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ANALYTICAL CALCULATION AND EXPERIMENTAL VERIFICATION OF LATERAL STIFFNESS OF A FLEXI-COIL SPRING WITH TILTING RUBBER-METAL PAD

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1.Introduction

In design of rail vehicles, especially locomotives and passenger coaches, flexi-coil springs are often used as a basic elastic element of secondary suspension nowadays. Besides the transmission of vertical forces, the flexi-coil springs allow their lateral loading which can be realized in two perpendicular directions in relation to the coordinate system of the vehicle – laterally and longitudinally. The force transmission in the lateral direction ensures a lateral suspension of the vehicle body; in the longitudinal direction, the flexi-coil springs are loaded especially at the rotation of bogies against the vehicle body, i.e. at the run of the vehicle through curves and switches, for example.

Requirements on parameters (especially the stiffness) of the secondary springs are influenced with various aspects. The basic requirements on the vertical (axial) stiffness comes from required values of eigenfrequencies of vertical carbody oscillations and permissible range of buffer height over the top of rail at defined range of loading of the vehicle. In case of utilization of only the flexi-coil springs themselves, their lateral stiffness (and therefore also the lateral stiffness of the whole secondary suspension and the resistance against bogie rotation) is only a “secondary product” which is influenced with constructional parameters of the designed spring (winding diameter, wire diameter, height of the spring, number of winding etc.) and arrangement of the springs on the bogie. However, the lateral stiffness must also meet some requirements. At first, the lateral stiffness of individual springs is related with the stiffness of whole lateral suspension of the carbody and therefore this stiffness must be high enough to prevent a contact of bump stops between the bogies and the vehicle body during the run through a curve at projected cant deficiency. Secondly, the lateral (or longitudinal – in the coordinate system of the vehicle) stiffness of individual springs (and their arrangement on the vehicle) influences the resistance against bogie rotation. And the resistance against bogie rotation influences magnitudes of guiding forces in small radius curves as well as stability behaviour of the vehicle at higher speeds. Besides to that, the resistance against bogie rotation has to meet a requirement of the European Standard EN 14363 [1] on a limit value of so-called *X*-factor.

Because of relatively high values of lateral stiffness of commonly used flexi-coil springs and a negative influence of the high resistance against bogie rotation on reached quasistatic guiding forces of the vehicles in small radius curves (the influence of the resistance against bogie rotation on magnitudes of the guiding forces is demonstrated on results of a sensitivity analysis performed by means of computer simulations in paper [2]), sometimes it is necessary (and also desirable) to modify the lateral stiffness of flexi-coil springs by means of rubber pads. Because the resistance against bogie rotation is related above all with the longitudinal loading of the springs whereas the stiffness of lateral suspension corresponds to the lateral loading of the springs, the influence of the used rubber pad should be directionally specific. An option for relevant modification of lateral stiffness of a flexi-coil spring can lie in application of "tilting" rubber-metal pads. Therefore, this paper deals with analytical estimation of lateral stiffness of such assembly consisting of a spring and a pad and also with experimental verification of the computed lateral stiffness.

2.Investigated assembly spring–pad

Investigated assembly of the flexi-coil spring and rubber-metal pad was created with a spring with parameters defined in tab. 1 and a GMT pad with characteristics (i.e. the dependency of moment on the tilt angle of the pad) depicted in fig. 1. The whole assembly can be seen in fig. 2.

Tab. 1 *Nominal values of parameters of investigated flexi-coil spring*

Parameter	**Sign**	**Value**
Free height of the spring	H_0	630 mm
Mean diameter of winding	$\varnothing D$	240 mm
Diameter of wire	$\varnothing d$	48 mm
Number of active coils	n	7
Total number of coils	n_t	9

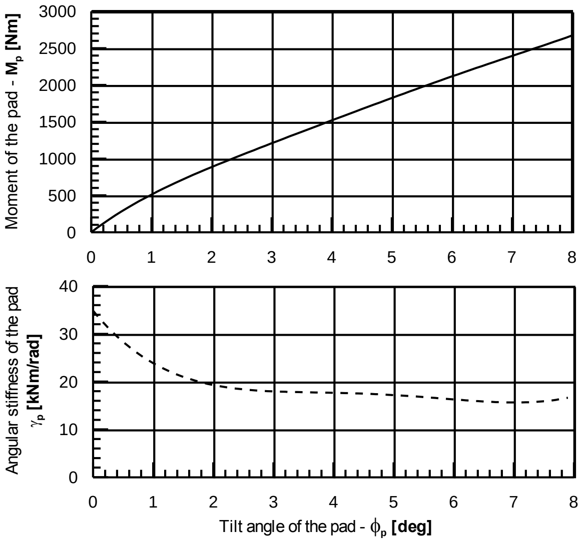


Fig. 1 *Characteristics of used rubber-metal pad (top) and calculated angular stiffness (down)*

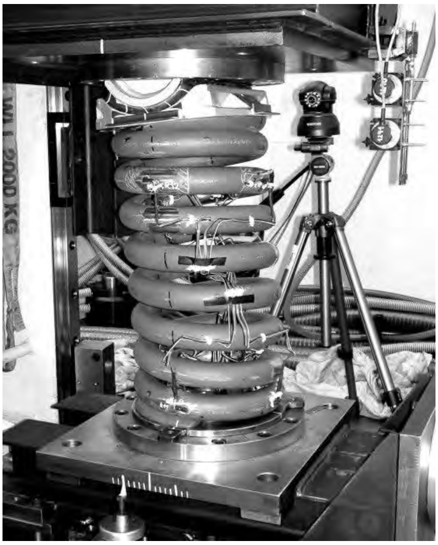


Fig. 2 *Assembly of the flexi-coil spring and tilting rubber-metal pad*

3.Analytical calculation of the lateral stiffness

For purposes of calculation of the lateral stiffness of flexi-coil springs, several empirical formulae (according to Gross, Wahl, Timošenko-Ponomarev, British Standard etc.) are used nowadays. Generally, these formulae provide different results (see paper [4], for example) and each of them is suitable for different type of spring. However, if the flexi-coil spring is supplemented with a pad, the lateral stiffness of the whole assembly can be influenced by this pad very significantly. In case of thin pads which do not allow tilting of the end coil of the spring, the resulting lateral stiffness $k_{x\text{-}res1}$ of the assembly spring–pad can be calculated as a resulting stiffness of two serious springs, i.e. as:

$$k_{x-res1} = \frac{k_{x-s} \cdot k_{x-p}}{k_{x-s} + k_{x-p}}, \qquad (1)$$

where $k_{x\text{-}s}$ is the lateral stiffness of the flexi-coil spring and $k_{x\text{-}p}$ is the lateral stiffness (i.e. the shear stiffness) of the pad.

In case of the “tilting” pads, which allow tilting of the end coil of the spring at its lateral loading (see e.g. fig. 2), the equation (1) cannot be used for calculation of the resulting lateral stiffness of the assembly spring–pad. The reason for that is a fact, that the lateral stiffness of the flexi-coil spring itself is influenced with the tilting of the end coil very significantly, and majority of the empirical formulae for calculation of the lateral stiffness of flexi-coil springs assume rigid fixing of the spring on both its ends. In the next, a formula for calculation of lateral stiffness of the flexi-coil spring with tilting pad will be derived with using of modified Gross’ calculation.

3.1 Gross' calculation of lateral stiffness of a flexi-coil spring

At first, the original Gross' calculation of the lateral stiffness of a flexi-coil spring will be shortly presented. According to paper [3], the Gross' calculation uses assumption that the spring is rigidly fixed on both its ends (see fig. 3) and a tangent line to its bending axis can be expressed as a sum of contributions σ from the bending moment M and ρ from the shear force T, i.e.:

$$\frac{dx}{dz} = \varphi = \sigma_{(M)} + \rho_{(T)} . \tag{2}$$

Then, the differential equation of bending axis can be expressed in following form:

$$\frac{d^2x}{dz^2} = \frac{d\sigma}{dz} + \frac{d\rho}{dz} , \tag{3}$$

where the individual parts of the equation can be calculated as:

$$\frac{d\sigma}{dz} = -\frac{M_y}{B} , \tag{4}$$

$$\frac{d\rho}{dz} = \frac{d}{dz}\left(\frac{F_x + F_z \cdot \varphi}{S}\right) = \frac{F_z}{S} \cdot \frac{d^2x}{dz^2} , \tag{5}$$

where:

M_y .... bending moment,
B .... bending stiffness according to Gross,
S .... shear stiffness according to Gross,
F_x .... lateral loading of the spring,
F_z .... axial (vertical) loading of the spring.

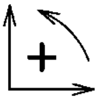
The Gross' bending and shear stiffness of the spring, which are used in equations (4) and (5) can be expressed as:

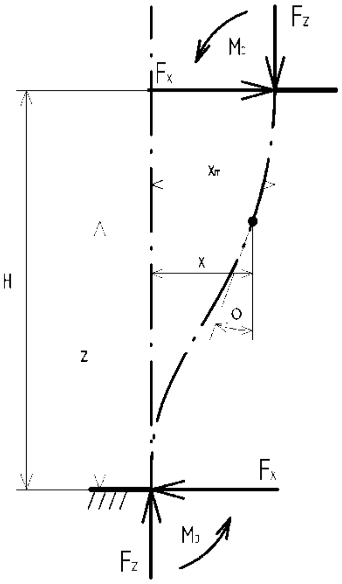
$$B = \frac{H}{\pi \cdot n \cdot R \cdot \left((E \cdot I_1)^{-1} + (G \cdot I_p)^{-1} \right)} , \tag{6}$$

$$S = \frac{E \cdot H \cdot I_2}{\pi \cdot n \cdot R^3} , \tag{7}$$

where:

E .... modulus of elasticity in tension/compression,
G .... modulus of elasticity in shear,
H .... height of loaded spring,
I_1, I_2 .... moments of inertia of wire cross section,
I_p .... polar moment of inertia of wire cross section,
n .... number of active coils,
R .... mean radius of winding.





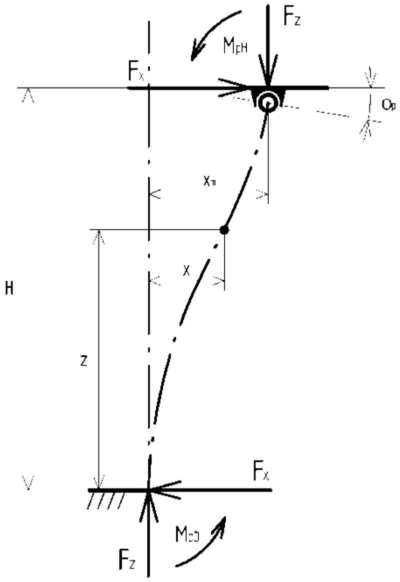


***Fig. 3** Scheme of flexi-coil spring for the Gross' calculation of lateral stiffness (rigid fixing)*

***Fig. 4** Scheme of flexi-coil spring with a tilting pad on the upper end*

By means of constitution of expressions (4) and (5) into the equation (3), the differential equation of bending axis of the spring can be modified into following form:

$$\frac{d^2x}{dz^2}+\frac{M_y}{F_z}\cdot k^2=0\,, \tag{8}$$

where the constant k can be expressed as:

$$k=\sqrt{\frac{F_z}{B\cdot\left(1-\frac{F_z}{S}\right)}}\,, \tag{9}$$

and the bending moment M_y in a defined point of the spring (given by its coordinates [x; z]) under a condition of maximum lateral deformation of the spring x_m (see fig. 3) can be calculated as:

$$M_y=M_p-F_z\cdot(x_m-x)-F_x\cdot(H-z)\,. \tag{10}$$

Because of the assumption of rigid fixing of the spring of both its ends, the moment of pad M_p can be calculated by means of constitution of following condition (expressing the theoretical symmetry of the bending axis of the spring) into the equation (10):

$$z=\frac{H}{2}\quad\Rightarrow\quad\left(M_y=0\wedge x=\frac{x_m}{2}\right). \tag{11}$$

The calculated moment of pad can be constituted into the equation (10) and this equation can be constituted into the differential equation of bending axis of the spring (8):

$$\frac{d^2x}{dz^2}+k^2\cdot x=k^2\cdot\left[\frac{F_x}{F_z}\cdot\left(\frac{H}{2}-z\right)+\frac{x_m}{2}\right]. \tag{12}$$

Solution of this differential equation can be performed by means of conventional mathematical methods; integration constants can be determined by means of limiting conditions which define zero lateral deformation and zero angle of the bending axis on the bottom end of the spring. By means of a next limiting condition defining the maximum lateral deformation of the spring on the upper end of the spring, this maximum lateral deformation can be expressed as:

$$x_m=x_{(z=H)}=\frac{F_x}{F_z}\cdot\left(\frac{2}{k}\cdot\tan\frac{kH}{2}-H\right). \tag{13}$$

Then, the lateral stiffness of a flexi-coil spring according to Gross can be calculated as a ratio of the lateral load F_x and the total deformation, i.e. the maximum deformation according to the equation (13) increased by shear effect of the lateral load F_x, i.e.:

$$k_{x-sG}=\frac{1}{\frac{1}{F_z}\cdot\left(\frac{2}{k}\cdot\tan\frac{kH}{2}-H\right)+\frac{H}{S}}. \tag{14}$$

3.2 Calculation of lateral stiffness of a flexi-coil spring with tilting pad

For purposes of analytical calculation of lateral stiffness of a flexi-coil spring with tilting pad on one its end (see the scheme in fig. 4), a modified Gross' calculation is used. It is possible to state that the differential equation of bending axis of the spring has also a form of the equation (8), including the definition of the constant k by means of the expression (9). However, because of the tilting joint and its finite angular stiffness, the bending axis is not symmetric in this case. Therefore, the bending moment M_y must be defined in following form:

$$M_y=M_{pH}-F_z\cdot(x_m-x)-F_x\cdot(H-z), \tag{15}$$

where M_{pH} is a moment in place of the tilting pad and can be calculated by means of the angular stiffness of this pad γ_p and the angle of tilt of the pad φ_p as:

$$M_{pH}=\gamma_p\cdot\varphi_p=\gamma_p\cdot\left(\frac{dx}{dz}\right)_{(z=H)}. \tag{16}$$

Then, the differential equation of the bending axis (8) can be modified into a form:

$$\frac{d^2x}{dz^2}+k^2\cdot x=k^2\cdot\left[\frac{F_x}{F_z}\cdot\left(\frac{H}{2}-z\right)+x_m-\frac{\gamma_p\cdot\varphi_p}{F_z}\right] \tag{17}$$

and its solution can be found in a form of following expression:

$$x=\frac{F_x}{F_z}\cdot\left(\frac{1}{k}\cdot\sin kz+H-z\right)-\left(\frac{F_x}{F_z}\cdot H+x_m-\frac{\gamma_p\cdot\varphi_p}{F_z}\right)\cdot\cos kz+x_m-\frac{\gamma_p\cdot\varphi_p}{F_z}. \tag{18}$$

For calculation of the maximum lateral deformation of the spring and the tilt angle of the pad (which is not known, as well, and corresponds to the angle of tangent line to the bending axis of the spring on its upper end) can be used following limiting condition:

$$z = H \quad \Rightarrow \quad \left(x = x_m \wedge \frac{dx}{dz} = \varphi_p \right). \tag{19}$$

Resulting lateral stiffness of the flexi-coil spring with a tilting pad, which is situated on one end of the spring, can be then expressed as:

$$k_{x-sp} = \frac{1}{\dfrac{\dfrac{1}{k}\cdot \tan kH - H - \gamma_p \cdot \left(1 - \dfrac{1}{\cos kH}\right)\cdot \dfrac{1-\cos kH - k\cdot H\cdot \sin kH}{F_z + \gamma_p \cdot k\cdot \sin kH}}{F_z \cdot \left(1 + \gamma_p \cdot k \cdot (1-\cos kH)\cdot \dfrac{\tan kH}{F_z + \gamma_p\cdot k\cdot \sin kH}\right)} + \dfrac{H}{S}}. \tag{20}$$

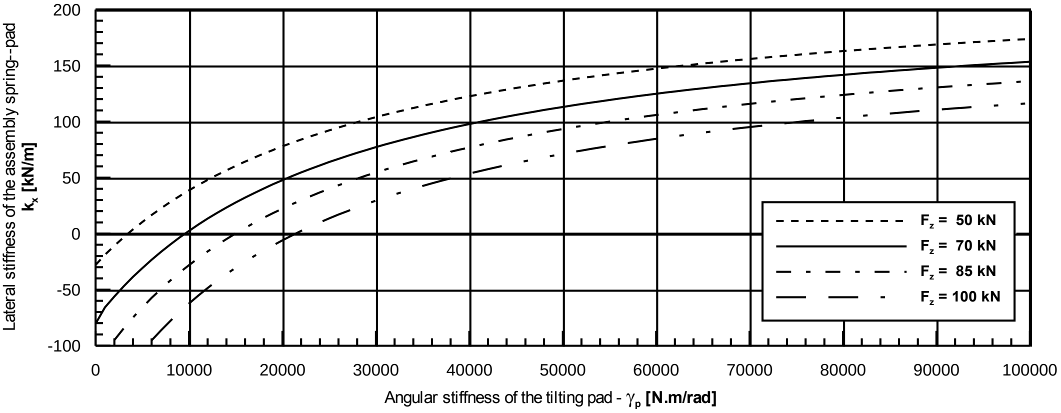


Fig. 5 *Influence of angular stiffness of the tilting pad on resulting lateral stiffness of the whole assembly flexi-coil spring–tilting pad*

An influence of a tilting pad on the resulting lateral stiffness of the whole assembly spring–pad can be very significant. This influence is demonstrated in a graph in fig. 5. In the graph, the dependencies of the calculated lateral stiffness of the flexi-coil spring with parameters defined in tab. 1 are depicted for various values of vertical (axial) load. For an infinite value of the angular stiffness of the pad, the resulting lateral stiffness of the assembly spring–pad calculated according to the equation (20) converges to the lateral stiffness of the spring itself calculated according to Gross (see the equation (14)). In case of the opposite extreme, i.e. for a zero angular stiffness of the tilting pad, the resulting lateral stiffness of the whole assembly converges to a theoretical value corresponding to a spring with a (free) joint on one its end, which can be derived as:

$$k_{x-sJ} = \frac{1}{\dfrac{1}{F_z}\cdot\left(\dfrac{1}{k}\cdot \tan kH - H\right) + \dfrac{H}{S}}. \tag{21}$$

However, the derived formula (20) is valid only for a pad with linear characteristics, i.e. for a pad which shows a constant value of its angular stiffness γ_p. As it is evident from the characteristics of the used rubber-metal pad (see fig. 1), the assumption of the linear characteristics is not fulfilled in this case. Therefore, a numerical method for calculation of the resulting lateral stiffness of the assembly spring–pad, which allows covering of the non-linear characteristics of the pad, was also created in framework of this work. This method is based on the fact that the maximum lateral deformation of the spring with pad (or the resulting lateral stiffness) can be expressed in two different ways. For derivation of these expressions, the equations (18), (19) and (16) can be used. The first expression of the maximum lateral deformation of the spring with pad depends on the moment of the pad M_p and can be written in a form:

$$x_{m-sp1} = \frac{1}{F_z} \cdot \left(\frac{1}{k} \cdot \tan kH - H \right) - \frac{M_p}{F_x \cdot F_z} \cdot \left(\frac{1}{\cos kH} - 1 \right) \tag{22}$$

and the second expression depends on the tilt angle of the pad φ_p and can be written in following form:

$$x_{m-sp2} = \frac{1}{F_z} \cdot \left(\frac{2}{k} \cdot \tan \frac{kH}{2} - H \right) + \frac{\varphi_p}{F_x \cdot k} \cdot \tan \frac{kH}{2} . \tag{23}$$

The proposed method is based on an iterative determination of suitable point of the characteristics of the pad, which is given by means of its coordinates [φ_p; M_p]. Only in the state corresponding to this desired point, the equations (22) and (23) provide identical values of the maximum lateral deformation of the assembly spring–pad. For purposes of the iterative calculation, the characteristics of the pad, i.e. the dependency of M_p on φ_p (see fig. 1) can be approximated by means of a polynomial function. Results of the calculation of lateral stiffness (in dependency on lateral load) of the assembly consisting of the spring with parameters given in tab. 1 and the pad with characteristics given in fig. 1 are presented for three various values of vertical (axial) load in fig. 6.

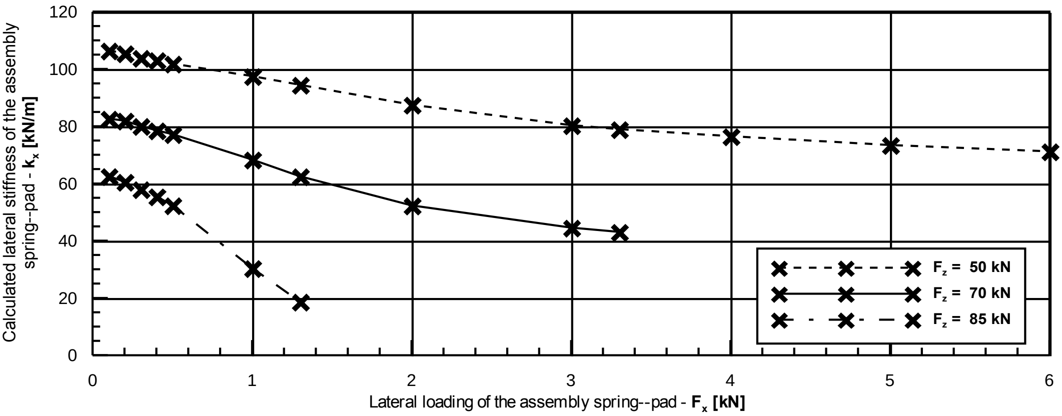


***Fig. 6** Calculated lateral stiffness of the assembly flexi-coil spring–tilting pad in dependence on the lateral loading*

4.Experimental verification of the lateral stiffness

Experimental verification of the calculated lateral stiffness of the assembly flexi-coil spring–tilting rubber-metal pad was performed in framework of extensive measurement of characteristics of flexi-coil springs and strain in material of the spring in laboratories of the Jan Perner Transport Faculty in 2013. A configuration of the electrohydraulic test stand, on which the measurement was carried out, is depicted in fig. 7. Because a very large set of measurements covering various loading states was realized, the attention is paid only the measurement, which is relevant for the verification of the calculated lateral stiffness, in this paper. Parameters of the measured spring as well as characteristics of the pad are given in chapter 2; the measured assembly spring–pad is depicted in fig. 2. Some further information about the realized measurements can be also found in the paper [5].

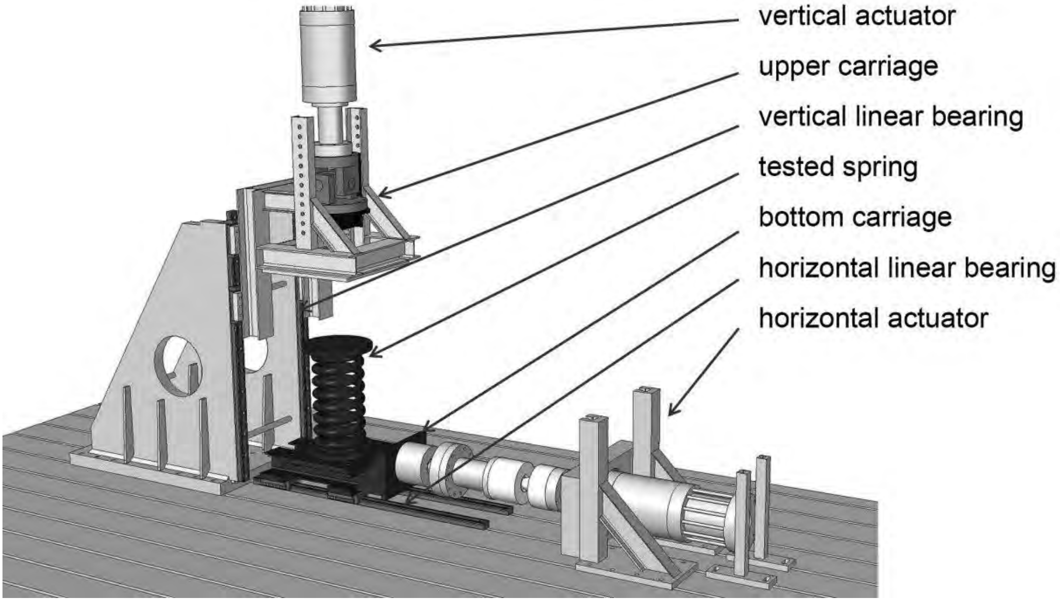


Fig. 7 *Test stand of the Jan Perner Transport Faculty of the University of Pardubice for testing of flexi-coil springs*

The measurement of the lateral stiffness of the flexi-coil spring with the rubber-metal pad was performed for three different values of the vertical load of the whole assembly: 50, 70 and 85 kN. At each level of the vertical load, the assembly was loaded laterally, i.e. in horizontal direction, in 10mm steps up to the maximum lateral deformation ± 50 mm. The measured lateral characteristics of the investigated assembly for the used levels of the vertical load are presented in fig. 8. On the first view it is possible to confirm that increasing vertical load causes decreasing lateral stiffness (i.e. decreasing slope of the measured curves depicted in fig. 8) of the spring with pad, which is a trend following from the analytical calculations, as well. If the values of the stiffness should be compared directly, it would be necessary to calculate them from the measured characteristics.

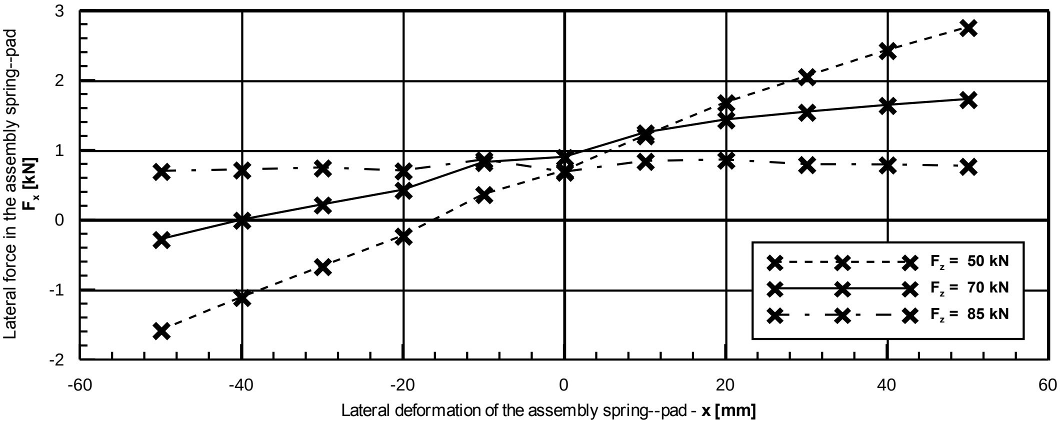


Fig. 8 *Measured lateral characteristics of the assembly flexi-coil spring–tilting pad*

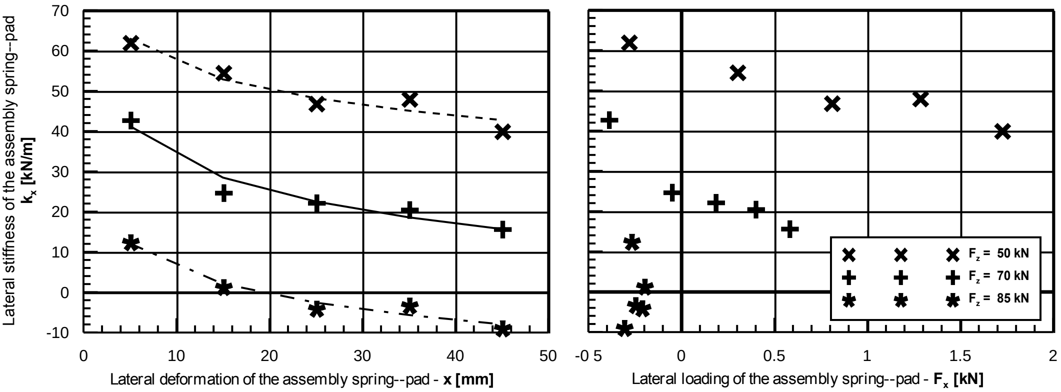


Fig. 9 *Measured lateral stiffness of the assembly flexi-coil spring–tilting pad – dependency on the lateral deformation (left) and on the lateral loading (right)*

The experimentally determined values of the lateral stiffness of the investigated assembly spring–pad are presented for the three used levels of vertical load in graphs in fig. 9. Dependencies of the lateral stiffness on the lateral deformation of the assembly are depicted in the left graph; dependencies on the lateral loading (the lateral force acting on the assembly) in the right one. On basis of a comparison of results of the theoretical calculation of lateral stiffness (see the graph in fig. 6) and relevant measurements (see the graphs in fig. 9) it is possible to state that the results provide similar trends in results regarding dependencies of the lateral stiffness on vertical as well as lateral loading of the investigated assembly; however, the measured values of the stiffness are approximately about 40 kN/m lower than the calculated ones. Therefore, the relative deviation of the calculated and measured values of the lateral stiffness increases with increasing vertical load (and decreasing lateral stiffness). From the graph in fig. 8 (and the right graph in fig. 9) is also evident, that the measured characteristics show an asymmetry, i.e. that a non-zero lateral force acts in the assembly at its zero lateral deformation.

5.Conclusion

The results presented in this paper confirm that addition of the standard flexi-coil springs with rubber-metal tilting pads allows modifying (decreasing) of lateral stiffness of the spring elements in very large measure. Because the tilting effect of the usually used pads is dominant only in one direction, its influence on the lateral stiffness of the spring is directionally specific. This fact can be used in suspension of rail vehicles advantageously, especially for a minimization of resistance against bogie rotation at preservation of lateral stiffness of the secondary suspension. Possibilities of decreasing of the lateral stiffness of a flexi-coil spring by means of a tilting pad are demonstrated on an analytical calculation and subsequent experimental verification of the lateral stiffness on a sample of assembly spring–pad which is described in chapter 2.

In chapter 3.2, an analytical relationship for calculation of the lateral stiffness of a flexi-coil spring with tilting pad is derived by means of modification of Gross' calculation, which can be used for calculation of the lateral stiffness of flexi-coil springs themselves. A parameter defining the tilting pad for purposes of the proposed calculation is its angular stiffness. This calculation can be used e.g. for a preliminary estimation of the required angular stiffness of the pad which is necessary to avoid a negative stiffness of the assembly spring–pad in case of the maximum presumptive vertical load. However, the angular stiffness of a real tilting pad must not be constant; i.e. that its characteristics can be non-linear. For that case, a numerical method of calculation of the lateral stiffness of the assembly spring–pad was proposed and is mentioned in chapter 3.2, as well. Against the calculation with constant angular stiffness of the pad, the resulting lateral stiffness of the assembly can be dependent of its vertical load (and not only on the vertical load) in case of the non-linear characteristics of the pad.

The experimental verification of the calculated lateral stiffness of the assembly spring–pad is described in chapter 4. On basis of results of performed measurements, it is possible to state following conclusions:

- Results of the measurement confirm the calculated trends in stiffness behaviour, i.e. that the lateral stiffness of the investigated assembly spring–pad decreases with increasing vertical load and also decreases with increasing lateral load.
- The calculated lateral stiffness of the investigated flexi-coil spring with tilting pad is ca. about 40 kN lower than the measured stiffness. However, this fact can be caused with neglecting of a shear stiffness of the pad, which also plays a rule but its value is not known (is not defined by the manufacturer and was not determined experimentally). If the shear stiffness of the pad was known, it would represent a serially arranged additional stiffness and the calculated resulting lateral stiffness of the assembly spring–pad could be modified in accordance with the equation (1).
- The measured lateral characteristics of the investigated assembly spring–pad are not symmetric. This fact is caused especially with an asymmetry of real springs.

Because of the observed deviations between the calculated and measured values of the lateral stiffness of the assembly spring–pad, it seems to be necessary to perform some further improvements including experimental verification of the tilting pad itself, i.e. a measurement of its characteristics and also its shear stiffness, because the used characteristics (see fig. 1) is only a nominal curve given by the manufacturer and the real characteristics can be different. Besides to that, detailed clarification of influence of the asymmetries should be performed, as well. Then, the proposed calculation can be used as a simple and sufficiently accurate description of the flexi-coil spring with tilting pad for utilization in multi-body simulations of rail vehicle running performance.

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Literature

1. EN 14363:2005. *Railway applications – Testing for the acceptance of running characteristics of railway vehicles – Testing of running behavior and stationary tests.* Brussels: CEN, 2005.
2. MICHÁLEK, T. – ZELENKA, J. *Sensitivity analysis of running gear parameters on dynamic behaviour of an electric locomotive.* (in Czech) Proc. of the 21st Conf. with int. participation Current Problems in Rail Vehicles 2013, pp. 85-92. Pardubice: University of Pardubice, 2013.
3. MOHYLA, M. *Příčná tuhost šroubových pružin – Teorie a výsledky měření.* Technické zprávy Výzkumného ústavu kolejových vozidel, č. 2, (1971). Praha: VÚKV, 1971.
4. VÁGNER, J. – HÁBA, A. *Possibilities of assessing lateral stiffness of flexi-coil springs.* (in Czech) The Scientific and Technological Anthology, No. 30, (2010). Praha: GŘ ČD, 2010.
5. VÁGNER, J. – ZELENKA, J. – KOHOUT, M. *Experimental verification of the influence of fastening of flexi-coil springs.* (in Czech) Proc. of the 21st Conf. with int. participation Current Problems in Rail Vehicles 2013, pp. 253-260. Pardubice: University of Pardubice, 2013.

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Summary

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This paper deals with possibility of modification of lateral stiffness of flexi-coil springs by means of rubber-metal tilting pads. On basis of the Gross’ calculation of lateral stiffness of a flexi-coul spring, a modified calculation of lateral stiffness of a flexi-coil spring equipped with a tilting pad is derived. Besides to the analytical calculation of the lateral stiffness of the assembly spring–pad for constant value of angular stiffness of the pad, a numerical method of the calculation, which allows considering of non-linear characterictics of the pad, is proposed. In the next part of the paper, the calculated lateral stiffness of the spring with pad is compared with results of measurement performed for several loading states on a test stand in heavy laboratories of the Jan Perner Transport Faculty. The experimental verification shows that the proposed calculation describes the trends in lateral stiffness behaviour very good; however, it seems to be necessary to perform some further improvements because the absolute values of the measured and calculated stiffnesses show certain deviations.

Resumé

ANALYTICKÝ VÝPOČET A EXPERIMENTÁLNÍ OVĚŘENÍ PŘÍČNÉ TUHOSTI FLEXI-COIL PRUŽINY S NAKLÁPĚCÍ PRYŽOKOVOVOU PODLOŽKOU

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Tento článek se zabývá možnostmi úpravy příčné tuhosti flexi-coil pružin s využitím naklápěcích pryžokovových podložek. Na základě Grossovy metody výpočtu příčné tuhosti samotných flexi-coil pružin je zde odvozen vztah pro výpočet příčné tuhosti flexi-coil pružiny s naklápěcí podložkou. Kromě metody analytického výpočtu příčné tuhosti sestavy pružina–podložka pro konstantní úhlovou tuhost podložky je zde navržena i numerická metoda výpočtu umožňující zahrnutí nelineární charakteristiky podložky. Dále je v článku provedeno porovnání vypočtených příčných tuhostí pružiny s podložkou s výsledky měření provedeného pro různé zatěžovací stavy na zkušebním vzorku flexi-coil pružiny s podložkou na zkušebním stavu v těžkých laboratořích Dopravní fakulty Jana Pernera. Toto experimentální ověření ukazuje, že navržená metodika výpočtu popisuje trendy v chování příčné tuhosti velmi dobře, avšak s ohledem na zjištěné odchylky absolutních hodnot vypočtených a naměřených příčných tuhostí bude potřeba provést ještě další vylepšení.

Zusammenfassung

ANALYTISCHE BERECHNUNG UND EXPERIMENTALE VERPROBUNG VON QUERSTEIFIGKEIT DER FLEXI-COIL-FEDER MIT GUMMI-METALL-SCHWENKAUFLAGE

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Dieser Beitrag beschäftigt sich mit Möglichkeiten von Modifikationen der Quersteifigkeit der Flexi-Coil-Feder durch Ausnutzung von Gummi-Metall-Schwenkauflagen. Auf der Grundlage der Flexi-Coil-Federquersteifigkeitsberechnung gemäß Gross ist hier eine analytische Gleichung für Berechnung von Quersteifigkeit der Flexi-Coil-Feder mit Gummi-Metall-Schwenkauflage abgeleitet. Zusätzlich zu dieser analytischen Berechnung, die nur für konstante Winkelsteifigkeit ausnutzbar ist, ist hier noch eine numerische Berechnungsmethode, die eine Einbeziehung von nichtlinearen Schwenkauflagecharakteristik ermöglicht, vorgeschlagt. Dazu ist in diesem Artikel ein Vergleich der berechneten Quersteifigkeiten von der Flexi-Coil-Schraubenfeder mit der Schwenkauflage mit Ergebnissen der Messungen, die für verschiedene Lastfälle auf einem Probestück in schweren Labors der Jan Perner Fakultät für Verkehrswesen realisiert waren, durchgeführt. Diese experimentale Verprobung zeigt, dass die vorgeschlagene Quersteifigkeitsberechnungsmethode die Trends im Quersteifigkeitverhalten gut bescheibt, aber in Bezug auf beobachtete Abweichungen zwischen Absolutwerte der berechneten und gemessenen Quersteifigkeiten es nötig wird, weitere Verbesserungen noch auszuführen.