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# PRELIMINARY STEPS FOR INVESTIGATING THE AIR PRESSURE INSIDE THE TYRE

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***Abstract:*** *This scientific paper presents a series of initial steps for measuring the air pressure inside the tyre. Two pressure transducers are selected for the system and presented in the paper. One of the main objectives is to verify the calibration of the transducers and confirm that they can be used for the pressure measurements. Another objective is to develop a system attached to the wheel that includes the two transducers. For the verification of the transducers' calibration, a pressure calibration rig was built, and several pressure measurements were done with the transducers connected to a pressurized enclosure. Initially, the relative errors for both transducers were significant. By repeatedly adjusting the value of the transducers' sensibilities, the errors could be lowered to acceptable values. Both measuring characteristics are quasi-linear with very small linearity errors. The paper shows that, although the measuring characteristics differ from the ones specified by the manufacturer, the transducers can be used for the proposed system. For the measuring system attached to the wheel, two modules have been developed, a central module attached to the wheel disk with bolts, and another module that will be placed inside the tyre, glued on the surface of the wheel rim. The support components for both modules were manufactured using 3D printing with a thermoplastic material (PLA).*

***Keywords:*** *Tyre, air pressure, pressure measurement*

## 1. Introduction

Inner tyre pressure is a very important functional parameter of the tyre. It influences vehicle handling, fuel consumption, traction and braking performance and tyre life. In general, a low interior pressure can lead to tyre overheating. In cases of very low pressure, great deformations of tread and sidewall can appear, which lead to tyre damage [1]. Also, the pressure variation from the manufacturer's recommended pressure has a great impact on tyre life [2]. In addition, inner tyre pressure influences the rolling radius of the tyre, a fundamental parameter for vehicle dynamics. In most cases, the rolling radius is an input parameter based on formulas that do not take into consideration inner tyre pressure [3].

The study of air pressure variation inside the tyre is rarely mentioned in literature. In general, inner tyre pressure is considered constant, a value characteristic to the tyre, usually adopted or measured when the tyre is cold. An experimental way for using tyre pressure as a parameter is setting the tyre pressure at a certain value, stopping the experiment, and then readjusting the pressure after a period of tyre rolling. Paper [4] describes this method. However, there is no mention of the pressure variation between the two states of the tyre (cold tyre / warm tyre). Also, stopping the experiment for measuring may induce errors.

Another way of measuring inner tyre pressure is using a "dynamic tyre pressure sensor" [5]. The method uses a transducer mounted to the wheel, as close as possible to the wheel rotation axis. The pressure reaches the transducer via a hose connected to the tyre valve. The electrical connection between the transducer (mounted at the wheel) and the electrical transmission system (mounted in the vehicle) is achieved with a series of slip rings. This allows measurements during tyre rolling to be performed. However, the authors do not use the system for precisely measuring air pressure, only for pressure monitoring, and do not provide data for the pressure values used.

Also, the system can have large measurement errors due to the introduction of electrical noise by the sliding contact rings, making it unsuitable for accurate measurements.
“Tyre pressure monitoring system” (TPMS) is a widely used system that presents a series of versions which could be used for measuring the air pressure inside the tyre. A miniature sensor placed on the inside of the wheel rim measures the pressure and converts it into an electrical signal wirelessly sent to the car's on-board computer. Unfortunately, review of the literature showed that the system has insufficient resolution (8.3 kPa [6]) and accuracy (±7 kPa [7]).
Since the rolling radius is directly influenced by the pressure, which changes during the running of the vehicle, the pressure must be known accurately at each moment of the tyre running. Thus, one of the objectives of the paper is to develop a system attached to the wheel for measuring the pressure inside the tyre, which can be mounted on any wheel of the vehicle. The system should include two low-cost pressure transducers. Also, another objective is to verify the calibration of the included transducers and confirm they can be used for the measuring system.

## 2. Pressure transducers

Two transducers from NXP have been chosen for the development of the tyre air pressure measuring system: MPX5500DP and MPXH6400A. The MPX5500DP transducer is a small sized, general purpose, differential pressure transducer. The MPXH6400A transducer has a very small size and measures absolute pressure. A third transducer, the Turck PT040R pressure transducer, which is in the equipment of the Vehicle Testing Laboratory of the Department of Road Vehicles, Faculty of Transport, will also be used for the calibration check of the two chosen transducers. It was chosen as the reference transducer in the calibration process of the other two transducers. Figure 1 shows the three transducers and Table 1 shows the main parameters of interest for the chosen transducers.

**Table 1:** Main parameters for the chosen transducers [8,9,10]

| Transducer | Relative Pressure Range [kPa] | Supply Voltage [V] | Output Voltage [V] | Sensitivity [mV/kPa] | Accuracy [%] | Price [€] |
|---|---|---|---|---|---|---|
| MPX5500DP | 0 ÷ 500 | 5 ± 0.25 | 0.2 ÷ 4.7 | 9 | ± 2.5 | 18 |
| MPXH6400A | 0 ÷ 300 | 5 ± 0.36 | 0 ÷ 4.8 | 12.1 | ± 1.5 | 17.5 |
| PT040R | 0 ÷ 4000 | 11.4 ÷ 33 | 0 ÷ 10 | 2.5 | ± 0.3 | – |

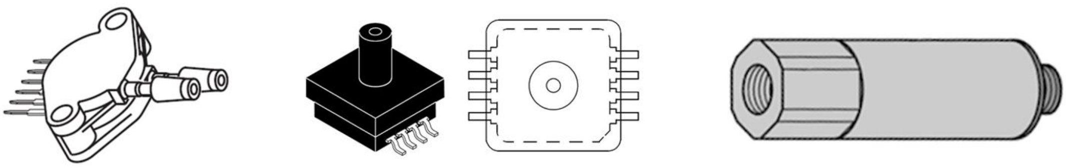


**Fig. 1.** Chosen pressure transducers [8,9,10]

When analysing the pressure ranges of the transducers, the MPX5500DP transducer has a pressure range suitable for the proposed application. Transducer MPXH6400A shows a maximum pressure of 300 kPa, lower than the previous transducer, but still usable for measuring the air pressure inside car tyres. The PT040R transducer has a maximum measurable pressure well above the measurement requirements of the proposed application.

## 3. Pressure calibration rig

To build the pressure calibration rig, a pressure enclosure was required. The enclosure should have at least two transducers connected at the same time. The measurements to check the calibration of the transducers were carried out in the Vehicle Testing Laboratory of the Road Vehicles Department. At the start of the rig development, the enclosure equipped with a pressure gauge already existed in the Department. It was modified to allow the transducers to be coupled. Only two of the five pressure outlets were used. A digital oscilloscope was used to visualize the transducer signals.

Figure 2 shows the block diagram of the rig. Particularly, the image presents the calibration of the MPX5500DP transducer. The main components of the rig are: 1 – pressure enclosure (common ramp) with five outlets and valve, 2 – plug, 3 – pressure source, 4 – pressure gauge, 5 – PT040R pressure transducer (T1), 6 – pressure transducer to be verified (T2), 7 – 24 V voltage source, 8 – 9 V voltage source, 9 – voltage step down module, 10 – Fluke 125 two-channel digital oscilloscope with internal memory. Figure 3 presents the calibration rig.

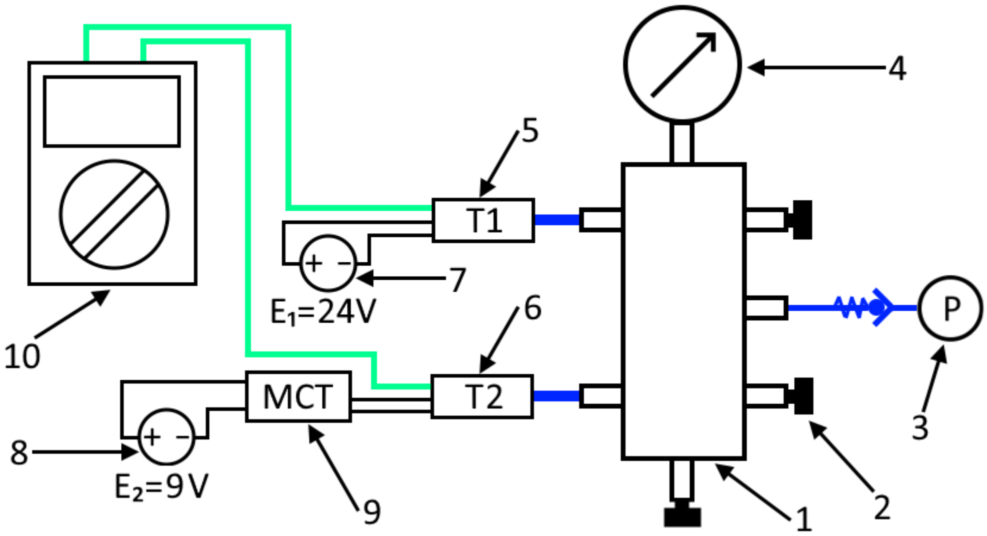


**Fig. 2.** Block diagram of the pressure calibration rig

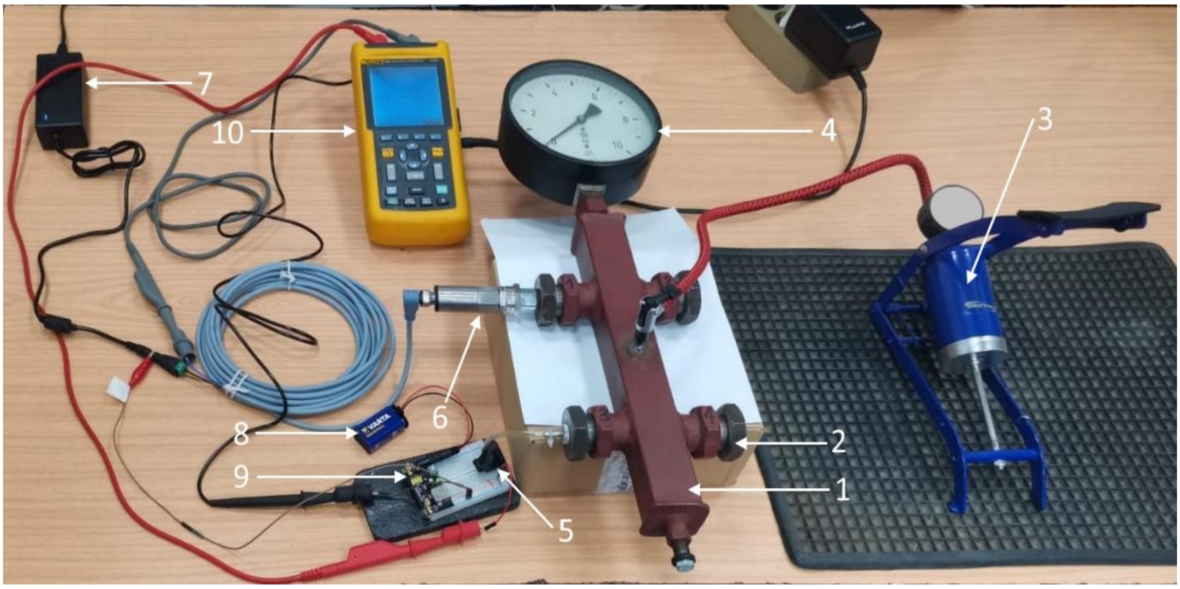


**Fig. 3.** Pressure calibration rig

First the calibration check of the MPX5500DP transducer was performed, then it was removed from the installation. The transducer MPXH6400A was connected and then its calibration check was performed.

The pressure source is a manually operated pump. It is connected to the enclosure's valve. The PT040R transducer is simply powered, directly from a 24V DC source. The power supply of the transducer to be verified cannot come directly from the 9V supply, as the supply voltage of the transducer is 5V maximum. Thus, a voltage step-down module is required, which supplied the MPX5500DP transducer with a voltage of 5V. The digital oscilloscope has two input channels, corresponding to the outputs of the two transducers.
For the MPX5500DP transducer, five sets of measurements were taken, ascending and descending pressure, in the range of 0 kPa to 400 kPa (relative pressure), with a 40 kPa interval between the measured values. Additionally, measurements were taken at 100 kPa and 300 kPa respectively. The pressure was read with the gauge and later verified with the readings from PT040R transducer. In the case of the MPXH6400A transducer, six sets of descending pressure measurements were performed, in the range of 100 ÷ 300 kPa with an interval between measured values of 25 kPa. For the ascending pressure measurements, the pressure was gradually increased to the desired value, then the pressure was allowed to stabilize and the two voltages were read. A similar procedure was followed for descending pressure measurements. The decrease in pressure was achieved by disconnecting the pressure source and repeatedly operating the valve.

## 3. Calibration results for MPX5500DP transducer

For each of the five measurements, the pressure is calculated from the obtained voltage. From this pressure, the relative error in relation to the pressure indicated by the gauge is calculated, expressed in percent. It has been observed that the relative errors obtained for the MPX5500DP transducer are very high, both in the ascending and descending measurements. The first set of ascending measurements shows relative errors in the range of 18.4 % ÷ 21.9 %. However, the variation of the relative error is not very large, with an average value of 19.9 % in the ascending measurement and 16.5 % in the descending measurement. The fact that the relative error does not show a very large variation suggests the existence of a slope error.
For the calculation of pressure, the manufacturer's sensitivity (9 mV/kPa) was used. Slope error correction involves determining the sensitivity of the transducer so that the errors become as small as possible. Through repeated attempts, the following sensitivity values were obtained for the first set of measurements: 7.28 mV/kPa (ascending), 7.37 mV/kPa (descending).

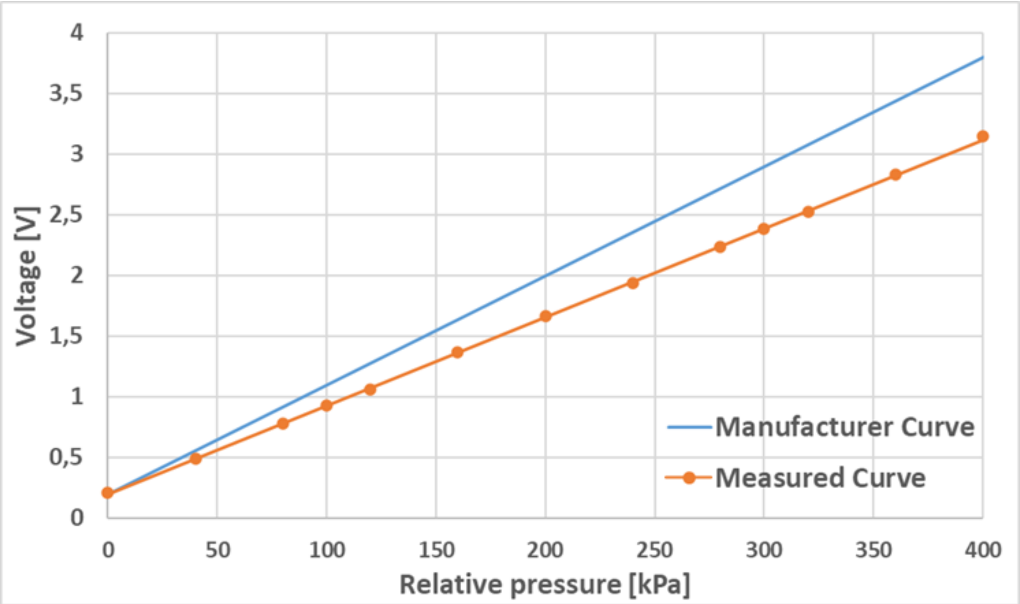


**Fig. 4.** Comparison between manufacturer curve and measured curve from set no.1 ascending

The overall average value of sensitivity (ascending and descending) is 7,39 mV/kPa. In this way, the MPX5500DP transducer shows very small error values in the range -0.9 ÷ 3.5%, with most of the errors being close to 1%.
For the offset of the MPX5500DP transducer expressed in voltage, an average value of 0.210 V and a range of 0.209 V ÷ 0.213 V was obtained, values close to the offset specified by the manufacturer (0.2 V).
Figure 4 shows the comparison between the characteristic obtained with the first set of measurements (the measured curve) and the characteristic provided by the manufacturer. The measured curve is quasi-linear with a very small linearity error. The figure highlights the large difference between the two characteristics, which mostly comes from the difference between the two measurement sensitivities (manufacturer and experimental).

## 4. Calibration results for MPXH6400A transducer

In the case of the MPX5500DP, the measurements were made in parallel with the Turck PT040R. The measurement errors of the PT040R were found to be comparable to those of the MPXH5500DP. Therefore, it was decided to verify the calibration of the MPXH6400A transducer in parallel with the MPX5500DP.
The pressure range of the MPXH6400A transducer is 0 ÷ 400 kPa, but it measures absolute pressure. Thus, at atmospheric pressure, the relative pressure value of 0 displayed by the gauge will actually represent a pressure of about 100 kPa in absolute pressure. For this reason, the pressure of 300 kPa, relative pressure at atmospheric pressure, cannot be exceeded.
From the analysis of the relative error values for the MPXH6400A transducer, the second set of measurements shows relative errors in the range of -6.2 % ÷ -4.6 %, a small error variance suggesting the existence of a slope error. To correct this error, it is necessary to determine the sensitivity of the transducer so that the errors become as small as possible. By analysing the values of all 6 sets of measurements, the actual value of the transducer sensitivity (12,75 mV/kPa) is determined. With this value the transducer pressure indications and relative errors are recalculated. The obtained pressure values are much closer to the reference values, and absolute relative errors drop below ±1% ( -0.9 % ÷ 0.7 % for set two).

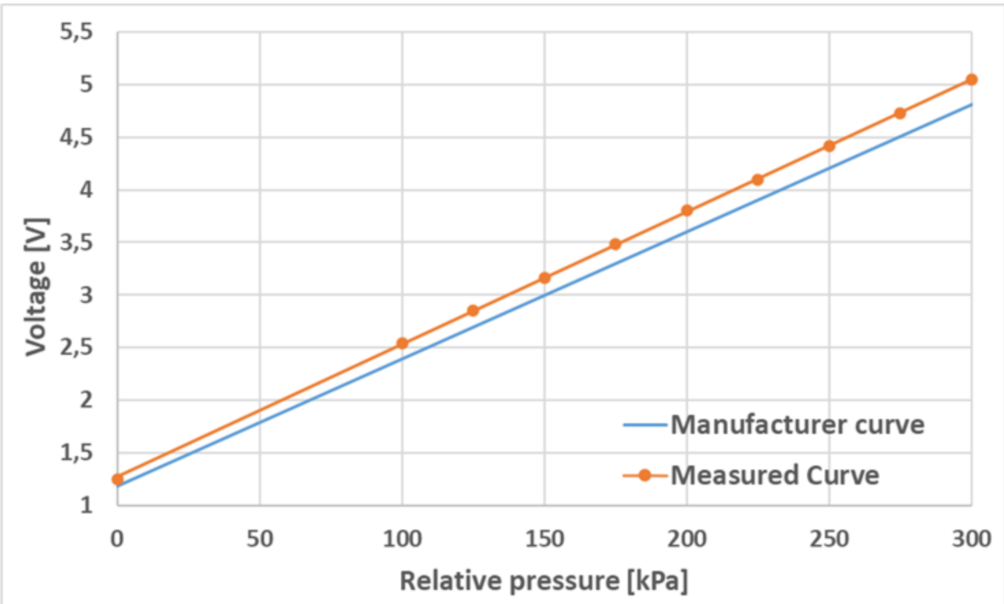


**Fig. 5.** Comparison between manufacturer curve and measured curve from set no.2

Figure 5 shows the comparison between the characteristic obtained with the second set of measurements and the characteristic provided by the manufacturer. For the MPXH6400A transducer there is a higher similarity of the two characteristics (very close values of transducer sensitivity and offset). However, even in this case it can be observed that at 300 kPa relative pressure, the transducer provides a voltage output signal over 5 V, above the 4.8 V limit indicated by the manufacturer.

## 5. Design of measuring system attached to the wheel

To be able to take measurements of the air pressure inside the tyre, it is necessary to develop a system attached to the vehicle wheel that includes the two pressure transducers detailed above and a voltage source. Since the indication of the MPXH6400A transducer changes as the supply voltage changes, it is very important that the supply voltage remains constant at 5V. This requires a voltage regulator.
The moment of inertia of the wheel should not be affected or should be kept as low as possible. Also, centrifugal forces should be limited as much as possible. This ensures the structural integrity of the assembly. With these two considerations in mind, it was decided to place the MPXH6400A pressure transducer on the inner surface of the wheel rim inside the tyre and place the other components in the centre of the wheel.
The mass of the assembly is also very important. The constructive solution for the supporting parts of the assembly components is 3D printing. In this way, it is possible to ensure adequate structural rigidity of the assembly and to reduce its mass. The assembly will be attached to the wheel by means of additional holes in the wheel disk.
To acquire the data from the two pressure transducers, it was decided to use a Raspberry Pi Pico W development board, which has an integrated Wi-Fi transmission module. Using this, the data will be transmitted to a second RaspberryPi board connected to a computer.
A pack of four AAA (R3) batteries is chosen for the power supply. Batteries have a voltage of 1.5 V at 100% state of charge, so a voltage of about 6 V will be obtained. The voltage delivered by the battery pack will be stabilized via the voltage regulator to a value of 5 V.
The measuring system will have two main modules. One module will be mounted in the centre of the wheel and the other module will be positioned on the inner surface of the wheel rim inside the tyre. Figure 6 shows the basic layout for the positioning of the two modules.

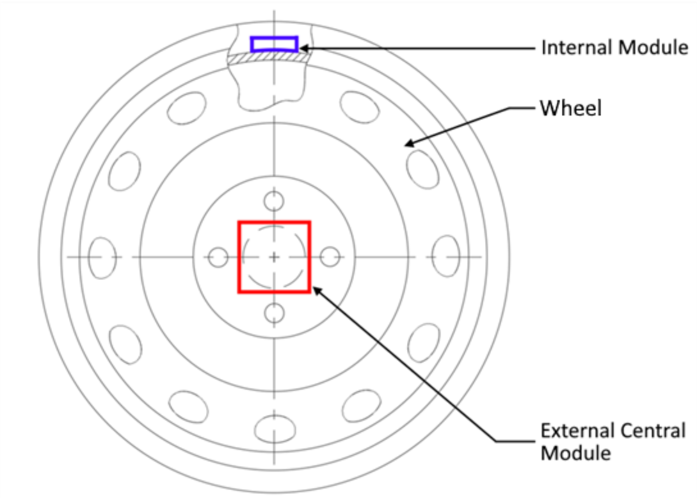


**Fig. 6.** Basic layout for positioning of the two modules

Figure 7 shows the functional schematic of the external central module assembly. The module base is mounted on the wheel disk's surface to support all necessary components of the module. The module has two 'stages'. The Pressure Transducer MPX5500DP is placed in the space between the outer surface of the disk and the inner surface of the base and will be bolted in place. The Rasbperry Pi board assembly is mounted to the base also by screws. For the voltage source a special socket is made in the lid of the module, where it is tightly inserted. Also, the voltage regulator is glued to the inner surface of the cover. Together with the two components the cover is attached to the module support by screws. Figure 8 presents the developed external central module.

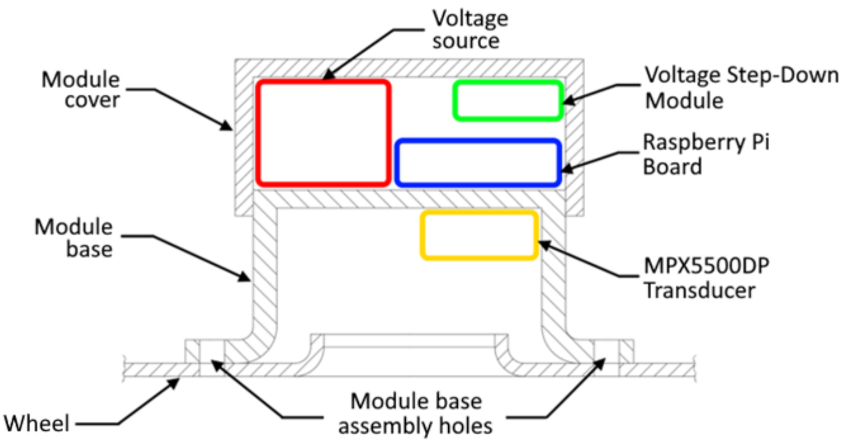


**Fig. 7.** External central module layout

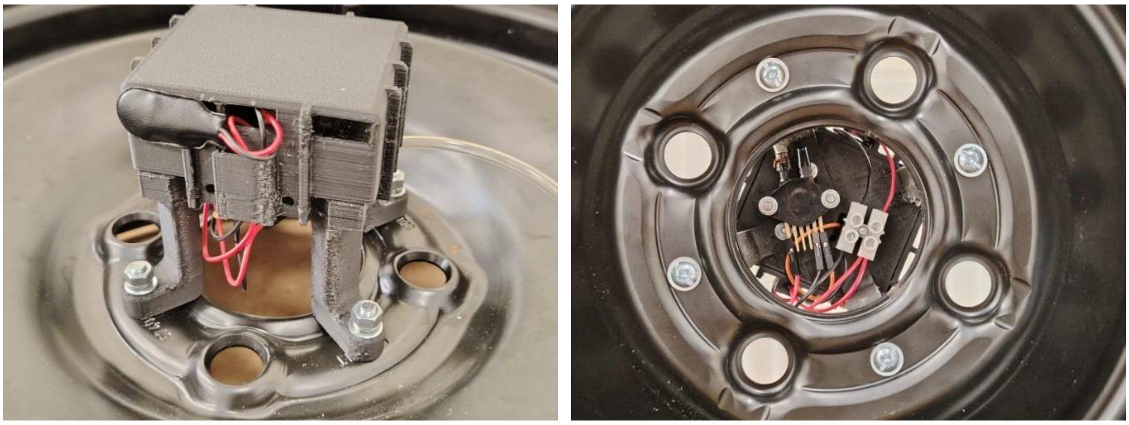

**Fig. 8**. External central module

Figure 9 shows the internal module assembly. On the inner surface of the wheel rim a base will be glued to support a board on which the MPXH6400A transducer will be placed. The module cover, which is assembled by means of screws, is placed over the board. At least one hole needs to be drilled in the module cover so that the transducer can measure the pressure.

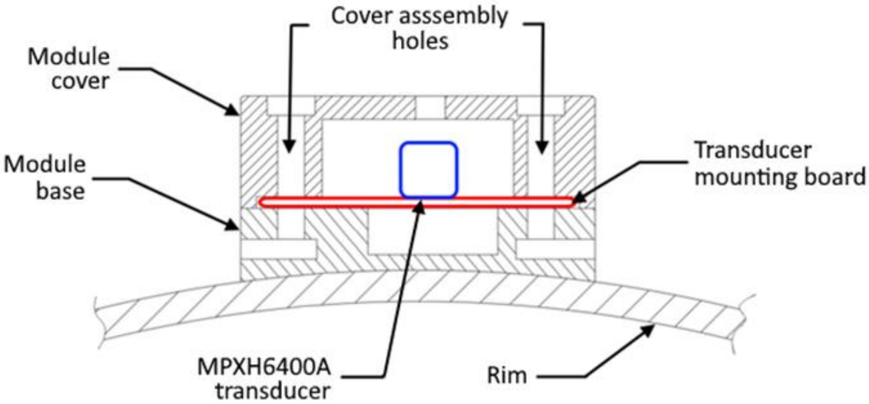


**Fig. 9.** Internal module layout

## 6. Conclusions

The selected transducers can be easily used for the given application, considering the real pressure characteristics. For the MPX5500DP transducer, there is a large difference between the two slopes of the characteristics, which shows a big difference between the actual sensitivity of the transducer and the one specified by the manufacturer.

For the MPXH6400A transducer, there is a higher similarity of the two characteristics (very close values of transducer sensitivity, small offset error). However, the transducer cannot measure above 300 kPa (relative pressure).

The measuring system attached to the wheel successfully includes all the necessary components for measuring air pressure inside the tire. It can be observed that both modules are compact, small and low mass. However, it is necessary to study the impact that the two modules have on the wheel and then to restore its dynamic balance.

A further direction of research is the influence of the position of the voltage regulator above the Raspberry Pi board. It is possible that the module and its wires create parasitic electromagnetic fields that interfere with the RaspberryPi board and its Wi-Fi module.

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