Measurement of the Torque of an Internal Combustion Engine Using Equipment of Our Own Design

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***Abstract*—This work deals with verification of a proposed measuring method, as well as calibration and linearization of a sensor. The proposed torque measurement method is based on the use of a measuring element of our own design. In order to obtain as much data as possible, the engine was fitted with a combustion pressure sensor allowing the engine torque to be monitored. In order to install the pressure sensors and the engine torque sensor, it was necessary to modify individual parts of the engine. This article describes only part of the ongoing measurements taken to gain further new findings.**

***Index Terms*—torque measurement, power loses, equipment for torque measurement**

I. Introduction

Today's demanding society is under constant pressure from the growing demands for the acquisition of new and better items of daily consumption. This trend is increasingly reflected in the research and development of passenger cars and their sub-groups. Unfortunately, this situation has its consequences, mainly reflected in the behaviour of the consumer society, which causes damage to the environment. In order to avoid such a significant impact on nature, certain provisions and laws regulating the given situation are necessary. The pressure created by consumers and legislators is most felt by manufacturers, who try to find new ways to develop and produce individual products. In our case, this means the drive units of passenger cars. If we look through the eyes of both camps, the customer-consumer wants a car that has acceptable performance parameters, low consumption and in particular the lowest possible price. On the contrary, the manufacturer looking for profit tries to offer a car with suitable parameters at the best possible price, so the highest profit will be generated. Therefore, compromises must meet the needs of all and at the same time minimize the burden on the environment.

II. Methods for Measuring Torque

Methods for measuring torque can be divided into two basic groups:

- Indirect measurement of torque
- Measurement using torque or force sensors

A. Indirect Measurement of Torque

1) Measurement of torque using electrical machines

When a combustion engine is connected to an electric generator, the power can be measured by measuring the voltage, current and speed using an electric machine. This method is rarely used because a large error is introduced into the measurement due to measuring several physical quantities at the same time. An appropriate and often used alternative is to supplement this measurement with a torque sensor and use the electric machine purely to load the internal combustion engine. [1]-[5]

2) Measurement using a piezoelectric pressure sensor

This method is exclusively used at AVL, mainly for measuring on special powertrain measuring stations or cylindrical brakes. This method measures the pressure directly in the cylinder by pressure sensors placed inside the cylinder. If the piezoelectric sensors are loaded with a force perpendicular to the silicon wafer, an electrical charge is produced that is directly proportional to the force the wafer is loaded with. In order to determine the course of the indicated torque, it is necessary to know the course of the indicated pressure, depending on the rotation of the crank mechanism. To determine the position of the crank mechanism, it is possible to use an incremental sensor directly connected to the crankshaft. To determine the effective torque using this method, it is still necessary to know the friction torque and moment of inertia of the engine. [1]-[5]

3) Determination of torque from the moment of inertia

The engine power, or its torque, can be determined by measuring the rotation and the time required to rotate the body at a known moment of inertia. It is essentially one of the simplest measurement techniques. Today, this method is used only under non-professional conditions, because the measurement is burdened with large errors. In addition, it cannot be used for long-term measurements. Nevertheless, it can serve as a comparative method and provide a sufficient amount of information. [1]-[5]

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B. Measurement Using Torque and Force Sensors

Measurement using torque sensors is most often used for its high accuracy and repeatability. The principle is based on the direct measurement of torque and the various types of sensors differ only in the essence of how they sense the measured quantity.

In the case of torque sensors, the shaft is most commonly used as the deformation member. Sensors may vary depending on whether they have their own shaft or whether they use the shaft of the device being measured. In the latter case, measurements may be to a large extent inaccurate. [1]-[5]

The different types of torque sensors:

- Resistance sensors
- Induction sensors
- Capacitive sensors

1) Resistance sensors

These are the most widespread sensors with a simple design. The measurement is based on the deformation of the measuring element, which in most cases is the shaft. The sensors can be divided into two basic groups. The first uses its own sensor shafts and is inserted into the measuring track. The second uses the shaft of the equipment being measured. [1]-[5]

2) Sensors with resistance potentiometers

These sensors work based on the principle of sensing the angular displacement of the measured shaft. The sensor requires a large deformation of the measuring element. Resistance is transferred to an electrical signal that is directly proportional to the deformation of the sensor. [1]-[5]

3) Sensor with resistive strain gauge

The principle of these sensors is based on the measurement of shear stress using a strain gauge. Strain gauges are very often used because a measuring element does not have to be construction inserted in the design.

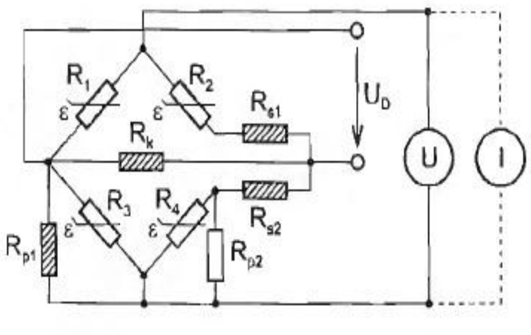

Figure 1. Full tensometric bridge [1].

Unfortunately, however, it is necessary to transmit a signal from a rotating component. The measured element is most commonly a cylindrical rotating part, on the surface of which the shear stress is measured by means of several resistive strain gauges placed at a 45 ° angle to the axis of rotation. The assembly creates a so-called full strain gauge bridge. [1]-[5]

4) Induction sensors

These are sensors with a small air gap. Angular displacement of the cross-section of the shaft will result in a change in the air gap. The force of the sensor is located on the stator parts, thereby eliminating problems with the transmission of the signal with rotating shafts. [1]-[5]

5) Capacitive sensors

Capacitive sensors are made up of two tooth-shaped electrodes that are firmly attached to the shaft, with a sufficient gap between the teeth. Deformation of the shaft causes the electrodes to rotate and the tooth clearance to reduce, which leads to a reduced capacity. One electrode must be sufficiently insulated from the shaft, otherwise there would be no change in capacity. [1]-[5]

III. Measuring Element for Analysis of the Course of the Torque

The proposed method is largely non-standard and it is necessary to follow predetermined rules when constructing the sensor, in order to obtain credible data and not destroy the sensor used. The measuring element is designed to be part of the drive unit. In this case, it is located between the crankshaft and the engine flywheel. A torque sensor commercially available from Kiestler is used in the measuring element.

Figure 2. Kistler 4504B measuring flange [6].

Unfortunately, the design of the sensor is not suitable for direct installation between the crank mechanism and the flywheel, so it was necessary to design individual components so that the sensor could be used. During the construction, it was necessary to consider the function of the clutch, which is part of the flywheel. Therefore, it was necessary to take into account the forces that could affect the sensor and, in the worst case, damage it. The torque sensor used can only be subjected to torsional loads, so the load from other forces is totally inadmissible. Therefore, the measuring element is equipped with a support bearing that holds the radial and axial forces. Unfortunately, due to this design, additional inertial masses are added onto the crankshaft, so it was necessary to modify the original flywheel of the engine so that the moment of inertia of the measuring element is at the moment of inertia of the original flywheel. [7]

TABLE I. TABLE OF MOMENTS OF INERTIA. [8]

	moment of inertia [$Kg*m^2$]
Torque sensor	0.01164
Crankshaft Flange	0.00452
Flange for engine flywheel	0.01106
Ball-bearing	0.00707
Original flywheel	0.073
Adjusted flywheel	0.03871

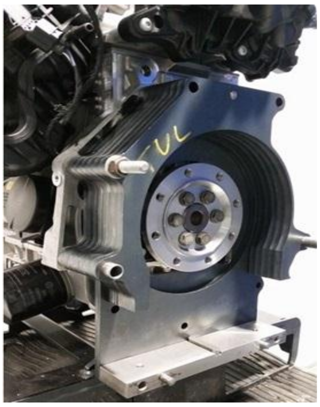

Figure 3. View of the box of the measuring member. [8].

Figure 4. View of the installation measurement flange. [8].

The assembly of the sensor, the mounting flanges greatly increased in length, creating a space between the gearbox and the engine, which was completely filled with an assembly of sheet metal burnouts.

Figure 5. Overall view of the measurement elements mounted on the engine. [9].

Figure 6. Overall view of the measurement elements mounted on the engine. [9].

IV. DESCRIPTION OF THE EXPERIMENT

A. Description of Tested Engine and Equipment

The measuring element was designed to cover a large number of used engines. This is largely due to the fact that manufacturers use universal parts to simplify production. That is why the measuring block can be used for almost the whole range of Škoda engines. For our needs, an EA 211 four-cylinder petrol engine was specifically used. The engine is supercharged with internal mixture formation. Its design parameters are included in the table.

TABLE II. ENGINE PARAMETERS. [10]

Type of engine	EA 211
Bore x stroke	74.5mm x80 mm
Cubic capacity	1398 ccm
No. of cylinders	4
Number of valves per cylinder	4
Type of fuel injection	Direct injection with turbocharger overcharging
Maximum power output	103 Kw
Maximum torque	250 Nm

The engine head was modified so that the indicated pressure can be monitored to determine the engine torque. This modification consisted of drilling directly into the combustion chamber. In order to prevent the bore from interfering with the other functions of the engine head, such as cooling, it was necessary to insert metal sinks into the resulting holes. These were mainly used for the subsequent storage of miniature pressure sensors. The engine assembly and an element for measuring the torque were installed on a braking station equipped with an electric asynchronous dynamometer.

B. Description of the Experiment

During the experiment, it was necessary to consider the maximum torque the sensor is able to measure. In our case, this was a maximum of 1000 Nm. Due to the maximum engine torque, this value was considered sufficient. It is also necessary to consider that the stated maximum engine torque is effective, and at peak times the torque can reach even four-fold values. As a consequence of the above, the values of speed and torque were proposed and strictly followed during the experiment. See tables.

TABLE III. ENGINE LOAD PER REVOLUTION

Load torque [Nm]									
5	10	25	50	75	100	125	150	175	200

TABLE IV. OPERATING SPEED OF THE ENGINE

Speed of the engine [RPM]		
1000	2000	3000

During the experiment, the difference between the effective moment measured by the brake and the torque measured by the measuring rod was recorded. For this reason, the entire measuring system was calibrated so that the cause of the measurement error could be determined. The calibration is described in chapter: "Torque sensor calibration and linearization".

C. *Torque Sensor Calibration and Linearization*

In order for the measurement to proceed correctly, it is necessary to first calibrate the sensor and carry out its linearization. Calibration consists in determining the calibration curve. The calibration curve is defined by three points, no load, maximum load and minimum load. In order for the torque to be measured by the sensor, the measuring element must be equipped with precisely defined arms on which precise weights can be hung. Calibration is based on the physical principle of defining the torque. By knowing the length of the arm and the weight of the load, it is also possible to know the torque on the sensor. Linearization involves the progressive loading and unloading of the torque sensor. By recording the measured values, it is possible to describe the behaviour of the sensor.

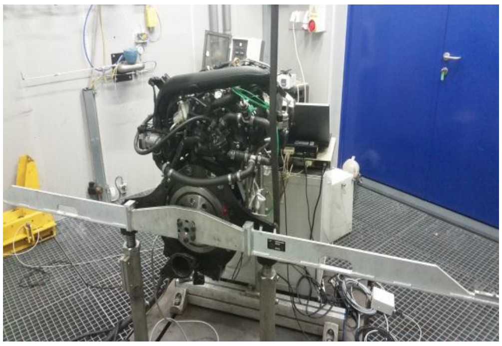

Figure 7. View of the calibration arms.

Figure 8. Calibration weights.

INDICOM 619 indicator equipment from AVL was used to measure the torque. This device is primarily used to monitor the combustion pressure of the engine but can be used to record any signals from different sensors. In order for the indicator to work correctly, information on the speed of the engine is required. Normally, a very accurate incremental speed sensor is used for this purpose. In our case, the engine does not rotate so it is necessary to obtain different speed information. Fortunately, it is possible to simulate the speed by using a VISISCOPE device from AVL.

V. RESULTS OF THE MEASUREMENTS

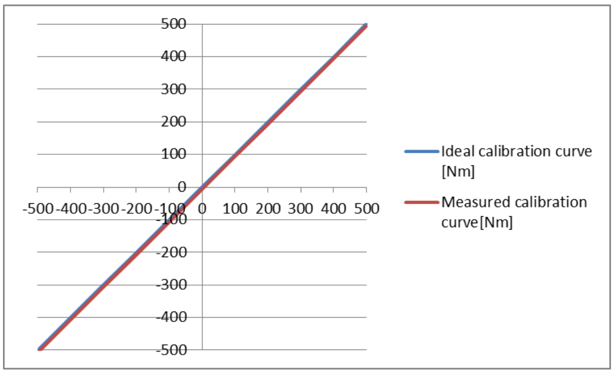

Figure 9. Comparison of measured and theoretical calibration curves.

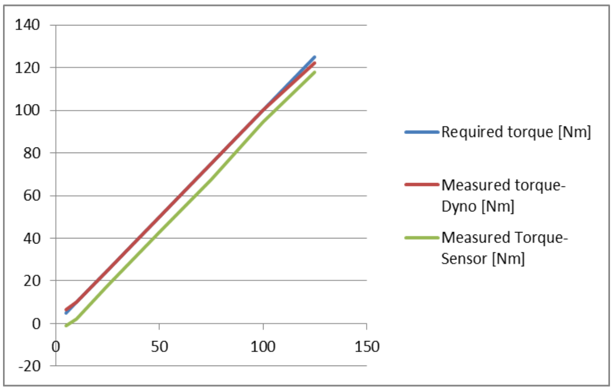

Figure 10. Course of the torque at 1000 rpm.

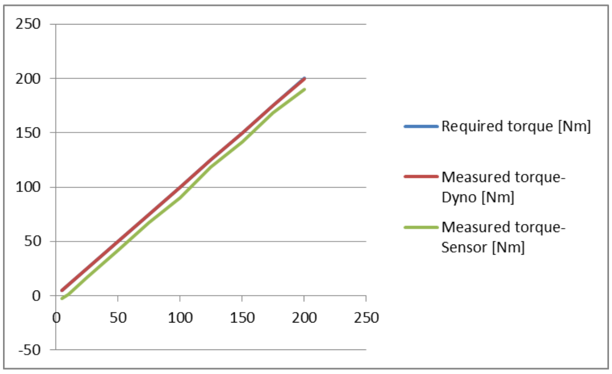

Figure 11. Course of the torque at 2000 rpm.

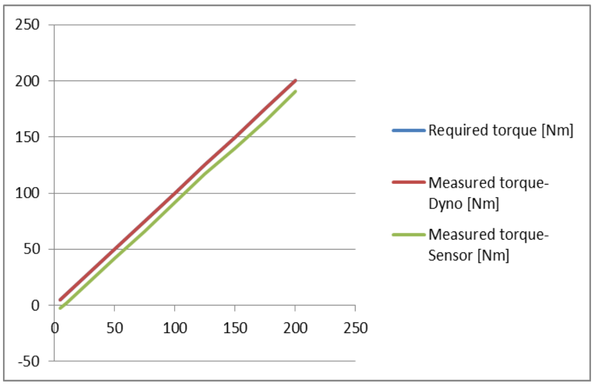

Figure 12. Course of the torque at 3000 rpm.

VI. Conclusion

Measurements on the tested engine took place at several levels of control. In addition to the measurements of the power parameters on the engine brake and the designed measuring elements, the values of the combustion pressure inside the four cylinders were also recorded. The obtained values were used to form a comprehensive picture of the function of the measuring element as well as of the suitability of using the measuring method as a whole. The dynamometer measurements revealed a certain disparity between the measured data, the effective parameters, the brake and the measuring element. The assumption was that the sensor used works with a torque offset. Based on this assumption, the whole measuring system was re-calibrated. During the calibration and linearization of the designed measuring element, it was determined that the torque sensor measures with a certain disparity, which repeats at any load regardless of whether the sensor is loaded or lightened. This disparity is approximately 7 Nm. This fact led us to feel that the sensor works with a torque offset. The measuring element can therefore be considered as functional and is prepared for further testing, which is underway in connection with the gearbox. Therefore, the drive unit will be measured as a whole. Such measurement may lead to additional uncertainties that will need to be addressed.

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Conflict of Interest

The authors declare no conflict of interest.

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Josef, after finishing his master degree studies, began study his Ph.D. study program at the Department of Vehicles and Engine of the Faculty of Mechanical Engineering at Liberec. At the same time, he began to work as a junior research scientist at the Laboratories of the Vehicle and Engine Department. During this work, he worked on several specific projects in the field of alternative fuels and engines working with these fuels. He also participated in several contractual researches for the industrial sphere. At the University he also acted as a lecturer in the project for education of young people. Since 2018 he has been assistant professor at the Department of Vehicles and Engines at the Technical University in Liberec. In the period from 2010 to 2018 he published several articles as author or co-author.