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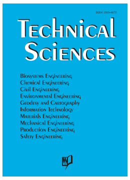

MAGNETIC FIELD OF A RADIAL TIRE AFTER PUNCTURE CAUSED BY FERROMAGNETIC ELEMENTS

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Abstract

Tire, an element of wheel, is made in a sophisticated vulcanization process of many components and some of which such as: bead wire, belt and carcass exhibit ferromagnetic properties. Such components create variable in direction and intensity magnetic field, which expands around tire and the complete wheel. Since the layout of magnetic field is exceptional for every single wheel many of information might be obtained on the basis of it alteration. The reported since now application concentrates on rotational speed measurement, wheel rotations counting and therefore also vehicle linear speed and distance estimation. However up to the present the known solutions did not describe changes in magnetic field in case of damage induced by e.g. puncture caused by ferromagnetic elements. This paper's aim is to test the thesis that it is possible to detect puncture in tire made by ferromagnetic element by using measurement and analysis of changes of magnetic flux density around tire. The tests were executed using original measuring device, designed especially for such experiments. It registers a magnetic profile, which consists of data series of magnetic flux density measured in this investigations 55 mm above tire's tread and arranged along with rotation angle. Tire magnetic properties were assessed by using of circumferential magnetic profiles and parameters such as: minimum value ($M_{\min}$), maximum value ($M_{\max}$), peak to peak value (M_m), average value of ordinates of profile (M_b), skewness of ordinate distribution (M_s) and kurtosis of ordinate distribution (M_k). Magnetic profiles before after puncture were analysed as well as the parameters. Moreover differential signal caused by puncture were determined. It turned out that detected changes are directly related to tire damage and showing in rotation angle where puncture occurs.

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Introduction

Monitoring condition of tires in the context of detecting a potential tire's puncture is important for road traffic safety. Tire puncture could lead to diminishing tire pressure which may affect car stability and control. The rate of pressure changes is a separate aspect. It could be slow, when driver has time to react and counteract to effects of fall in tire pressure unless the fall is rapid which frequently ends in a serious damage to wheel, vehicle or other vehicles in traffic. Because of that modern vehicle has been endowed in systems diagnosing selected wheel parameters. An example of such a system is TPMS (Tire Pressure Monitoring System). This solution can be direct or indirect. Indirect system (monitoring) detects difference in dynamic radius of the wheel in car and on this basis indicates which tire in vehicle has lost pressure. Direct system (diagnosing) determines a state of a wheel on the basis of pressure measured in a tire.

Car tire is a complex element created in a multi-stage process. Some components of a tire i.e. bead wire or carcass have ferromagnetic properties and their magnetic field can be measured with resistomagnetic sensors (GONTARZ, RADKOWSKI 2011, CHMIELEWSKI et al. 2011, BROL, SZEGDA 2017). Changes in the magnetic field created due to puncture of a tire with a ferromagnetic penetrator might constitute a basis for wheel diagnosis.

In previous research of the magnetic field around a wheel the focus was mainly directed on examining the influence of low frequency changes in magnetic flux density on human health. In the position by (JENS 2002) the distribution and strength of the magnetic field in different vehicles were compared. Magnetic flux density value was measured in eight points of the vehicle when the engine was running and, e.g. running alternator, fuel pump and other devices in a car that generate magnetic field. The measurement was made using TriField meter by Alpha Labs. The researchers in investigation determined a EMF distribution (Electromagnetic Field) at driver's seat. In the article (GAJŠEK et al. 2010) it was also claimed that hybrid cars have stronger magnetic field than cars with traditional diesel or gasoline engines. In the works MILHAM et al. (1999) and STANKOWSKI et al. (2003) an influence of low frequency changes in the magnetic field of radial tire on human health was examined as well as distribution of the field in a car. By using fluxgate magnetometer (Walker FGM-301) and a simple magnetic compass (R.B. Annis Company, Magnetic Equipment) changes of the magnetic field in both new and old tires were examined. The researchers carried out research on radial tires before and after demagnetization. They concluded that a magnetic field value is directly related with magnetism of a steel wire used in tire. In the paper the researchers have also analyzed changes in tire magnetic field by magnetizing and demagnetizing it in a controlled way. The magnetic field was registered by NARDA EFA200 Electromagnetic Field Analyzer together with a BN2245/90.10 field probe (Telemeter

Electronic, Ellighausen, Germany). The results confirmed that tire magnetism is affected by steel wire located in a tire, moreover it was noted that used tires are characterized by higher magnetic field variance that new ones. Areas in a car were also isolated, characterised by different intensity of low frequency magnetic field change.

In the cited articles (GAJŠEK et al. 2010) the focus was mainly on determining magnetic field distribution in different vehicles as well as on the influence of this magnetic field on human health. It was concluded that car tires create magnetic field. Statistical parameters e.g. maximum value, minimum value and peak to peak value were used to describe changes in magnetic field (MILHAM et al. 1999). It was also determined by what sensors a wheel magnetic field may be measured. Nevertheless none of the discussed works concerned research of magnetic field changes caused by puncture e.g. with a ferromagnetic penetrator.

Knowing changes of the magnetic field caused by puncture one may create opportunity to create a system which will warn the driver about possible puncture of a tire on the basis of changes in the magnetic field as a result of tire penetration.

At the moment 3 patent solutions concerning registration of tire magnetic field changes are known. Two US patents 6404182 B1 (*Method for detecting the magnetic field of a tire*) and US 6246226 B1 (*Method and apparatus for detecting tire revolution using magnetic field*) describe a way of measuring rotational speed and distance travelled by previously magnetized wheel (KAWASE, TAZAKI 2001, KAWASE et al. 2001). Polish patent 401304 (22)2012 10 22 (*The method of measuring wheel speed of a road vehicle and the system for measuring wheel speed of a road vehicle*) uses changes in wheel's natural magnetic field to register changes in angular speed of wheel. In the latter solution changes in the magnetic field are registered by a sensor mounted in a car. Other solutions require mounting additional elements which may influence the obtained results (BROL et al. 2014). Because of variety of technical solutions for measuring changes in magnetic field generated by a spinning wheel it was decided to build original measuring stand, which assures measurement of changes in magnetic field of a tire caused by puncture with ferromagnetic penetrator in a repeatable and controlled way.

The main assumption was to arrange magnetic flux density measurements in function of rotation angle which was not done by the predecessors because they applying magnetic flux density measurements in time domain. A measurement in function of wheel rotation angle enables a comparison of a state of a magnetic field both before and after puncture, if the examined wheel does not change its angular location to the spindle of the device during puncture.

Methodology of data gathering and analysis of the results

The research was carried out by using an original measuring device designed by Szegda and Brol. Devices kinematic diagram was shown in Figure 1*a* (Brol, Szegda 2017, Szegda, Brol 2017) and variability ranges of it parameters were shown in Table 1.

Table 1

Physical quantity and value of measurement device

Physical quantity	Value	Physical quantity	Value
Mass	40 kg	Measuring projections of **B** vector	3, (B_x, B_y, B_z)
Height	1022 mm	Sample frequency	75 Hz
Width	867 mm	Spindle speed	0.052–0.52 rad/s
Rims diameter	from 12” for 21”	Angular resolution	0.0015 rad
Kind of rims	Steel/light alloy	Type of **B** sensor	HMC5883L

A characteristic feature of the device is the fact that the magnetic flux density (**B**) sensor is located in a measuring arm, which enables carrying out research in different distances and orientation to the wheel rotation axis. Measurement and electric engines steering is done by the two separate microcontrollers (Fig. 1*b*) intentionally located in different places to eliminate their mutual influence and minimize mutual interference.

Moreover the device enables examination of either a wheel or a tire due to the fact that two different fixtures were designed.

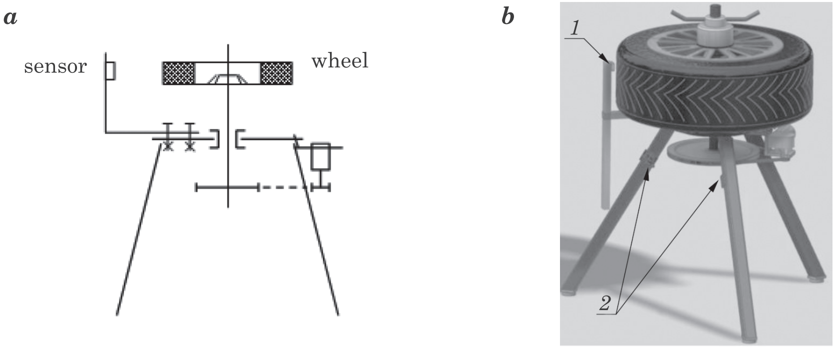

Fig. 1. Kinematic diagram of the measuring device (*a*) and the measuring device (*b*), where: *1* – measuring sensor, *2* – microcontrollers, respectively measuring and steering
Source: *a* – Brol, Szegda (2017), *b* – Szegda, Brol (2017).

The effect of the measurement is so called magnetic profile, consisting of organized values of one of magnetic flux density vector **B** constituents, as shown in Figure 2. It may be measured at sensor mounting point in three measuring directions B_x, B_y, B_z.

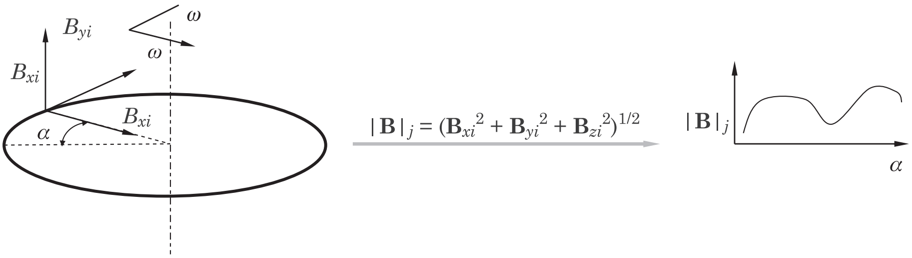

Fig. 2. Sensor orientation and magnetic profile creation diagram

Resultant profiles |**B**| were subject to further analysis. The |**B**| was chosen in this case because it counts changes at three measuring directions.

An object of the research was a radial tire (175/70 R14). The measuring sensor was located 55 mm over the tread of the tire and 765.5 mm from the ground.

At the beginning a measurement was done which was considered to be referential. An opening was made in tread with a 2 mm diameter drill. Next a ferromagnetic penetrator (a screw used for wood screwing) was screwed into an opening. After the penetrator was inside the opening, another measurement was made. The 2 mm diameter drill was chosen because in this case drilling did not tear steel belt wires and thus it did not alter magnetic signature of the wheel. Only screw penetration altered magnetic field of a tire (and of course the wheel). During the experiments wood screws of different, origin, diameters, and lengths served as penetrators as shown in Table 2. The different origin of wood screws were chosen to check if it may influence on results alignment. Moreover the puncture may be caused by different randomly distributed objects laying on the road.

Table 2

Diameter and length of the ferromagnetic penetrators used in research

Penetrator’s number	Diameter [mm]	Length [mm]
1	2.5	10
2	2.8	20
3	3.7	25
4	4.7	27

Magnetic profiles were analyzed before and after penetration as well as their parameters and differential profile (a series of results of algebraic subtractions of magnetic flux density before and after puncture for the same angular position along profile) as well as parameters of differential profile. This procedure was repeated four times for every penetrator. Thus obtained profiles were analysed by using statistical parameters and adopted from surface roughness analysis, described by formulas (1–6), presented in the Table 3.

Table 3

Parameters of magnetic profiles

Parameter name	Unit	Formula	Formula number
Minimum value	$\cdot 10^{-7}$ T	$M_{\min}$= min. (B_i)	(1)
Maximum value	$\cdot 10^{-7}$ T	$M_{\max}$= max. (B_i)	(2)
Peak to peak value	$\cdot 10^{-7}$ T	$M_m = M_{\max} - M_{\min}$	(3)
Average value of ordinary of profile	$\cdot 10^{-7}$ T	$M_s = \frac{\sum_N^{i=1} B_i^3}{N}$	(4)
Skewness of distribution of ordinates	$(10^{-7}\text{ T})^3$	$M_s = \frac{\sum_N^{i=1} B_i^3}{N}$	(5)
Kurtosis of distribution of ordinates	$(10^{-7}\text{ T})^4$	$M_k = \frac{\sum_N^{i=1} B_i^4}{N}$	(6)

B_i – measured magnetic flux density value described by i index, i – measurement number around the perimeter from 1 to N.

Results

Analysis of profiles before and after puncture

At the first part of examinations the magnetic profiles of |**B**| were compared before and after puncture. In all cases the differences are barely visible. The reason for that is that the penetrator caused magnetic flux density changes of several dozen 10^{-7} T while |**B**| values in profiles changed values in a range of more than a thousand 10^{-7} T. The penetrator introduced changes 100 times smaller than range of profile variability. Obviously magnetic flux density changes depend on the distance between sensor and tread but in this case (55 mm from a tread) change in values for this examined wheel caused by penetrators were of several dozens 10^{-7} T. It is especially visible in Figure 3 after puncture it with the penetrator 2 (Fig. 3*b*) and biggest ferromagnetic penetrator (Fig. 3*c*).

In case of $M_{\min}$, $M_{\max}$ and M_m parameters (Tab. 3) which represents the smallest and the highest value of |B| in profile, the values change in this case is caused rather by measurement noise than by penetrator itself because

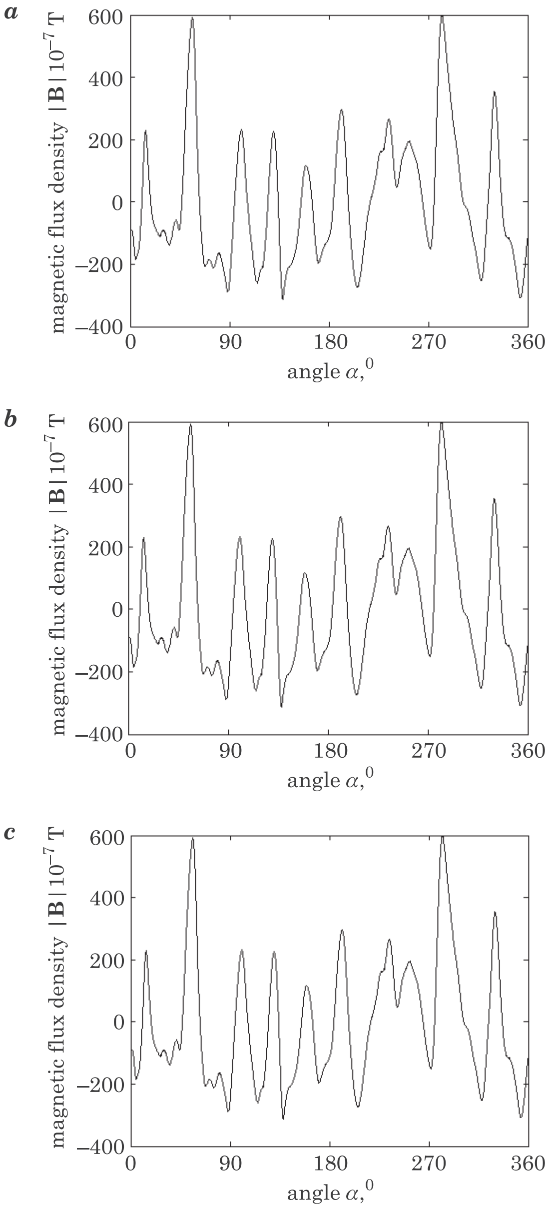

Fig. 3. Magnetic profiles of |**B**|: referential (*a*), and after penetration with penetrator 2 (*b*), penetrator 4 (*c*)

Table 3

Average values of parameters describing changes of magnetic profiles before and after puncture made by ferromagnetic penetrator

Penetrator number	Reference		After puncture	
	$M_{\min}$	$M_{\max}$	$M_{\min}$	$M_{\max}$
1	–312.48	606.21	–312.95	606.53
2	–313.59	597.00	–313.24	596.40
3	–314.34	598.90	–313.80	598.62
4	–313.50	597.84	–313.59	597.92
	M_m	M_b	M_m	M_b
1	918.69	166.38	919.48	166.29
2	910.60	165.48	909.64	165.61
3	913.24	165.76	912.42	165.68
4	911.34	165.45	911.52	165.55
	M_s	M_k	M_s	M_k
1	0.79	3.14	0.79	3.14
2	0.82	3.21	0.81	3.21
3	0.82	3.22	0.82	3.22
4	0.82	3.22	0.82	3.22

the puncture place is not in the same angular position with max and min value of profile. Only if such alignment will happen the $M_{\min}$, $M_{\max}$ and M_m would be sensitive to tire damage.

The M_b parameter represents the mean value ant therefore should be not sensitive to noise with median equal to zero. Since measurement noise may be assumed to be constant and sample count is sufficient (2048) than any change in M_b value should be caused by profile shape change – the effect of penetration. The difference in this investigations are about 0.1 to 0.2 $\cdot 10^{-7}$ T, which suggest that this value, because of its averaging property, "reacts" with very small increase on puncture. The same can be told about M_k and M_s parameters.

Analysis of differential profiles

At the next stage of investigations differential profiles (Fig. 4) of value |B| were analyzed.

The differential signal shown in Figure 4*a* differs from others. The signal course and distribution is similar to that of magnetic sensor when no magnetic field of tire were present during measurement. Therefore, it can be concluded that penetration with a 2.5 mm screw does not change the image of the measured magnetic field. This can be explained by the fact that, as a result of drilling and subsequent screwing, the steel belt was not damaged (see Fig. 5).

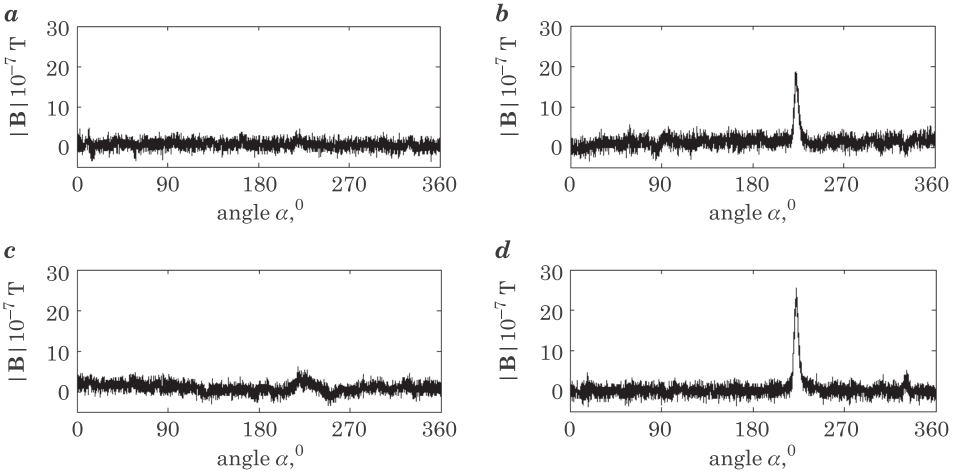

Fig. 4. Differential profiles after puncture for used penetrators

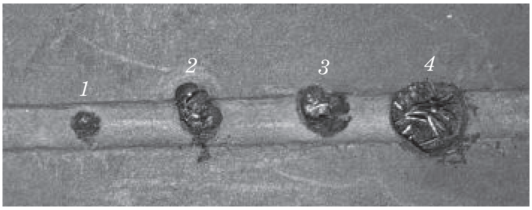

Fig. 5. Holes after penetration. Good visible damage to the belt, especially in the second and fourth hole

A drill with a diameter of 2 mm and later a 2.5 mm screw penetrated the tire in such a way that it did not damage the belt wires. The belt is made of two layers of wire one over the other. The wires in each layer are guided parallel to each other and at an angle to the longitudinal axis of the tread. The lower layer has already routed wires from another angle.

From this it follows that if the penetrator has a sufficiently small diameter it does not damage the belt and thus does not change the magnetic field of the tire in a detectable manner with the measuring instrument used in these tests. This can be due to a circumferential resolution (0.46 mm) for this measurement device settings and for this free wheel radius. In addition, the distance between the sensor and the tread (55 mm) may be too large for this specific penetrator (3.7 mm in diameter). Farther investigation will be performed in the future to settle this dilemma.

In the signal before and after the penetration, a clear "peak" was observed at the penetration site of the tire in three of four cases (Fig. 4*b*–*d*).

The largest “peak” was observed after using Ø4.7 mm diameter penetrator, which was greater than the peak after penetration of 2.8 mm by 6.8 10^{-7} T. Interestingly, the 3.7 mm penetrator generated the smallest “peak” in these tests. It is assumed that this may be due to other magnetic properties of the material used for its production than for the other penetrators. Parameter values describing differential profiles are summarized in Table 4.

Table 4

Selected values of parameters of differential magnetic profile

Differential profile parameters	Number of penetrator			
	1	2	3	4
M_{min}	–3.61	–3.56	–3.58	–3.87
M_{max}	4.74	18.55	6.23	25.43
M_m	0.55	1.33	0.94	0.40
M_b	1.09	1.94	1.26	2.23
M_s	–0.02	3.03	0.06	5.49
M_k	3.14	23.91	3.16	47.74

It can be noted that all the parameters applied on differential profiles (beside M_{min}) change their values due to the tread break. The smallest changes were observed for the impact of penetration with a penetrator of 3.7 mm in diameter but further mean values were higher than for that penetrator of 2.5 mm diameter.

The greatest increase in values was observed for the M_k parameter (Fig. 6). The M_k value describes the statistical moment of the fourth order of distribution of the ordinates of the profile and is therefore sensitive (as M_s) to the local peaks. The mean value of M_s as a result of the puncture changed from a negative near zero (actually oscillating around zero) to positive.

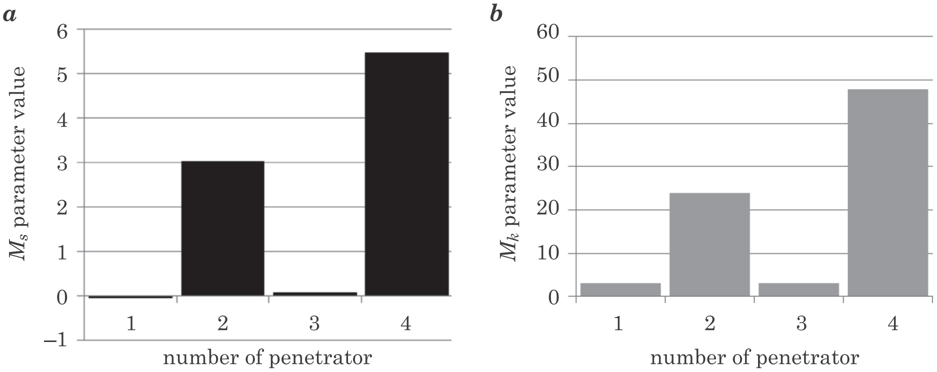

Fig. 6. Parameter values M_s and M_k for different penetrators calculated on signals which represents difference of magnetic profiles before (*a*) and after (*b*) puncture

The authors state that the most useful parameter in this application is the M_b parameter (Fig. 7). As the average ordinary profiles, it is insensitive to local peaks and disturbances, but its value has increased by at least as much as 15% (for a 3.7 mm penetrator and for other much more) after penetration. This implies that the “punctured peak” has the shape of an inverted or relatively wide funnel, and this type of profile shape has a significant effect on the value of the M_b parameter.

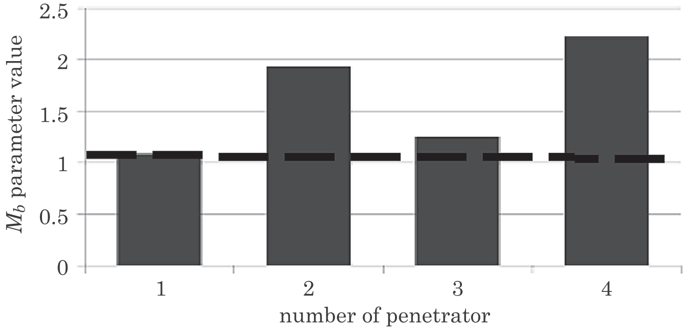

Fig. 7. M_b parameter value for differential magnetic profiles before and after puncture for different penetrators

Summary

Puncture detection based on quality analysis of profiles before and after penetration with a ferromagnetic penetrates is difficult, because the changes in the magnetic field caused by the penetration itself are small. The changes in the magnetic field caused by the penetration itself are two magnitudes smaller than the changes in the magnetic flux density variability prior to the penetration.

The quantitative analysis using parameters defined by the dependencies (1–6) also does not provide any information about the penetration.

The magnetic profiles before and after puncture are different. It can be clearly see a characteristic peak at the puncture angle. The peak height seems to be correlated with the distance between the sensor and the tread and the size of the penetrator.

The material of the penetrator plays a significant role. It is especially visible while using a penetrator with a 3.7 mm diameter. The peak height also could give an insight to the damage of the belt. The differential profile (of the magnetic profiles before and after the puncture) allow to collect the data about the perforated tire. In order to detect differences caused by puncture it is recommended use the values of M_b, M_s and M_k. It is necessary to keep in mind that M_s and M_k are very susceptible towards noise, thus it might be problematic to apply them on magnetic profiles obtained from road studies.

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