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ANALYSIS OF UNCONTROLLED WEAR IN THE AREA OF A BELLEVILLE SPRING OF A FRICTION TORSIONAL VIBRATION DAMPER IN A MOTOR VEHICLE CLUTCH

ANALIZA NIEKONTROLOWANEGO ZUŻYCIA W OBRĘBIE SPRĘŻYNY DOCISKOWEJ CIERNEGO TŁUMIKA DRGAŃ SKRĘTNYCH W SPRZĘGLE SAMOCHODOWYM

Key words: vibration damper, exploitation, spring, abrasive wear, dry sliding friction.

Abstract: The article describes the problem of excessive tribological wear of a torsional vibration damper built into a single-disc friction clutch of a truck vehicle. In contrast to the controlled, design-based wear of damper's friction rings, i.e., wear whose kinetics are known and predictable, uncontrolled wear at Belleville spring contact surfaces effects in a premature decrease in the damper's friction torque and, consequently, loss of durability. As a result of the analyses and experimental work, the causes of accelerated wear were identified. Sets of springs and friction rings from the 10 used vibration dampers that worked under similar operating conditions but with different operating periods were used as the basic research material. The influence of abrasive wear of Belleville springs on their load-deflection characteristic was identified. A comparative analysis of the characteristics of the new spring and the used springs is also presented to illustrate changes in the axial load in the assemblies of the analyzed dampers.

Słowa kluczowe: tłumik drgań, eksploatacja, sprężyna, zużycie ścierne, tarcie ślizgowe suche.

Streszczenie: W artykule opisano problem nadmiernej intensywności zużycia ściernego tłumika drgań skrętnych, wbudowanego w jednotarczowe sprzęgło cierne pojazdu ciężarowego. W przeciwieństwie do kontrolowanego konstrukcyjnie przewidzianego zużywania się pierścieni ciernych tłumika, tj. zużycia, którego kinetyka jest znana i przewidywalna, niekontrolowane zużycie powierzchni oporowych talerzowej sprężyny dociskowej skutkuje przedwczesnym spadkiem momentu tarcia tłumika, a co za tym idzie, utratą jego trwałości. W wyniku przeprowadzonych analiz i prac doświadczalnych zidentyfikowano przyczyny przyspieszonego zużycia. Jako podstawowy materiał badawczy wykorzystano zestawy sprężyn oraz pierścieni pochodzących z 10 używanych tłumików drgań, które pracowały w podobnych warunkach eksploatacyjnych, ale różniących się okresem eksploatacji. Zidentyfikowano wpływ zużycia ściernego sprężyn dociskowych na charakterystyki siły w funkcji ugięcia. Przedstawiono również analizę porównawczą charakterystyki nowej sprężyny i sprężyn używanych w celu pokazania zmian wartości sił osiowych w złożeniach analizowanych tłumików.

INTRODUCTION

Torsional vibrations in the drive systems of motor vehicles are the result of uneven operation of the reciprocating internal combustion engine, where the main source of these vibrations is periodically occurring gaseous forces resulting from the combustion of the fuel-air mixture **[L. 1]**, but also inertia forces resulting from partial balancing of the piston-crank mechanism **[L. 2]**. Torsional vibrations with too high amplitude may cause rattling of a transmission, i.e., noise resulting from the impact of teeth of gears against each other, and in the long term, fatigue cracking

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of these teeth, as well as cracking of drive shafts joints, clutch disc spline, and other connections **[L. 3, 4, 5]**. In order to minimize torsional vibrations transmitted to the drive system, frictional torsional vibration dampers are installed directly behind an engine in a powertrain system, which are usually integrated with a clutch disc or flywheel. Wear of friction elements of the vibration damper occurs throughout the operation of the engine, so proper durability and stability of the frictional torque is crucial to ensure failure-free operation of powertrains. The principle of operation as well as the calculations of frictional dampers of powertrains have been very well described in the literature **[L. 6, 7, 8]**, but publications relating to their wear are very rare **[L. 9]**, in contrast to many publications describing the wear of clutches **[L. 10, 11]** or brakes **[L. 12, 13]**, where there is a similar form of contact (ring contact), but the other parameters are completely different, i.e. unidirectional instead of oscillating movement, variable instead of constant surface clamping force **[L. 14, 15]**, etc.

During the authors' research on the stability of frictional processes occurring in frictional torsional vibration dampers, integrated with the friction clutch disc of a truck, the main factors causing the change in the frictional torque characteristics in the predicted service life were identified. These factors can be divided into controlled (operational) factors resulting from the design-assumed wear of parts involved in friction, i.e., the operation of which is known, and the symptoms are predictable, and uncontrollable factors, which result in deterioration of reliability and failures. Regardless of this division, in order for the value of the damper frictional torque to change, one or more factors must change in the following formula 1, i.e.

$$T = F \cdot r_m \cdot \mu \cdot z \quad (1)$$

where:
T – frictional torque of vibration damper [N·m],
F – normal force of Belleville spring [N],
r_m – average radius of friction [m],
μ – coefficient of friction [-],
z – number of pairs of friction surfaces [-].

The controlled factors include primarily a change in the coefficient of friction μ of the sliding cooperating parts (e.g. due to the occurrence of wear products at the friction contact interface), and a slight change in the F normal force that acts at the surfaces of these parts and which is caused by the static deformation of the Belleville spring by a certain height achieved during the assembly of vibration dampers. Knowing this height, the F force can be deduced from the experimentally determined characteristics of Belleville springs **[L. 16]. Fig. 1** shows an example of a spring characteristic, the nonlinearity of which makes it possible to maintain a relatively constant load regardless of the level of wear of the friction package, resulting in progressive spring expansion. In the case of controlled wear of the analyzed design of passive vibration dampers, this expansion should cause a change in the spring height (compressed) from the initial value of 2.4 mm (new damper) to the value of about 2.8 mm (worn damper).

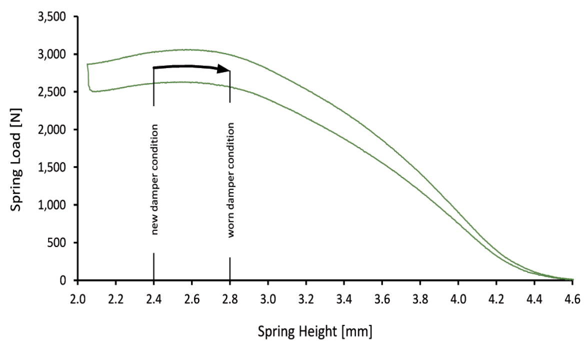

Fig. 1. Belleville spring characteristics of a vibration damper
Rys. 1. Charakterystyka sprężyny dociskowej tłumika drgań

Uncontrollable factors were identified during the assessment of the durability of the analyzed vibration dampers. As it turned out, the main factor causing a significant decrease in the frictional torque value in the case of the analyzed design is uncontrolled wear in the area of a Belleville spring. **Fig. 2** illustrates the location of the Belleville spring (1) in the damper assembly, which is by design assumed not to be subjected to sliding, which should be effected by its position between the outer left drive plate (2) and the left friction ring (3), where the drive plate is connected to the hub (4) by means of rivets, and the friction ring (3) is connected to the same hub by means of a spline connection, so that the ring can move freely in the axis of damper during progressive wear.

In practice, however, friction ring splines have some angular clearance in the outer hub spline, and within this angular clearance range, if, due to dimensional tolerance or later wear of spline drivers the clearance is excessive, the friction ring will not

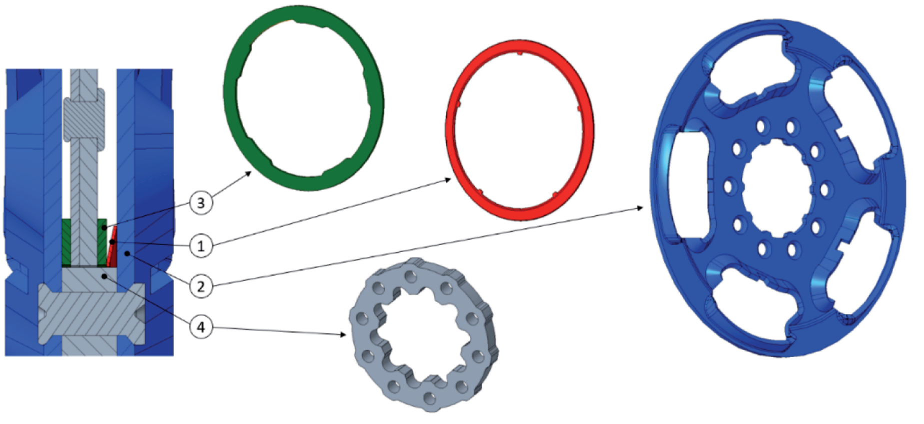

Fig. 2. Positioning of the Belleville spring in vibration damper assembly
Rys. 2. Umiejscowienie sprężyny dociskowej w złożeniu tłumika drgań

slide in relation to the internal drive plate (means controlled wear) but remains in contact with this disc and together with it will slide in relation to the Belleville spring, causing its abrasive wear (means uncontrolled wear). **Figure 3** shows a diagram of wear occurrence in the area of a Belleville spring, where the spline clearance has been artificially increased to better illustrate the wear mechanism. Assuming that the internal drive plate begins to oscillate within ± 8°, with each change in the direction of movement, the friction ring will rotate together with plate until the spline clearance is exhausted. This will only happen if the frictional torque between the left friction ring and the internal drive plate is higher than the frictional torque on either side of the Belleville spring contact. The Belleville spring has a conical structure, so if it is in contact on both sides with similar material (similar friction coefficient), it will start to slide at a smaller-diameter side, which is due to the smaller average radius of friction, and, thus, lower frictional resistance of this contact. In the case of the analyzed damper design, the spring is in contact with the friction ring on its inner diameter, and this is where the greatest wear occurs due to the lower average radius of friction (lower torque) and a higher contact stress, as compared to the ring-plate contact surface.

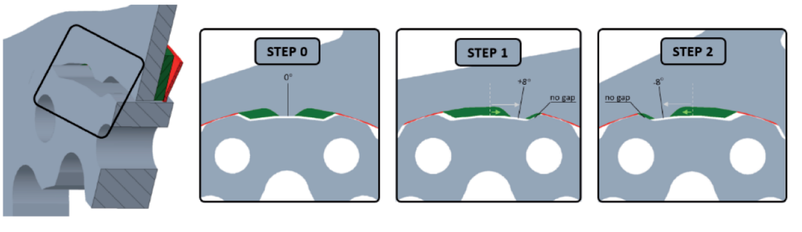

Fig. 3. Diagram of uncontrolled wear formation in the area of a Belleville spring
Rys. 3. Schemat powstawania niekontrolowanego zużycia w obrębie sprężyny dociskowej

Therefore, a certain compromise must be reached in the damper design with respect to the acceptable amount of angular clearance, resulting from the need for free axial movement of the friction rings caused by their constant wear and the risk of the Belleville spring wear.

RESEARCH DETAILS

In order to observe trends, an analysis was carried out of 10 vibration dampers with an outer diameter of 254 mm, differing in usage period during normal operation of commercial vehicles. **Fig. 4** shows the relationship between the road distances (mileage) covered by the vehicles during the use of the selected dampers and their usage time period (including stops). As shown, the relationships for all dampers are similar, which is undoubtedly due to the similar operating conditions of the vehicles: all dampers come from Volvo FH13 tractors driven mainly on the motorways of European countries, equipped with 13,000 cc engines and automated 12-speed I-Shift transmissions.

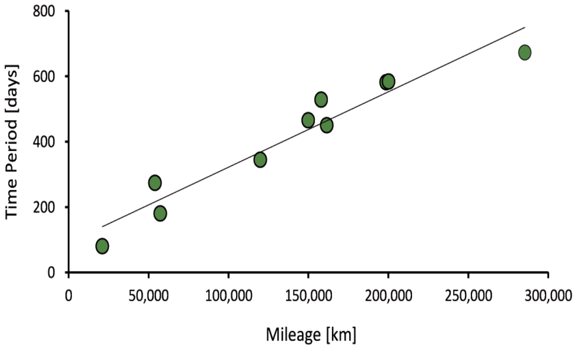

Fig. 4. Operation data of selected vibration dampers
Rys. 4. Dane eksploatacyjne wybranych tłumików drgań

Wear of selected parts of used vibration dampers

After disassembling the dampers (before cleaning), a visual analysis and photographic documentation of the parts were performed. Next, the components were thoroughly cleaned, and several measurements were taken on them. The results were presented as a percentage of wear, determined by the methods of mass loss and loss of wall thickness (volume loss). Since the parts from the analyzed used dampers were not measured before operation, in order to calculate the percentage of wear, these results were compared to the average values calculated from the measurement results of 10 new parts, measured in the same way and at the same time. The mass of the parts was measured on a Camlab ACB 3000 electronic scale (resolution 0.1 g). The wall thickness was measured using a HOLEX 0-25 mm micrometer (DIN 863), and the grooves created by the friction of Belleville springs into the mating parts were measured with a TESA micro-hite plus M600 height gauge equipped with a measuring tip with a 2 mm ball (permissible measurement error 0.002 mm, resolution 0.0001 mm). In the case of friction rings, measurements were taken for 5 measuring points (every 72°) and then an average was calculated. In the case of Belleville springs, measurements were made on the inner and outer cone diameters, in both cases again based on the average of 5 measuring points. In addition, the height of the Belleville springs was also measured using a TESA micro-hite plus M600 height gauge.

Decrease in axial loads in the used vibration dampers

The new Belleville spring in a damper assembly has average deflection of 1.93 mm, which helps achieve a pressure load on friction surfaces of about 2,800 N. During the operation of the analyzed dampers, there was an uncontrolled wear in area of Belleville springs, which caused their axial relaxation. This axial relaxation is not the same as a decrease in spring deflection, because the initial height of the worn springs (in the no-load state) will be reduced by their axial wear. Formula 2 made it possible to estimate the level of axial relaxation of springs due to uncontrolled wear of dampers' components during their operation, it can be written in the form of

$$f_{relax} = w_d + w_{s_d} + w_{s_c} + w_c \tag{2}$$

where:
f_{relax} – Belleville spring relaxation during vehicle operation [mm],
w_d – friction ring axial wear in contact with a Belleville spring [mm],
w_{s_d} – Belleville spring axial wear in contact with a friction ring [mm],
w_{s_c} – Belleville spring axial wear in contact with a drive plate [mm],
w_c – drive plate axial wear in contact with a Belleville spring [mm].

Wear measurements of parts also made it possible to calculate the height of worn Belleville springs installed in used dampers (statically compressed), which allows the estimation of the axial force change in the analyzed dampers during their operation. Formula 3 shows how to calculate the height of worn springs in the assembled state, i.e.

$$h_{worn} = h_{new} + w_d + w_c \tag{3}$$

where:
h_{worn} – worn Belleville spring height installed in a used damper [mm],
h_{new} – new Belleville spring height installed in a new damper [mm].

Fig. 5 shows uncontrolled wear in area of damper's Belleville spring. In addition, the figure shows the controlled wear between the friction rings and the internal drive plate to illustrate the friction surface area predominance of the parts responsible for controlled wear.

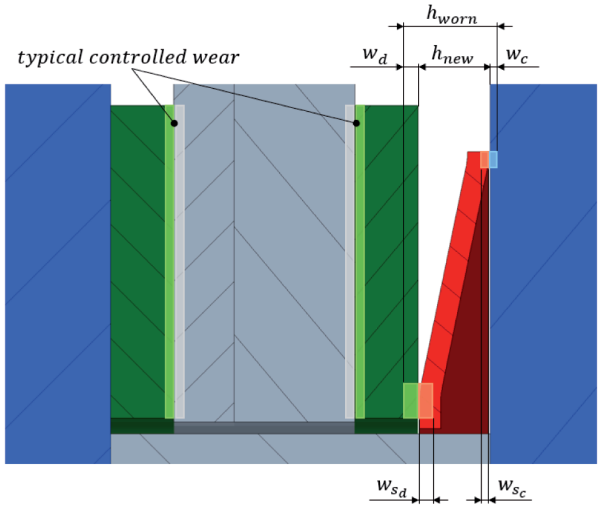

Fig. 5. Uncontrolled wear in the area of a Belleville spring
Rys. 5. Niekontrolowane zużycie w obrębie sprężyny dociskowej

Formula 3 does not take into account the wear of the Belleville spring itself, because the determination of a damper axial force consists in reading the load generated by a spring when it is deflected to the h_{worn}, i.e., to the height resulting from the installation of the spring in a used damper, regardless of its wear (simulation of the used damper system). To do this, the characteristics of the worn Belleville springs (height vs. load) were measured, which were made on a MTS Criterion C45.305 testing machine. The MTS LPS.204 force sensor with a measuring range of 20 kN (class 0.5, ANSI C12.20) was used for the measurements. Before measuring each spring, 3 pre-presses were performed, followed by a target measurement, which consisted of slowly pressing the tested spring (0.5 mm/s) from a preload of 5 N to reaching a minimum spring working height of 1.8 mm and then slowly relaxing to the initial height to take friction hysteresis into account.

RESEARCH RESULTS

The wear analysis was mainly based on comparing the measurement results of the used parts with the average calculated from the measurement results of the 10 new parts. To illustrate this wear, **Figure 6** shows a comparison of a new Belleville spring with a worn one. As can be seen, the predominant wear occurred on the inner diameter of the Belleville spring cone and the significantly smaller wear on the outer diameter, while the cone angle did not change, which was confirmed by additional measurements.

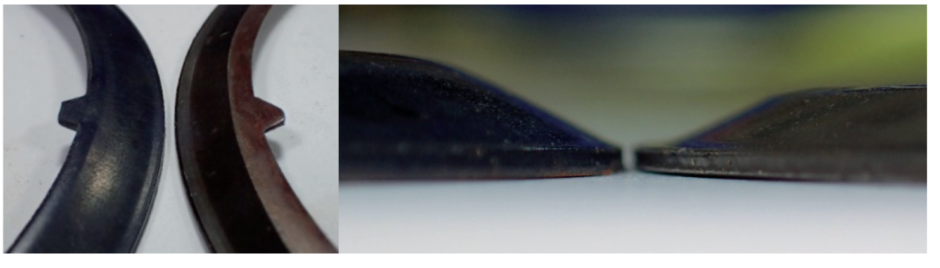

Fig. 6. Comparison of a new Belleville spring (left) with a worn one (right)
Rys. 6. Porównianie nowej sprężyny dociskowej (po lewej) ze zużytą (po prawej)

Wear of selected parts of vibration dampers used

Table 1 shows the results of the thickness and mass measurements of the friction rings included in the so-called damper friction package (**Fig. 5**).

In the case of A-rings, a similar percentage loss of wall thickness (3.0% to 8.4%) and percentage loss of mass (2.4% to 7.5%) can be observed. This is due to the correct wear of the rings, i.e., uniform wear of the entire friction surface of the rings (controlled wear). In the case of B-rings, the loss of wall thickness is negligible (-0.4% to 1.9%), which is due to slight wear of the friction surface. The minuses "-" indicates that the thickness of the ring used was greater than the calculated average thickness of the 10 new friction rings, which is due to the dimensional tolerances of new parts. For the B-rings, however, we can observe an increased mass loss (1.7% to 4.4%), which is not only due to the wear of the friction surface of the rings, but also to the uncontrolled wear of the opposite surface, i.e., in contact with a Belleville spring. The deepenings formed on the friction rings B caused some relaxation of the Belleville springs, i.e., a change in the height of springs in the assemblies of the analyzed dampers, and, thus, a probable change in

Table 1. Measurements of the friction rings from used dampers
Tabela 1. Pomiary pierścieni ciernych z używanych tłumików

DAMPER DATA			FRICTION RING A				FRICTION RING B (spring contact)					
			Total Wear (controlled only)				Controlled Wear		Spring Contact Wear		Total Wear	
No	Mileage	Time Period	Thickness	Loss	Mass	Loss	Thickness	Loss	Wear	Loss	Mass	Loss
[-]	[km]	[days]	[mm]	[%]	[g]	[%]	[mm]	[%]	[mm]	[%]	[g]	[%]
New	0	0	2.13	0.0	74.91	0.0	2.13	0.0	0.00	0.0	74.91	0.0
1	21,064	80	2.03	4.8	71.60	4.4	2.11	1.2	0.14	6.8	72.40	3.4
2	54,050	273	1.97	7.8	70.60	5.8	2.09	1.9	0.11	5.3	72.30	3.5
3	57,389	180	2.07	3.0	73.10	2.4	2.12	0.4	0.17	8.2	73.60	1.7
4	120,000	344	1.95	8.4	70.60	5.8	2.09	1.8	0.22	10.1	72.00	3.9
5	150,000	465	2.01	5.6	70.20	6.3	2.09	1.9	0.17	8.1	72.40	3.4
6	158,000	528	1.97	7.4	71.00	5.2	2.11	1.2	0.16	7.7	73.00	2.5
7	161,602	450	2.05	3.9	72.90	2.7	2.13	0.0	0.34	15.9	71.60	4.4
8	198,698	581	2.03	4.8	71.80	4.2	2.10	1.5	0.24	11.1	72.50	3.2
9	200,107	584	2.00	6.1	70.80	5.5	2.12	0.4	0.11	5.3	73.40	2.0
10	285,425	672	1.98	7.2	69.30	7.5	2.14	-0.4	0.21	9.7	72.30	3.5

Table 2. Measurements of the Belleville springs from used dampers
Tabela 2. Pomiary sprężyn dociskowych z używanych tłumików

DAMPER DATA			BELLEVILLE SPRING									
			Inner Surface Wear		Outer Surface Wear		Total Wear		Free Height		Spring Cone Angle	
No	Mileage	Time Period	Thickness	Loss	Thickness	Loss	Mass	Loss	Height	Loss	Angle	Loss
[-]	[km]	[days]	[mm]	[%]	[mm]	[%]	[g]	[%]	[mm]	[%]	[°]	[%]
New	0	0	1.00	0.0	0.98	0.0	29.1	0.0	4.33	0.0	26.48	0.0
1	21,064	80	0.33	67.1	0.90	7.9	24.4	16.2	3.32	23.3	25.80	2.6
2	54,050	273	0.45	54.6	0.90	7.9	25.9	11.0	3.43	20.7	25.70	2.9
3	57,389	180	0.87	13.1	0.90	7.5	27.7	4.8	3.73	13.9	25.72	2.9
4	120,000	344	0.57	42.6	0.88	9.7	26.0	10.7	3.70	14.4	25.96	2.0
5	150,000	465	0.53	47.0	0.90	7.7	25.8	11.3	3.60	16.7	26.64	-0.6
6	158,000	528	0.54	45.4	0.90	7.3	26.0	10.7	3.52	18.7	26.06	1.6
7	161,602	450	0.58	41.4	0.68	29.8	25.1	13.7	3.60	16.8	26.04	1.7
8	198,698	581	0.78	21.5	0.93	4.8	26.4	9.3	3.77	12.9	26.42	0.2
9	200,107	584	0.34	66.1	0.84	14.3	23.8	18.2	3.32	23.2	26.24	0.9
10	285,425	672	0.33	66.5	0.91	7.1	25.2	13.4	3.35	22.7	26.96	-1.8

the load pressing the friction rings. Another factor that causes relaxation of Belleville springs is the wear of the springs themselves, which is shown in **Table 2**.

In the case of the Belleville springs, a significant loss of wall thickness was observed on the internal diameter of a cone (13.1% to 67.1%), i.e., in contact with the B friction rings. The high percentage wear of the springs compared to the grooves of the B-rings is due to the different wall thickness of the new parts (1.0 mm in the case of springs and 2.13 mm in the case of rings), but when comparing the geometrical wear of both parts, one can notice a higher wear of the springs, which may be due to some material differences between the two parts. The outer diameter of the spring cone did not suffer any significant loss of wall thickness (4.8% to 29.8%), with the exception of samples no. 7 and 9. Additional measurements of the springs included mass wear measurement, no-load spring height measurement and no-load cone angle measurement. As it turned out, the percentage loss of height of the springs without load (12.9% to 23.3%) is due only to the volume loss, as there was no loss of cone angle for the springs used (-1.8% to 2.9%), and, thus, the material of the springs did not suffer any loss of its mechanical properties during operation due to the influence of the high temperature inside a friction damper.

Decrease in axial forces of the vibration dampers used

Along with uncontrolled abrasive wear during the operation of the analyzed dampers, the Belleville springs were relaxed. This relaxation is estimated using Formula 2 and shown in **Fig. 7** as the sum of uncontrolled wear in area of Belleville spring. The wear between the friction ring (w_d) and the Belleville spring (w_{sd}) is shown in green, and the wear between the spring (w_{sc}) and the left drive plate (w_c) is shown in blue. In addition, the static deflection of a new spring installed in a damper before operation is shown by a solid line, and the deflection of a worn spring after operation is shown by a dotted line.

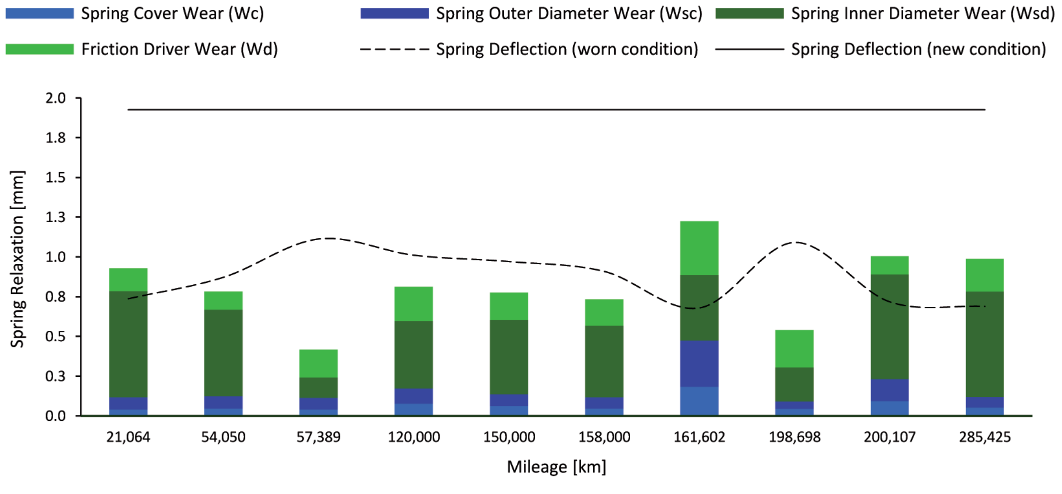

Fig. 7. Axial relaxation of the Belleville springs arising during damper operation
Rys. 7. Rozprężenie osiowe sprężyn dociskowych powstałe podczas eksploatacji tłumików

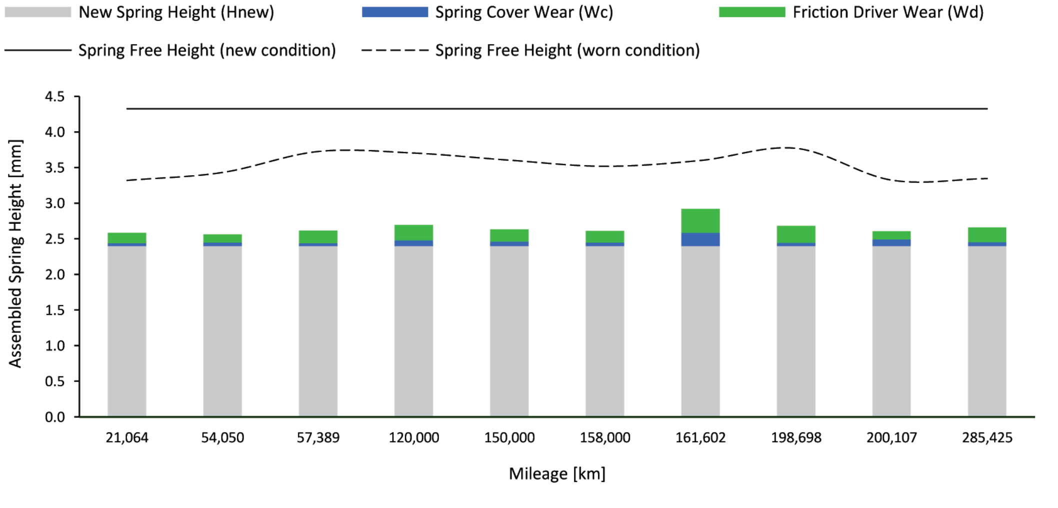

Fig. 8. Results of spring height calculations statically deflected in used dampers
Rys. 8. Wyniki obliczeń wysokości sprężyn statycznie ugiętych w używanych tłumikach

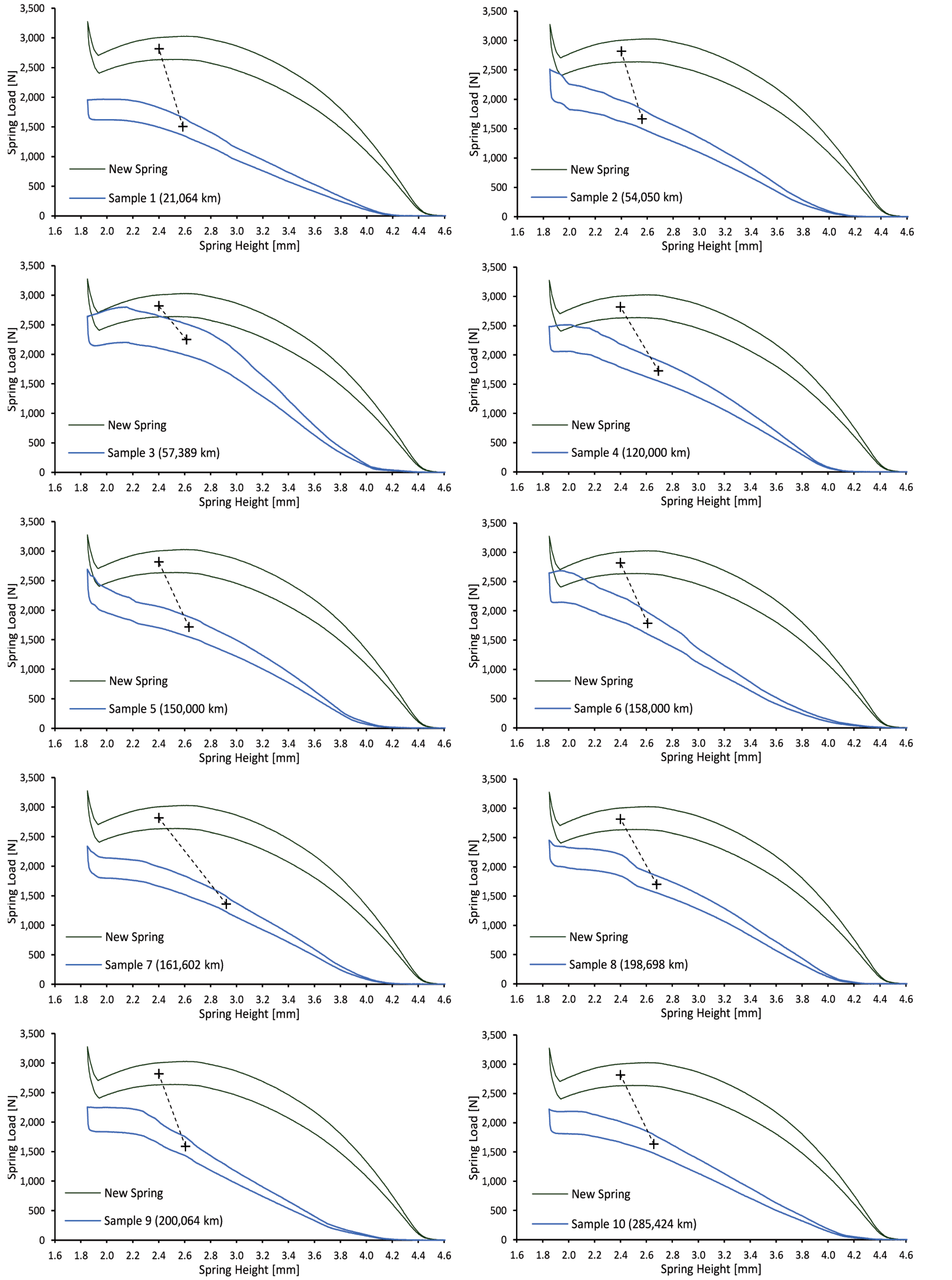

Fig. 9. Characteristics of the Belleville springs from the used dampers

Rys. 9. Charakterystyki sprężyn dociskowych z używanych tłumików

However, it is not possible to estimate the change in axial forces of the used dampers based on the determined deflection of the springs due to the nonlinearity of their characteristics, which are additionally deformed due to abrasive wear. Therefore, the next step was to estimate the height reached by the Belleville springs in the damper assemblies at the end-of-life stage, solely due to the uncontrolled wear (formula 3). The results of the calculations are presented in the column chart (**Fig. 8**), where each column contains the constant initial height of the statically deflected spring in the assembly of the new damper (gray), and the wear of the parts in contact with the spring, i.e., the friction ring (green) and the left drive plate (blue). In addition, the chart shows a line indicating the height of a new spring in no-load condition (solid line) and a line indicating the height of the worn springs also in no-load condition (dashed line).

The characteristics of Belleville springs from all analyzed dampers are presented at the collective **Figure 9**. Each characteristic of the worn spring (blue) has been compared to the characteristic of a new spring (black). The dashed line shows the load decrease of a worn spring compared to a new one due to a change in spring geometry in damper assembly due to uncontrolled wear. As you can see, these lines start and end inside the characteristics (crosses), i.e., between the curves measured during the compressive movement and the curves measured during the relaxation movement, which is due to the friction hysteresis occurring during the measurements (motion resistance), which does not occur in a damper assembly condition when springs are pre-compressed and press friction rings statically.

Figure 10 shows the load values read from the worn spring characteristics of the analyzed dampers. Additionally, the chart shows the solid line, which means typical load of a new Belleville spring installed in a new damper, i.e., 2,818 N (average value of 10 measurements), also two dotted lines, means upper and lower specification limits (2,385 N to 2,915 N).

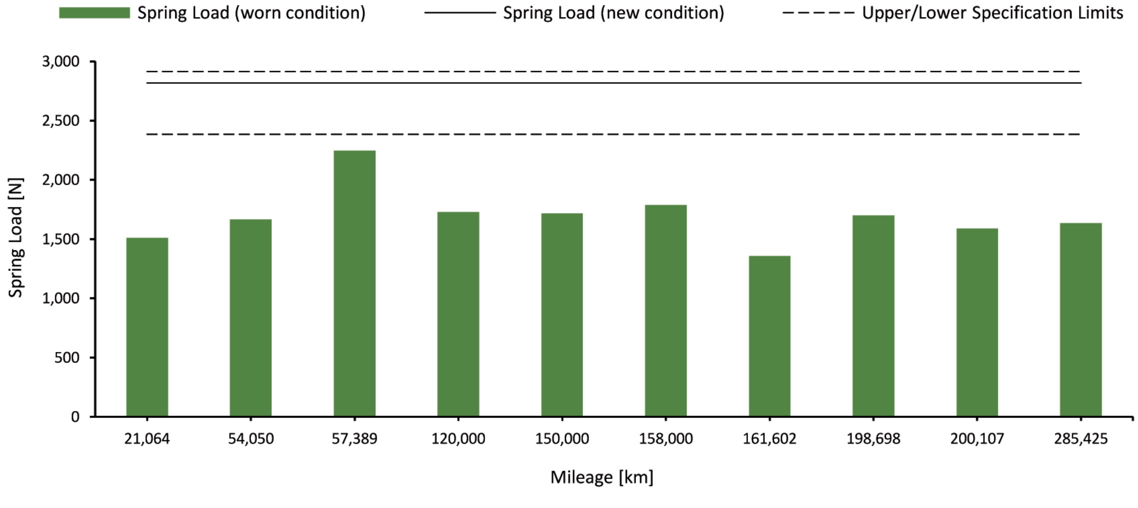

Fig. 10. Determined loads of Belleville springs assembled in the analyzed vibration dampers
Rys. 10. Wyznaczone obciążenia sprężyn dociskowych w złożeniach analizowanych tłumików drgań

SUMMARY

The phenomenon of wear in the area of a Belleville spring is undoubtedly difficult to diagnose during vehicle operation, and the consequence of a decrease in the damping capacity of a damper is an increased level of amplitudes of torsional vibrations transmitted from an engine to a drivetrain system, which in the long run may lead, among other things, to fatigue cracking of gear teeth or cracking of drive shaft joints.

Accelerated wear in area of a Belleville spring, in the case of the analyzed vibration dampers, caused some relaxation of the Belleville springs and affected the shape of the characteristics of these springs through the loss of their volume.

It can also be stated without a doubt that during the operation of the analyzed dampers there was a significant decrease in the clamping of the elements on the working surfaces of the so-called friction package (in each case the load fell below the lower specification limit set by the manufacturer) and, consequently, a decrease in the ability of the dampers to effectively dampen torsional vibrations. An interesting conclusion regarding the analysis is the fact that the level of uncontrolled wear is not dependent on the operation period of these dampers. For example, for the sample with a mileage of 21,064 km as well as for the sample with a mileage of 200,107 km, we can observe the wear of the Belleville springs at a similar level, which may suggest that the predominant wear occurred at a very early stage of the dampers' operation, and then decreased when the axial forces generated by the Belleville springs decreased significantly.

Further research will therefore focus on a better understanding of the wear mechanism, which will require the design and performance of an accelerated durability test for the sliding spring-ring contact. It will be necessary to prepare samples with different angular clearance between the friction ring drivers and the hub grooves in order to observe the correlation between wear and friction travel. It is also planned to monitor the coefficient of friction of this friction contact during the test, which will be determined by simultaneously measuring the frictional torque and the axial force of the damper (formula 1). The knowledge gained from the experience will not only be used to develop the optimal Belleville spring wear reduction solution for the vibration damper design under consideration but will also be used to create design recommendations for future designs.

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