INNOVATIVE METHOD OF EXPERIMENTAL IDENTIFICATION OF THE DEFORMATION OF VEHICLE TYRES

PART 1: SYSTEMATICS OF THE KNOWN TYRE DEFORMATION MEASUREMENT METHODS

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Summary

The existing theoretical tyre models are not perfect; on the other hand, tyres have a significant impact on the safety of vehicle traffic. Therefore, the problem of measurements of tyre deformation when interacting with road surface still must be dealt with. The review of the state of the art in the field of transducers and tyre deformation measurement methods, presented in this article, shows the abundance and diversity of the solutions having been made available so far. Nevertheless, it has been shown, based on the systematic classification adopted, that transducers representing each of the classification groups are characterized by separate properties, which in many cases are hardly compatible with each other. The lack of a transducer that would be free from drawbacks induces attempts to aggregate selected positive features of the solutions that are known in the present state of the art and can be taken as a basis for developing an innovative deformation transducer of new generation. Such a transducer will be presented in the next article.

Keywords: tyre deformation transducers, measurement of tyre deformation components, state of the art

1. Introduction

The factors that induce the undertaking of research on tyre deformation components simultaneously show two major lines of research, which determine the development of tyre deformation transducers. The first one is aimed at the development of "intelligent

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tyres", capable of self-diagnostics and cooperation with traction control systems of new generation, the use of which in vehicles could help to improve road traffic safety [18, 21, 24]. The goal to be pursued by the other one is the quantitative description of the mechanical tyre characteristics that would well represent individual tyre rigidities. The principal rigidities may be defined by relations (1)–(6) (Fig. 1):

- radial rigidity $$c_z = \frac{\partial |F_z|}{\delta z}, \tag{1}$$
- lateral rigidity $$c_y = \frac{\partial |F_y|}{\delta y}, \tag{2}$$
- tangential rigidity $$c_x = \frac{\partial F_x}{\delta x}, \tag{3}$$
- circumferential rigidity $$c_{M_A} = \frac{\partial M_A}{\varepsilon_y}, \tag{4}$$
- torsional rigidity $$c_{M_z} = \frac{\partial M_z}{\varepsilon_z}, \tag{5}$$
- wheel tilt rigidity $$c_{M_x} = \frac{\partial M_x}{\varepsilon_x}, \tag{6}$$

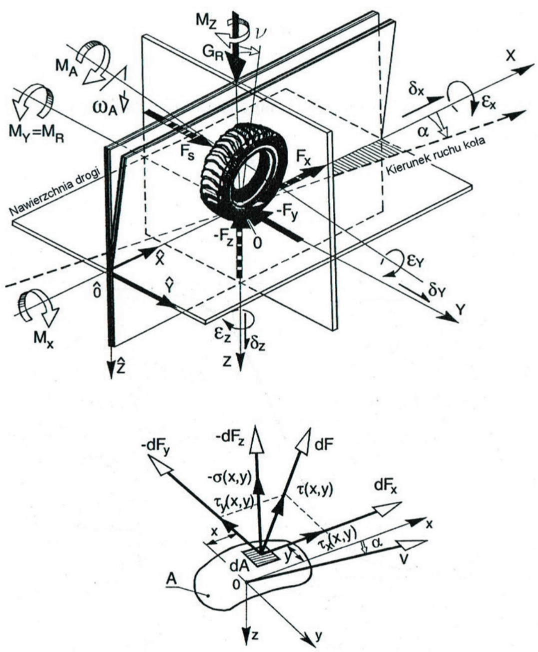


Fig. 1. Illustration of a tyre deformation occurring and forces acting on the tyre during interaction between the tyre and the road surface [7]

In the global approach to tyre stiffness, especially the radial, lateral, and tangential rigidity are important input data in the modelling of both static and dynamic issues related to vehicles, e.g. energy absorption at motion or vehicle body vibrations, including the pitching of industrial vehicles [17]. An equally important role in the effective prediction of machinery behaviour is played by the theoretical tyre models adopted at analytical calculations or implemented in simulation computer programs. On the other hand, it has been shown in the relevant literature that there are such cases of road wheel loading where the classic tyre calculation models do not work. An example may be here the process of start-up of a road wheel [1]. The mechanical characteristics of tyres can be determined with the highest accuracy by experimental tests and such tests unquestionably can contribute to the development of existing tyre models and to the formulation of new models of vehicle tyres.

In the modelling of tyre interaction with "rigid" or deformable ground, the simultaneous tyre deformation in the three principal directions must be known. According to authors' knowledge, many tyre deformation measurement methods are now in the phase of concept or prototype solutions and an accurate and economically reasonable method that could ensure adequate fulfilment of the above task is still unavailable.

With an intention to meet the needs of engineering practice and following a systematic analysis of the current state of the knowledge and technology presented in this article, an attempt was made to develop an innovative method of laboratory examination of the three components of tyre deformation in the process of interaction of the tyre with ground of any kind.

2. State of the art

Due to the importance of the issue of tyre deformation measurements and the said divergence of the lines of research that determine the development of deformation transducers, a wide variety of such transducers have been developed and the diversity of the solutions has resulted in a large number of criteria of their classification. The systematics adopted in this article has been illustrated in Fig. 2.

In the case of contacting transducers, physical contact between the sensing element of the transducer and the surface of the tyre under test is required for a measurement to be carried out. With the non-contact transducers, the opposite is the case. The presence of transducers of these groups within the tyre can be easily noticed, although on the condition that in some cases the tyre would have to be removed from the wheel rim. The sensors integral with the tyre, like those referred as contacting, require a contact of the sensing element with the tyre, but their presence cannot be noticed without disturbing the tyre structure into which they are incorporated. In the classification within these groups, the physical phenomenon on which the deformation measurement is based has been adopted as an additional criterion, with the intended application of the measuring instrument being taken as a criterion of higher order.

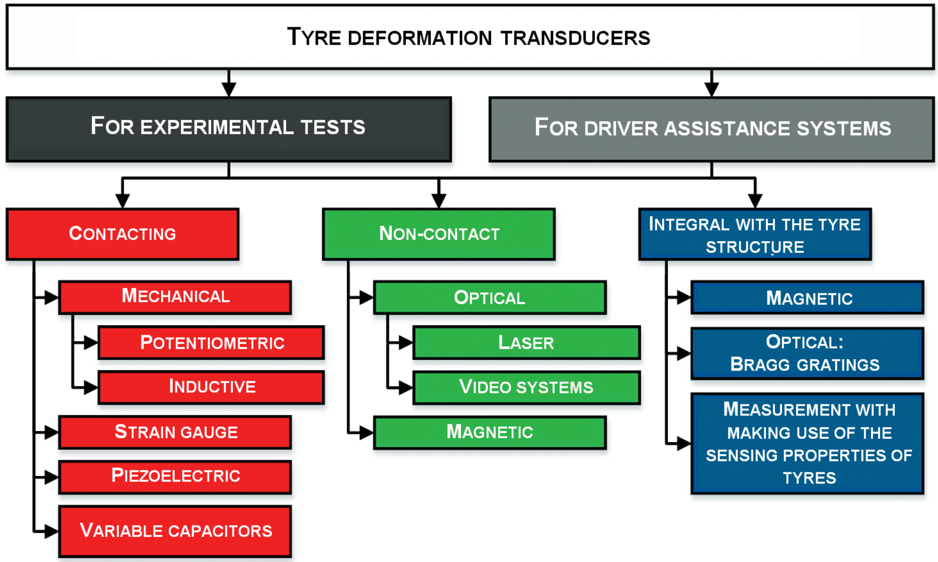


Fig. 2. Classification of tyre deformation transducers discussed in the article

The transducers intended for empirical tests, used e.g. for determining the rigidities and damping coefficients of tyres, are characterized, first of all, by high measuring accuracy. They are built with the use of sensing elements having monotonic, exactly known and repeatable characteristics. Moreover, efforts are made to minimize their impact on the pattern of deformation of the tyre under test. In this group, the transducers that enable direct measurements of the deformation are preferred. In the case of the devices where the measurement is carried out indirectly, the relation between the measurement data produced and the tyre deformation components should be uncomplicated. In consideration of the nature of laboratory tests, which are carried out in most cases on dedicated test rigs, individual components of the measuring system may be placed outside of the tyre and wheel assembly under test. However, the measuring of tyre deformation from outside of the wheel reduces the scope of such measurements to the case of interaction of the tyre with rigid ground. When the measuring system is introduced into the wheel interior, the scope of modifications to the wheel rim and the constructional specifications of a laboratory transducer not always make it possible to balance the road wheel assembly. On the other hand, the load-bearing capacity of the wheel rim and the possibility of fastening it to the test stand structure must be maintained. The wheel assembly has only to be mounted on a vehicle in the case of road tests, but such tests are carried out quite rarely [10, 25]. The reliability of the transducers intended for experimental tests is defined by their immunity to the interference that occurs in the laboratory environment, while the shielding of the interference does not cause any problems. For the sake of convenience of use of laboratory transducers, the time between their successive maintenance operations should be as long as possible, but this period may even be considered acceptable if it covers a single measuring session.

The tyre deformation transducers intended for driver assistance systems are designed to function in vehicles on a permanent basis. They may be used as components of vehicle safety systems of new generation. Therefore, they must meet requirements different from those presented above. If a transducer is to provide the driver with information about the approximate state of the road surface, which may be quantitatively described by the value of the coefficient of adhesion, the rough estimation of the tyre deformation degree will be sufficient. In such a situation, a matter of interest will be the threshold value of the measuring signal, at which the coefficient of adhesion noticeably begins to drop, e.g. due to local icing of the road surface. The knowledge of exact characteristic performance curve of the sensing element is important if the deformation transducer is a component of a safety system that functions separately from the driver, such as ABS or ESP. The transducer's accuracy rating, however, may be lower in comparison with that applicable to the devices used at experimental tests. From the measuring method point of view, the complexity of the algorithm of estimation of tyre deformation components on the grounds of the measuring signal should be such that the safety system coupled with the transducer should be capable of operating in real time. In the case of the group discussed here, the issue of reliability of the measuring device functioning in typical conditions of operation of a road wheel becomes particularly important. The time of uninterrupted transducer operation should be at least equal to the period between successive tyre replacements, whether the tyres had to be replaced for seasonal reasons or, as it is in the case of integral transducers, due to complete tyre wear. The transducer design and the scope of necessary modification to the wheel rim must not detrimentally affect the balancing of the road wheel assembly. In particular, they must not prevent the wheel from being fastened to appropriate components of the vehicle suspension system. The problem of alternating cycles of loading and relaxation of the monitored tyre section should also be taken into account. In normal tyre operation conditions, the number of such cycles is estimated at several million [18]. For contacting transducers, a matter of special importance is the reliability of fixing the transducer to the tyre surface, which may be achieved by e.g. adapting the transducer's modulus of elasticity to the modulus of elasticity of the rubber compound. The factors to which a transducer intended for driver assistance systems should be insusceptible include electromagnetic interference either generated in vehicle components or coming from vehicle surroundings, mechanical shocks, temperature fluctuations ranging from −30 °C to +70 °C, dirt, and the impact of water and chemicals such as oils or fuel.

Contacting tyre deformation transducers

A tyre deformation component that arouses significant researchers' interest is its radial deflection. An intuitive solution of the problem of measuring this parameter is the use of a potentiometric or inductive linear variable displacement transducer (LVDT) placed inside the tyre, with the transducer housing being fixed to the wheel rim and the gauge plunger tip resting on the tyre bottom surface at a selected point. This method is known in the practice of laboratory testing of motor and industrial vehicle tyres loaded in static conditions [2].

A disadvantage of this solution consists, however, in the fact that the point of contact between the gauge plunger tip and the tyre changes when a tangential or lateral component of tyre deformation appears. If these deformation components are not measured then the tyre surface point whose radial displacement is monitored becomes undefined.

Resistance strain gauges in the measurements of circumferential deformation of the tyre belt are exclusively used as reference sensors when examining the characteristics of prototype transducers dedicated to tyre deformation measurements [18, 21, 22]. They are unsuitable for being used as separate tyre deformation sensors because of a difference between elasticity modules of resistor alloys and elastomer materials. The difference is so big that the natural way of elastomer deformation would be disturbed in the area close to the measuring point, due to which the quantitative assessment of tyre deformation, interesting from the researcher's point of view, would become impossible. Besides, this difference would cause problems during long-lasting operation of the sensor in typical road wheel operation conditions as discussed above.

When sensors were sought whose principle of operation would be similar to that of strain gauges and that would be made of a material having the module of elasticity fit to that of the elastomer material, i.e. that would be suitable for permanent use in motor vehicles in their typical operation conditions, the idea of capacitive strain gauges was developed [14, 18, 21]. An important good point of variable capacitors is the possibility of building them as passive transducers, which is implemented by incorporating the sensing element in an RC or RLC circuit provided with a transmitting and receiving antenna. Thus, a radio wave filter is obtained, thanks to which the deformation-dependent circuit resonance frequency in the spectrum of the signal stimulating the transducer is amplified [20, 19, 22].

One of the better sensors of the type as described here is an interdigital capacitor with thin-layer electrodes fabricated on the surface of an elastomer substrate (Fig. 3a), intended for being fixed on the inner tyre surface (Fig. 3b). The tyre deformation in the area close to the place where the capacitor is mounted results in a deformation and relative movement of capacitor electrodes, which translates into capacitance changes. The linear relation between the capacitance and deformation is preserved for over a million loading/relaxation cycles. The basic application of the capacitor in the configuration as shown in Fig. 3b is the measurement of instantaneous circumferential deformation of the tyre belt in the conditions of tyre operation [18]. Such a transducer may temporarily supersede the wheel speed sensors used in present-day ABS systems. At a specific tensile rigidity of the tyre belt, the signal obtained from the transducer also represents the traction force value, used as an input data in the algorithm of controlling the ABS systems of the next generation [21].

In this configuration, the current values of radial deflection of individual vehicle tyres and of the length of the tyre-road contact patch can be additionally monitored. These data are considered particularly important from the point of view of maintaining the optimum value of the area of contact between motor truck tyres with the road surface regardless vehicle load [11]. For the above quantities to be measured, the instants when the capacitor enters and exits the tyre-road contact patch must be identified in the measurement signal; the values of the quantities thus measured are determined from the time spent by the transducer in each of the two tyre zones. A similar method is proposed for measuring

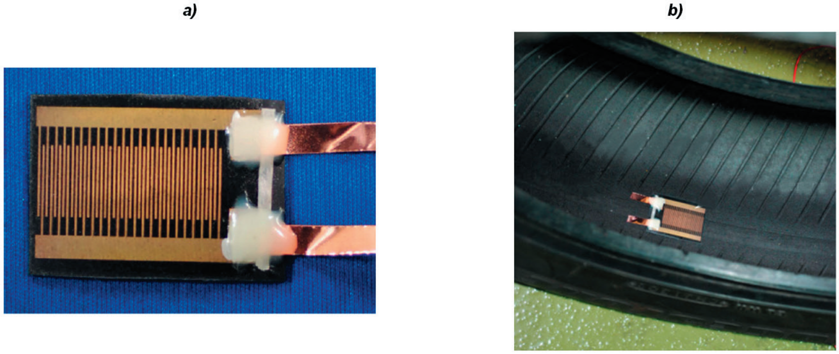


Fig. 3. Variable capacitance tyre deformation sensor: a) interdigital capacitor having a pair of electrodes fabricated by photolithography in a 150 nm gold layer deposited on a rubber substrate; b) tyre adapted to deformation measurement, having the interdigital capacitor fixed on the inner tyre surface [18]

the radial deflection of tyres with the use of piezoelectric sensors [11]. In another method of measuring the radial component of tyre deformation, a capacitor of similar design is fixed on a tyre sidewall in such an arrangement that a tyre sidewall deflection causes the capacitor to be bent around the axis parallel to the electrode fingers [14].

A system similar to the latter solution is based on a concept of a sensor installed inside the tyre in a configuration as shown in Fig. 4. In this case, a tyre sidewall deflection causes the flexible sensor housing to be bent around an axis defined by a V-shaped groove and, in consequence, the distance between a pair of cylindrical filamentary electrodes to be changed [6]. Moreover, an idea is also known according to which a sensor is made in the form of a pair of capacitors (C_1 and C_2, see Fig. 5), whose electrodes are so arranged inside the tyre that in the case of a lateral tyre deformation, the capacitance of one of the capacitors

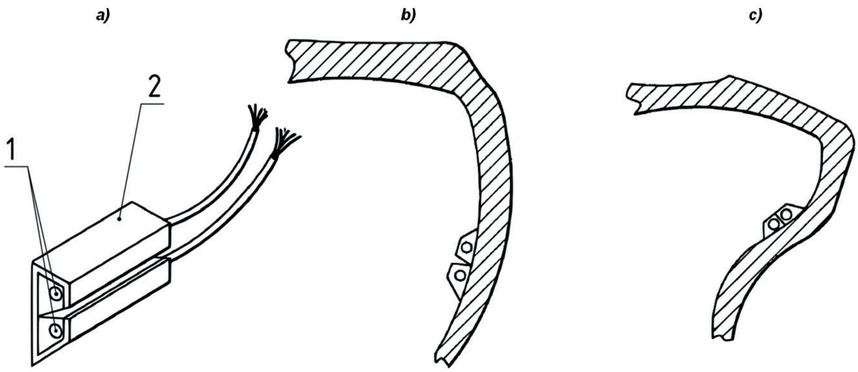


Fig. 4. a) Variable capacitance sensor of the radial deformation of a tyre; b) Sensor fixed to the inner surface of the tyre sidewall, with the sidewall being in a relaxed position; c) Sensor fixed to the inner surface of the tyre sidewall, with the sidewall being deformed owing to the load applied: 1 – electrode; 2 – sensor's housing with a V-shaped groove [6]

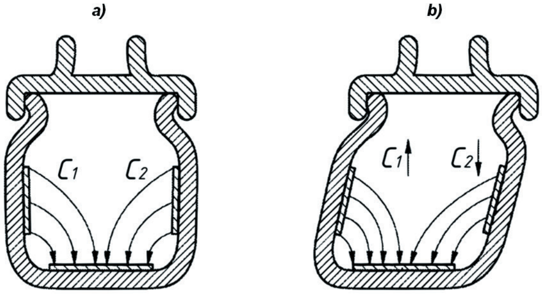


Fig. 5. Three-electrode plate capacitor as a variable capacitance sensor of the lateral component of tyre deformation, with the electrodes having been mounted on the inner tyre surface: a) tyre undeformed, $C_1 = C_2$, b) tyre deformed owing to a lateral force applied, $C_1 > C_2$ [14]

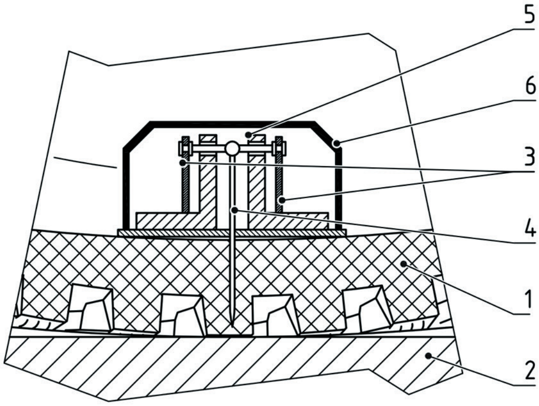


Fig. 6. Cross-section of a set-up (transducer) for the measuring of tread lug deformations with the use of Surface Acoustic Wave (SAW) sensors: 1 – tyre; 2 – road surface; 3 – SAW sensor; 4 – pin (acting as lever); 5 – overload protection; 6 – transducer housing [23]

increases while that of the other one decreases accordingly [14]. However, neither of these two solutions, developed for the purposes of current tyre diagnostics in the conditions of normal vehicle operation, has found wider application, according to authors' knowledge.

An example of a passive transducer, counted among those of the piezoelectric type, may be the one used for measuring tread lug deformations (Fig. 6). It has a pin, which is stuck in the tyre from inside to penetrate the lug. The free end of the pin, protruding above the inner tyre surface and following (as a lever) the lug movements, is connected with piezoelectric SAW sensors (SAW = Surface Acoustic Wave), whose functioning is based on the phenomenon of propagation of acoustic wave on the surface of piezoelectric material. The SAW sensor is excited by radio-frequency electromagnetic wave, whose parameters, such as frequency and phase, are modified by the sensor to a degree corresponding with the degree of deflection of the tyre lug. The transducer has been designed for permanent use in motor vehicles to estimate the current value of the traction force. According

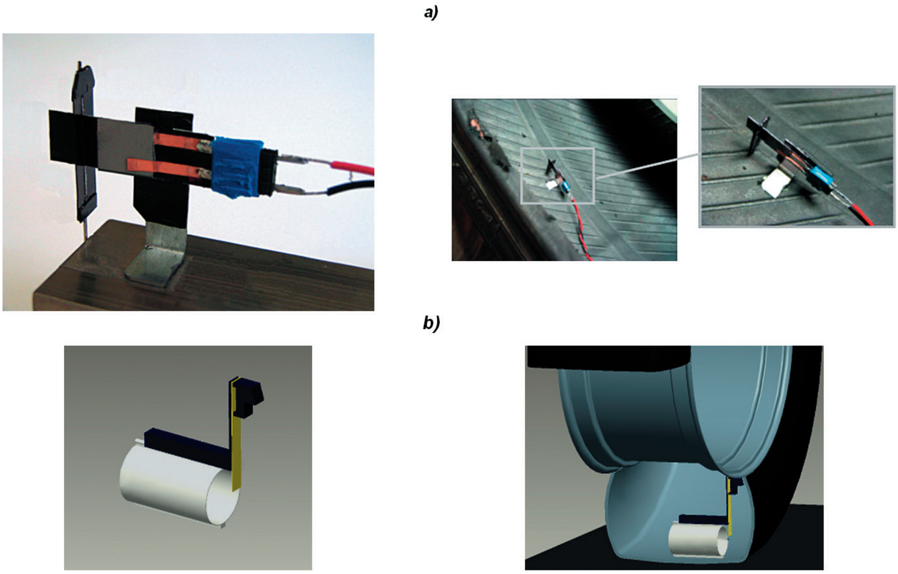


Fig. 7. Examples of piezoelectric transducers for measuring the lateral component of tyre deformation, utilizing a flexible beam coated with PVDF film [10]

to authors' knowledge, the transducer has successfully passed preliminary tests carried out to verify its suitability for this application [23].

The group of piezoelectric transducers also includes polyvinylidene fluoride (PVDF) strips glued onto the outer or inner tyre surface. In laboratory practice, they were used for experimental measurements of radial deflection of tyre carcass and circumferential deflection of the tyre belt in a light mobile robot during the interaction between the tyre and rigid ground when the robot was moving [26]. The PVDF film was also used for the construction of prototype transducers for measuring the lateral component of tyre deformation, where a flexible beam was a critical part of such a transducer (Fig. 7). The method of supporting the beam ends inside the tyre depended on the version of the transducer used (cf. Figs. 7a and 7b). In each case, however, the system configuration was so designed that the voltage generated on the surfaces of the PVDF coat of the beam represented the value of instantaneous increment in the lateral component of tyre deformation. The transducers of this kind have also found application at dynamic laboratory tests carried out to verify an innovative algorithm of estimating the tyre-road friction coefficient [10].

Non-contact tyre deformation transducers

Among the non-contact transducers, systems of optical cameras are the most popular.

One of the more extended systems of this kind is a test stand for laboratory measurements of tyre tread deformation, carried out with the use of a stereovision method (Fig. 8), which is an alternative to other tread deformation measuring methods useful in the tyre designing process. The measurements may be carried out either in static conditions or in the situation that a wheel and tyre assembly is slowly rolled on rigid ground. On the test stand, the wheel assembly pressed against a transparent base plate is observed by a pair of cameras, which synchronously take one photograph each, recording the image of deformed tyre tread in two different views. The coordinates of a single tread point in three-dimensional space are calculated from the coordinates taken from each photograph, camera positions on the test stand, and calibration data. The determining of the three-dimensional coordinates of the tyre points visible in both photographs makes it possible to reconstruct the tread surface topography [15].

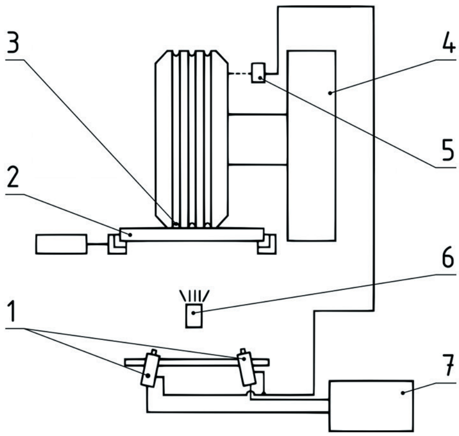
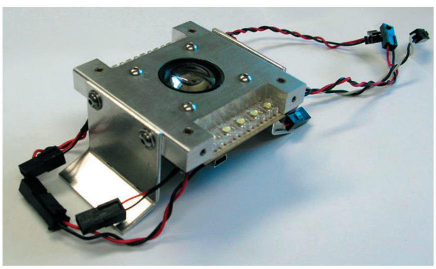


Fig. 8. Laboratory test stand with a stereovision system for measuring the geometrical dimensions and deformation of tyre tread: 1 – cameras; 2 – transparent base plate; 3 – tread grooves deformed when being in contact with the base plate; 4 – wheel loading device; 5 – synchronized camera release system; 6 – illuminator (light source); 7 – computing unit [15]

a)



b)

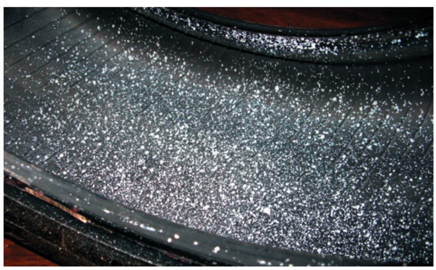


Fig. 9. a) Camera adapted for being mounted on the wheel rim inside the tyre, intended for tyre deformation measurements; b) inner surface of the tyre, with a random speckle pattern applied to it [13]

A reduction in the number of cameras to one and individualized construction of the camera (Fig. 9a) make it possible to analyse the tyre element displacements in three directions and the rotation of tyre surface in relation to the wheel rim as seen from inside of the wheel [13, 16]. The data used to compute individual tyre deformation components are obtained from photographs of the inner tyre surface coated with a random speckle pattern (Fig. 9). The values of the tangential and lateral components of tyre deformation are estimated with the use of an algorithm tracking the movement of the reference speckle pattern in the plane perpendicular to the optical axis of the lens. The radial component is represented by the apparent change in the size of elements of the speckle pattern in the image recorded and by the degree of loss of the image sharpness.

As a target, this solution is to be used for current analysis of the process of interaction between the motor vehicle wheel and the road surface. As far as the authors know, this solution is now at the prototype stage. Preliminary validation of the measurement method was only carried out in the conditions of static load being applied to the wheel by means of a strength-testing machine. During the validation tests, an error of the method was revealed, which was caused by imperfections in the workmanship of the lenses used in the optical system of the camera (Fig. 9a). The imperfections practically cannot be eliminated during typical manufacturing process of lenses. So as to provide sufficient measurement accuracy of the method, influence of said imperfections has to be taken into account by the algorithm of computing the tyre deformation components, especially when it comes down to the radial component estimation. As proposed within the method under consideration is characterized by a high degree of complication and high computational complexity. This is incompatible with the idea of real-time operation of a traction control system. At the present stage of development, the striving for simplification and miniaturization of the camera construction with simultaneously maintaining the optimum image sharpness additionally requires the geometrical parameters of the optical system to be fitted to the dimensions of the tyre under test [13]. At the moment then, both the measuring method requiring the use of a camera and the transducer per se should be classified in the group of solutions intended for experimental tests.

The energy consumption of the cameras is an additional factor that makes it difficult to use them for remote measurements, especially for tests where high-speed wheel movement is involved. A more energy-saving optical transducer, which however may theoretically be useful in simultaneous measurements of tangential, lateral, and radial components of tyre deformation, is similar in constructional terms to the camera, but the conventional CCD (Charge-Coupled Device) or CMOS (Complementary Metal-Oxide Semiconductor) matrix has been replaced with an analog position-sensitive detector in the form of a monolithic photosensitive semiconductor wafer responding to a change in the position of a point light source. The tyre deformation components are measured by tracking, with the use of the transducer, the movements of an LED fixed at a selected point on the tyre bottom surface [25]. According to authors' knowledge, this is the only solution among the non-contact devices that was successfully used for experimental tests in road drive conditions. During such tests, however, the radial tyre deformation measurement, although theoretically feasible, was found to be impracticable due to a problem with the stabilization of the intensity of light emitted by the diode used. Nevertheless, this drawback did not disturb the estimation of the traction forces in the tyre-road contact area and the examination of tyres in the aquaplaning conditions [25].

In the group of non-contact transducers, the use of laser heads for examining the radial component of tyre deformation in military vehicle wheels interacting with flexible ground is also known (Fig. 10a). The measurements with the use of such heads are carried out on a test rig in static wheel load conditions. The distance between the wheel rim surface and the tyre bottom is measured in the lateral and circumferential wheel coordinates. The laser head, immovable in relation to the wheel rim, measures the distance between the rim and the tyre bottom points in the lateral plane related to the wheel. The scanning of successive lines along the circumferential tyre coordinate is done by moving the head on a carriage driven by a stepper motor along a curved toothed guide with a curvature corresponding to that of the wheel rim, over an angular range of ±30 ° from the centre of the tyre-road contact patch (Fig. 10b). In result of this, both the contour of the selected longitudinal tyre cross-section and the shape of the tyre-road contact area can be determined [2]. This solution has been successfully introduced into the market and now it is offered commercially [28].

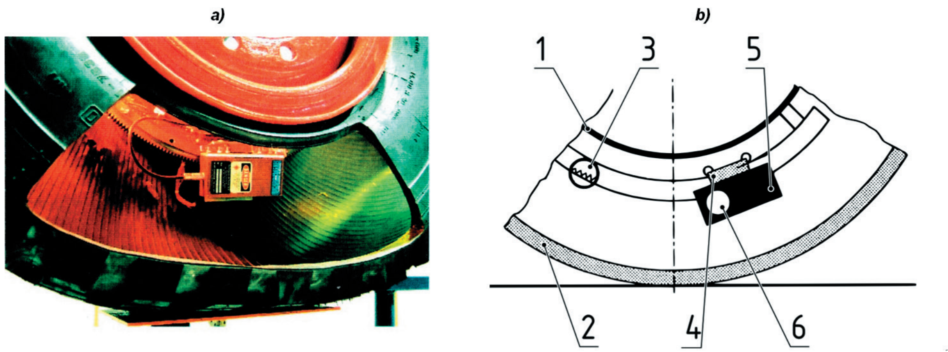


Fig. 10. Laser head adapted for measuring the radial component of tyre deformation: a) laser head assembly installed inside a tyre; b) measuring setup schematic: 1 – rim; 2 – tyre; 3 – toothed guide; 4 – self-propelled laser head carriage; 5 – laser head; 6 – stepper motor [2]

Tyre deformation transducers integral with the tyre structure

A solution classified somewhere between the groups of non-contact and integral transducers is a system where magnetic field sensors are used. In such a system, a belt consisting of alternately arranged opposite magnetic poles is incorporated into a tyre sidewall and undergoes deformations together with it; the belt generates a rotating magnetic field, which is detected by sensors (magnetoresistors or Hall effect sensors) deployed on suspension system components (1 and 2 in Fig. 11). Thanks to the sensor arrangement in relation to the tyre, the size of the radial component of tyre deformation is represented by the difference in the phases of the signals received from the sensors, while the lateral component is measured by the signal intensity. This system is intended for permanent use in motor vehicles; it is a part of a system capable of estimating the values of the forces acting at the contact of individual wheels with the road surface. According to intentions of the authors of this concept, such a system may be used as a substitute for the accelerometers and wheel speed sensors used in present-day motor vehicle safety systems [12]. However, the authors of this article have not met with any implementation of the patent that describes such a system.

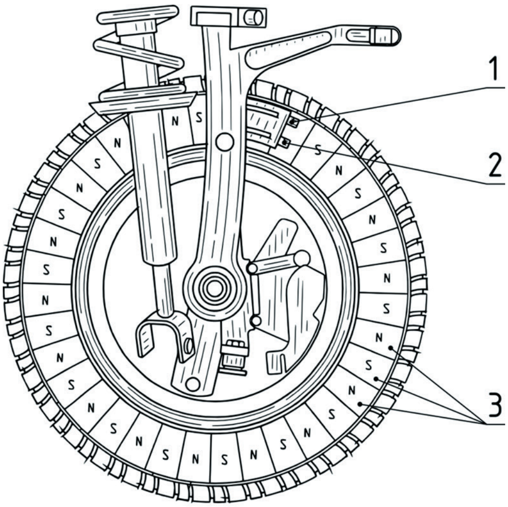


Fig. 11. System with magnetic field sensors being used for measuring the tangential and lateral components of tyre deformation: 1, 2 – magnetic field sensors (magnetoresistors or Hall sensors); 3 – alternating magnetic poles fabricated in a ferromagnetic band incorporated into the inner surface of the tyre sidewall [12]

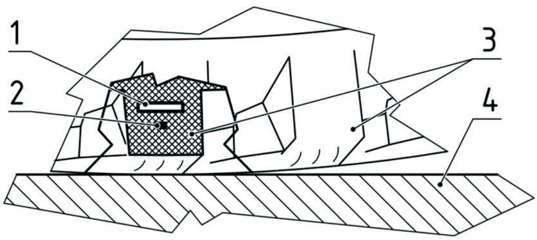


Fig. 12. Integral magnetic sensor of tread lug deformation, based on on a matrix of Hall sensors; schematic diagram of the measuring system: 1 – integrated circuit with a matrix of Hall sensors; 2 – permanent magnet; 3 – tread lugs; 4 - road surface [27]

A typical example of the transducers integral with the tyre structure is the magnetic transducer for measuring the deformation of tyre tread lugs. In such a device, a matrix of Hall sensors arranged on a cruciform plan is incorporated into an integrated circuit intended for being implanted in a pair with a small-size permanent magnet into a tyre tread lug (Fig. 12). The location of the magnet in relation to the matrix, which translates into the level of signals produced by individual Hall sensors, changes due to compression and bending of the flexible tread lug in the tyre-road contact zone. The solution presented here is the second to that shown in Fig. 6, intended for permanent use in motor vehicles in order to estimate the current value of the traction force based on the degree of deformation of tread elements. Contrary to that discussed previously, however, this solution has not been verified in road drive conditions, as far as the authors know. The information processing characteristics of the integrated circuit have only been determined for the transducer-magnet pair having not been incorporated in a tyre tread element [27].

Another type of the sensors suitable for being integrated into the tyre structure covers the sensors based on the use of fibre-optic Bragg gratings. A single optical fibre integrated into the tyre carcass circumferentially in relation to the tyre belt makes it possible to determine the contour of the deformed tyre in a selected longitudinal cross-section of the wheel. The placing of a group of optical fibres in mutually parallel planes provides a possibility of obtaining an image of the tyre surface, and especially of estimating the area and shape of the of the tyre-road contact patch, whether in laboratory rig testing or in typical road drive conditions. Subsequently, the tyre deformation measuring system presented may be used for indirect measurements of the tyre inflation pressure as an alternative for the tyre inflation pressure monitoring systems used in motor vehicles at present. In comparison with the other solutions being now available, a distinguishing feature of the fibre-optic sensors, being an argument for their wider application, is the fact that they additionally make it possible to measure the tyre temperature [3].

An alternative to the tyre deformation methods discussed above is the method where the sensing properties of the tyres are used, without the application of any additional sensing elements. An essence of such a method, similar to that of the method presented previously, where an interdigital capacitor is used to measure variable capacitance, is the measurement of the capacitance of a capacitor formed by mutually parallel tyre belt wires separated by rubber compound and connected together into two electrode groups, with the resistance of the rubber compound varying as a function of tyre deformation. At the present tyre development stage, the use of such a method requires the tyre structure to be disturbed (Fig. 13) and the capacitance of the capacitor thus formed is so small that the parasitic capacitances of the system cause unacceptable disturbance to the measuring signal. In the form as presented, therefore, the usability of this method for both laboratory experiments and current monitoring of tyre condition in road driving conditions is quite low [19].

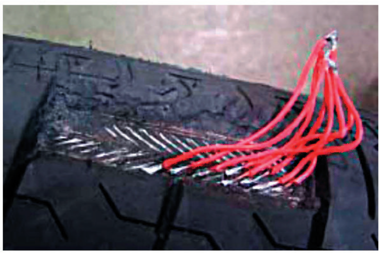


Fig. 13. Tyre prepared for sensorless measurement of tyre belt circumferential strain; deformation measurement based on investigation of the relationship between tyre belt strain and capacitance of an interdigital capacitor composed of tyre belt wires (as electrodes) and rubber (as a dielectric material) [19]

3. Recapitulation

This article offers a review of the state of the art in the field of vehicle tyre deformation transducers. The transducers counted in each of the groups having been discussed (Fig. 2) are characterized by a unique set of features, which exclude each other in many cases but predispose individual solutions to various applications (Table 1).

The contacting transducers known up to the present do not offer a possibility of simultaneous measuring of more than two tyre deformation components and the measurement of the tangential component by means of such transducers is definitely impossible. In addition to this, the accuracy of estimation of the radial component depends on the degree of the details taken into account in the theoretical tyre model adopted as a basis in the estimation algorithm, where additional input data, e.g. tyre inflation pressure, are required in selected cases [6]. Nevertheless, the results of measurements carried out with the use of contacting transducers seem to be the most reliable because the relation between the measuring signal and the deformation of tyre structure is in most cases rather uncomplicated. Within the scope as presented in this review, the only good point of the contacting sensors whose functioning is based on the phenomenon of propagation of surface acoustic wave (Fig. 6) and of the variable capacitors (Fig. 3), considered important in terms of development of the idea of "intelligent tyres", is the possibility of building passive transducers based on them. Other advantages of most of the contacting transducers discussed here include small dimensions and low mass, which have practically no impact on the wheel balancing, and the easy way of installation of such transducers on the surface of even the tyres that have already been in production.

The optical transducers, being most popular among those of the non-contact type, offer a possibility of comprehensive and non-invasive measurements of tyre deformation. Their distinctive good point is the potentially large number of measuring points whose movements can be recorded during a single measuring session, so that the mapping of the surface of a tyre having been deformed is theoretically feasible. However, the computation algorithms applicable to most of the methods where the use of cameras is involved are characterized by a high degree of complication and significant computing complexity, arising from the necessity to compensate the errors caused by imperfections of optical instruments. On the other hand, the failure to take into account the necessary corrections would prevent adequate estimation of the radial component of tyre deformation. In consequence, the coupling of the camera with the traction control system will require a compromise between the yield and accuracy of the tyre deformation calculations carried out. In spite of the absence of physical contact between the tyre and the wheel rim, the flexibility of the optical methods is limited because of the necessity of accurately fitting the geometrical parameters of the camera's optical system to the dimensions of the tyre under test. In addition to this, cameras used as transducers are characterized by high energy consumption, which reduces their suitability for road tests. The only non-contact solution among those presented here that has been verified in road driving conditions is the system that tracks the movements of an LED fixed at a selected point to the tyre bottom surface, although the measurement of the radial component of tyre deformation was found to be impossible in this case as well. A distinctive feature of the magnetic non-contact method is the fact that no signal has to be received from rotating parts. Due to the necessity of fixing the sensors to parts of the vehicle suspension system, however, the flexibility of the suspension system and its components is a source of measurement errors.

Table 1. Summary of the discussed state of the art in the field of tyre deformation transducers, with an assessment of the solutions presented at the present development stage:
„–" – transducer unusable at all;
„+" – transducer of low usability;
„++" – transducer of medium usability;
„+++" – transducer of high usability

Transducer			Measured value									Usability	
			Carcass deformation						Tread deformation				
Group	Subgroup	Sensing element	Tangential component of the tyre deformation	Lateral component of the tyre deformation	Radial component of the tyre deformation	Torsional deformation	Circumferential deformation of the tyre belt	Envelope and area of the tyre-road contact patch	Tread lug bending	Tread lug compression	Tyre temperature	For experimental tests	For driver assistance systems
Contacting	Strain gauge	Resistance strain gauge					x					+	–
Contacting	Mechanical	Potentiometer			x							++	–
Contacting	Mechanical	Inductive transducer LVDT			x							++	–
Contacting	With variable capacitance	Interdigital capacitor			x		x					++	+++
Contacting	With variable capacitance	Bifilamentary capacitor			x							+	+
Contacting	With variable capacitance	Plate capacitor		x								+	+
Contacting	Piezoelectric	PVDF film			x		x					+	+
Contacting	Piezoelectric	Flexible beam coated with PVDF film		x								++	+
Contacting	Piezoelectric	SAW sensor							x			++	+++
Non-contact	Optical	CCD matrix, a pair of cameras							x	x		+++	–
Non-contact	Optical	CCD matrix, a single camera	x	x	x	x						+++	+
Non-contact	Optical	Monolithic photosensitive wafer	x	x	x							++	++
Non-contact	Optical	Laser head			x			x				+++	–
Non-contact	Magnetic	Pair of magnetoresistors	x	x								+	++
Integral	Optical	Fibre-optic Bragg grating			x			x			x	++	+++
Integral	Magnetic	Matrix of Hall sensors							x	x		++	++
Integral	Sensorless	Tyre structure elements					x					+	–

The transducers incorporated into the tyre structure make the less numerous group, which is characterized by a narrow spectrum of their applications and by limited number of the tasks to be carried out by them simultaneously. However, the negligible impact on wheel balancing and anticipated high immunity to external influences may be considered their important advantage because of opening the door for them to commercial applications. A unique feature of the fibre-optic transducers is their capability of measuring the tyre temperature, which is particularly valuable as the monitoring of this parameter makes it possible to prevent tyre blowout caused by overheating. In spite of distinct advantages, the integration of sensing elements into the tyres being already in use is inevitably connected with disturbing the tyre structure; in the case of new tyres, such a solution significantly raises the tyre cost because of both the prices of the sensing elements as such and the considerable complication of the tyre manufacturing process. Some of these methods, e.g. the measurements based on the making use of the sensing properties of tyres, have not been sufficiently refined yet.

To sum up, many of the solutions known from the state of the art in the field of transducers for measuring the tyre deformation are still at the prototype stage. A transducer that would have an established position and would be free of serious drawbacks is still unavailable. In particular, there is no device that would make it possible to carry out comprehensive measurements of tyre deformations, i.e. measurements combined with separation and recording of a number of tyre deformation components at the same time, where a relatively low level of complication of the computation algorithm would be simultaneously maintained. An attempt to combine these objectives was made when developing an original concept of a mechanical contacting transducer for experimental tests [8, 9]; the said concept will be presented in the second part of this article.

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