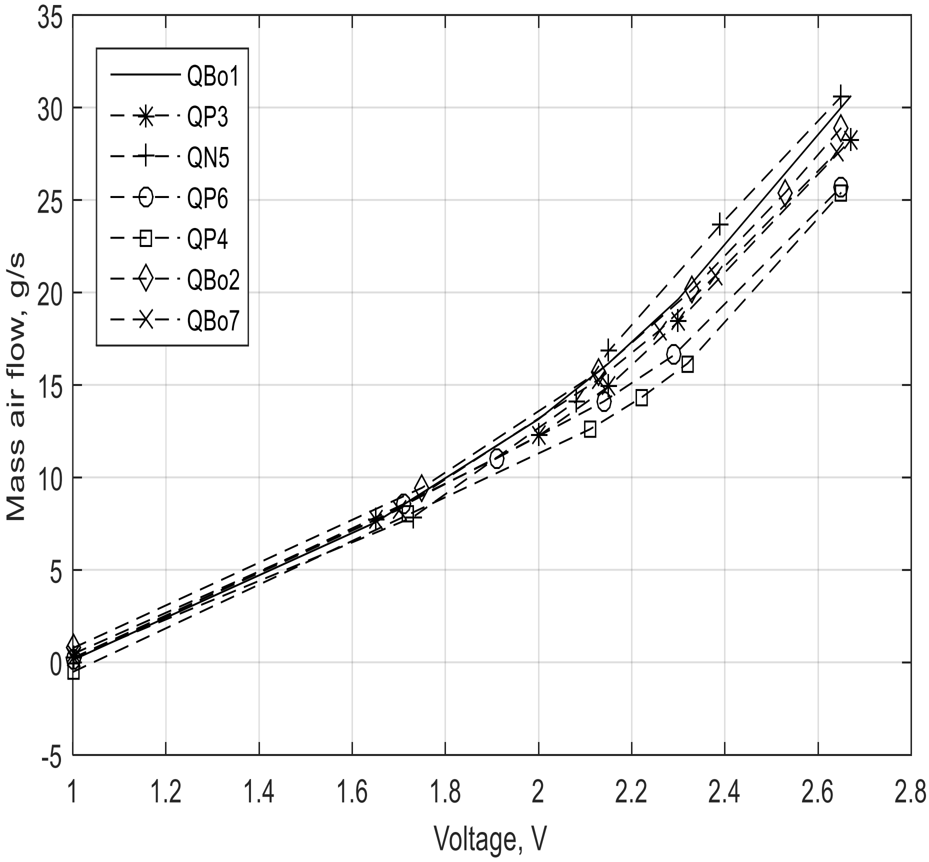

Fig. 3. Characteristics of the tested sensors

All calculations and figures in the article are made using a program written in the MATLAB language.

As it is shown on the Figure 3, the characteristics of the 6 sensors compared to that of the reference (QBo1) differ from each other.

The next figure shows the relative errors between each of the 6 sensors and the reference in percent. The first values are excluded from the graphics because the air quantity is close to zero and the relative difference is very large. In practice, the voltage at the input of the ECU when engine is idling is within limits of 1.6 ÷ 1.8 V.

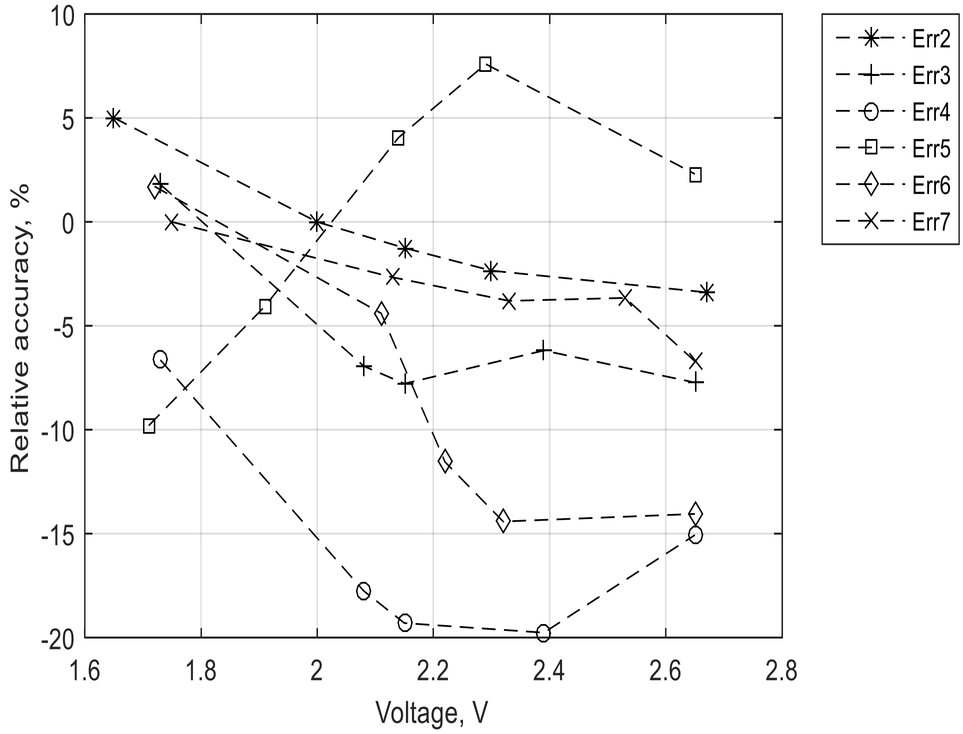

Fig. 4. Relative errors in Qm between sensors (the numbers 2 – 7 correspond to Table 1)

The minimum and maximum errors between the characteristics of the sensors № 2 to № 7 and the characteristic of the reference sensor № 1 are shown in table 5.

Table 5. Errors of the tested sensors

Sensor №	Error (negative), %	Error (positive), %	Difference (pos.-neg.), %
2.	- 3.39	+5.01	8.4
3.	-7.78	+1.81	9.59
4.	-19.76	-6.64	13.12
5.	-9.80	+7.60	17.4
6.	-14.41	+1.71	16.12
7.	-6.7	0	6.7

The results from above described experiment and Table 5 show that the deviations between characteristics of the sensors are larger than expected. In fact, the two of the sensors (2 and 7) with characteristics close to the reference one are used and original. Only one of the sensors (№ 3) made by manufacturers other than the original one has a measuring accuracy close to the reference. When sensors 1 and 7 were tested on the vehicle, no difference in engine behavior during driving was felt. For example, with sensor 4, a loss of power from the engine and slow acceleration is felt. As it can be seen from Table 5 the sensor 4 is the most inaccurate one. Moreover, a short-term voltage drop at its output almost to 0 V was observed during the experiments. This is believed to be the cause of the engine stalling.

Despite the large inaccuracies in the characteristics of some of the sensors, the ECU did not record a fault code with any of the sensors tested on the vehicle.

Sensors № 2 and № 7 have characteristic at voltages above 1.5 V close to the reference but their voltages at zero-air condition are out of specification (1 ±0.02 V). In practice, the voltage of sensor № 7 at zero-air (1.03 V) is very close to the specification and it can be used in the vehicle.

Conclusion

Out of a total of seven sensors tested, only two of them are usable (№ 1 and № 7).

It is recommended to replace the original sensor only with one from the same manufacturer. The sensor also can be replaced with a used one, as long as its output voltage at zero-air is within the limits of 1 ÷ 1.03 volts.

The methodology presented can also be used to test other types of sensors, for example ones with frequency output signal. In this case frequency meters must be used instead of voltmeters. It is also necessary to have data on the dependence between the output frequency and the air quantity.

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