Conical rubber suspension springs in the construction of railway vehicles

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Abstract. An important category of rubber suspension elements is represented by the tapered springs, to which the rubber is subject to shear and compression request. Such type of springs has a widespread use in the construction of rolling stock because, in addition to the advantages of good use of the rubber in terms of request to the stress, they are easier to use. The shape and dimensions of these springs make them usable in a very wide range, from elements for suspending aggregates to suspension elements. The paper presents the main constructive types of conical springs and their calculation elements. Special reference is made to the use of conical springs in the suspension of railway vehicles.

1. General considerations regarding the construction of suspensions

While movement, the vehicle is subjected to action of the some disturbances coming from the railroad. Its suspension elements have the role of reducing the effects of disturbances to acceptable values, both from the point of view of the quality of walking and the safety of railway traffic.[1-3]

Ensuring passenger comfort, the integrity of the goods transported and the construction of vehicles essentially depends on the quality of the vehicle suspension and its ability to isolate the vehicle from the disturbing impulses that occur in the rolling process of the axles both in the vertical direction and cross [4-6].

The vehicle suspension shall ensure a total dynamic capture, in straight line and in curves where the inertia forces between the vehicle and the track shall be maintained within the limits of the safety of railway traffic.

In the curve, there is a need for the friction forces in the contact points with the track to be as small as possible in order to reduce wear and thus maintain wheel and rail profiles within acceptable of the safety of railway traffic range.

In the curves, under the action of uncompensated centrifugal forces, the vehicle box moves in the transverse direction and tilts on the suspension springs, with the danger of leaving the gauge. The suspension contributes to the avoidance of this danger and also to the reduction of the transverse accelerations, the wheel load variations and consequently the increase of the safety against derailment.

„The flexibility coefficient” characterizes the ability of the vehicle to tilt transverse due to an excess or insufficiency of the cant of the tread.

On urban public transport vehicles, the suspension must provide an approximately constant height of the floor (at the height of platform of the stations). This condition can be achieved by the pneumatic suspension, also ensuring a proper running quality independent of the vehicle's load.
Of the bogie movements, the hunting oscillation is of particular importance for the stability of the vehicle, for both safety of railway traffic and transverse comfort.

A complementary quality to those presented is also the ability of the suspension to mitigate the noise due to running and propagation to the interior of the vehicle’s box.

The type of the vehicle and its travel regime influence the adoption of a specific suspension solution.

On subway vehicles in general, the suspension of the axles is like rubber springs and the central suspension with pneumatic springs.

2. Suspension with rubber springs

2.1. Characteristics of the rubber that are of particular interest in making a suspension

The basic feature of the rubber is its great elasticity, namely the ability to withstand large deformations under the influence of external forces and to return to its original form when the action of these forces ceases. In figure 1 the dependence between the specific stress and the deformation (elongation) of a rubber piece (curves) compared to the steel piece (curve 2) and the range of use of the rubber according to the size of the deformation. The deformation curve begins with a linear portion followed by a material flow area and a breakage portion that causes tearing. Currently, the tire is used for static deformations ranging from 10-35% of the original size of the part, generally within the load-proportional deformations. Dynamic stresses allow up to 50% deformations depending on the nature and frequency of these requests.

The deformation of the rubber is not perfectly reversible (Figure 2). One piece has a deformation under the action of a force P (curve 1 - characteristic of elasticity). In the reduction and cancellation of the load (curve 2), the piece does not return to its original shape, retaining a residual deformation (the hysteresis phenomenon), the area between curves 1 and 2 being equal to the mechanical work of the friction forces (damping effect in a suspension of the vehicle).

Upon a load reload, it was found that the same curves did not occur, nor did the same mechanically dissipated. On a new piece, the deformation feature stabilizes after a number of load-discharges. This is why the rubber suspension elements are subjected to the test of lifting the feature after a number of deformations at the maximum load (about 10 loads - discharges).

The stabilized feature is influenced by the deformation velocity due to a delayed rubber reaction (figure 3).

For a suspension element that deforms with the static arrow fst under the action of static force Pa, the stiffness is given by the angle of the angle αst (figure 4). If there is an alternate dynamic overload with a high deformation velocity when running the suspension, the rubber element will work on a-b-c-a-cycle. In this case the element behaves with a higher rigidity given by the tangent angle αd. The higher the deformation velocity of the rubber, it reacts with a more pronounced stiffness (curve a-b’-c-d’-a).
The percentage difference between the a-b-c-d-a surface, denoted by $A_c$, representing the mechanical work spent on deformation of the rubber and the c-b-d-c surface, denoted by $A_r$, representing the mechanical work restituted to the suspended mass, constitutes the hysteresis factor.

$$d = 100 \cdot \left( \frac{A_c - A_r}{A_c} \right) \%$$

(1)

The damping factor by hysteresis $d$ is generally between 5 and 50%, which represents a satisfactory percentage for railway vehicles, making use of special dampers unnecessary.

Constant flow and deformation are influenced by temperature, as can be seen in (Figure 5). This phenomenon is important at low temperatures that can be encountered on suspensions.

2.2. Principles for calculation of rubber elastic elements

The dimensioning of rubber parts presents some difficulties due to the less controlled mode of behavior of the material, which results from the above.

The basic relations for sizing are the dependencies between the elastic moduli and the admissible specific stress, and this is the name of the linear load bearing deformations.

In this situation we have for the parallel shearing $G = \tau \cdot h / f$ and for compression $E = \sigma \cdot h / f$ and if in specific request relationships is replaced by $\tau = P_f / A$ and $\sigma = P_c / A$ where $P_f$ and $P_c$ are the shear and compression forces to which the piece is subjected, and $A$ is the minimum section of the part according to the loading direction, the general rigidity relations of a rubber part are obtained:

for parallel shearing: $$c_r = P_f / f = G \cdot A \cdot P_f / h$$

(2)

for compression: $$c_r = P_c / f = E \cdot A \cdot P_c / h$$

(3)

In the case of torsional force application, instead of force $P_t$, the moment of torsion $M_t$ is introduced, and instead of arrow $f$ is introduced the torsion angle $\varphi$, and the torsional stiffness:

$$e_t = M_t / \varphi$$

(4)
In fact, the dimensioning of a rubber element consists in determining its dimensions in order not to damage itself under the action of the forces that require it and to determine the stiffness, respectively the dependence between the applied load and the deformation of the rubber.

In order to dimension a rubber part for the suspension, it is necessary to know the maximum static load, the value and characteristic of the dynamic load (amplitude, frequency), the required rigidity (or flexibility) and the gauge (or volume) available for mounting the rubber part.

A first dimensioning criterion is the determination of the volume that the rubber has to have in order to take over the mechanical deformation work under the action of the maximum static load. Depending on the specific mechanical deformation of the rubber in different loading modes, the volume or weight of the rubber piece can be determined.

For specific admissible requirements, their value varies according to the type of use of the elastic rubber elements, which justifies the different values indicated in the technical literature.

Following the recommendations of UIC (International Union of Railways), the admissible requests are indicated in Table 1

| Table 1. Static and Dynamic Admissions Admitted to Rubber, daN/cm² (after UIC) |
|---------------------------------------------|--------------|
| Static requests                          | Dynamic requests |
| Compression                             | σₐ = 8K 10   |
| Shear                                    | τₐ = 3K 4    |
| Torsion                                  | τₐ = 7K 9    |

In the field of rail rolling stock, taking into account a series of elastic rubber elements made and used in suspension systems by specialized firms, it is recommended that the values in Table 2 be measured for the dimensioning of the rubber parts.

| Table 2. Admissible static rubber applications (recommendations) in daN/cm² |
|---------------------------------------------------------------|
| The hardness of the rubber °Sh                                  |
| 40...50                                                       | 50...60       | 60...80       |
| Compression                                                   |               |
| σₐ = 4K 12                                                   | σₐ = 10K 25   | σₐ = 25K 50   |
| Parallel shearing                                            |               |
| τₐ = 3K 5                                                   |               |
| Shearing and compression                                     | τₐ = 20K 30   |
| Compression and Torsion                                       | τₐ = 15K 20   | τₐ = 25K 40   |

3. Conical rubber suspension springs

Another category of rubber suspension elements is the conical spring, to which the rubber is applied to shearing and compression as shown in figure 6, which is the basic shape of a spring. Starting from this form, there is a very large variety of conical springs.

![Figure 6. Conical rubber springs (section).](image)
The rubber is vulcanized between two metal fittings that have the shape of conical bushings, the generally small angle, of the 5...20°.

Under the action of an axial force \( P \), the rubber element deforms from the ABCD free position to the \( A'B'CD' \) position, the deformation deforming into a parallel shear \( BE \) and a compression \( B'E \).

Compared to the axial deformation of the part, the specific deformations are given by the geometric relations:

\[
\text{to parallel shear} \quad f_f = BE = f \cdot \cos(\alpha) \tag{5}
\]

\[
\text{to compression} \quad f_c = B'E = f \cdot \sin(\alpha)
\]

And in this category of suspension elements, the rubber is used advantageously, and can take on a specific mechanical deformation with high values.

In order for the deformations to remain linear, both in compression and shearing, respectively in the range of deformations of up to 20% of the compression rubber thickness and up to 35% of the shear thickness of the shear, the cone angle results from:

- the deformation limit at compression \( f_c = f \cdot \sin(\alpha) = 0,2 \cdot d \)
- the shear deformation limit \( f_f = f \cdot \cos(\alpha) = 0,35 \cdot d \)

where from: \( \tan(\alpha) = 0,2/0,35 = 0,57; \quad \alpha = 29'40' \)

Generally, no such angles are used in this suspension category, with shear stress being predominant.

For dimensioning it is considered with sufficient approximation that the piece is shear-like as a bush in which the rubber has an average radius \( r_m \), and on compression as a plate having the surface \( A = 2 \cdot \pi \cdot r_m \cdot H \)

Geometric relationships lead to:

- inner radius of the rubber bush \( r_i = D_i/2 - (h/2) \cdot \sin(\alpha) \)
- the outside of the rubber bush \( r_c = D_i/2 - (h/2) \cdot \sin(\alpha) \)
- the average radius of the rubber bush \( r_m = (1/2) \cdot (D_i + D_x)/2 - (h/2) \cdot \sin(\alpha) \)
- the height of the rubber bush \( H = h/\cos(\alpha) \)

With these geometrical elements it results:

- the force that causes deformation \( f_f \) at shear shearing

\[
P_f = f_f \cdot G \cdot 2 \cdot \pi \cdot H / \ln(r_i/r_f) = f \cdot \cos(\alpha) \cdot (G \cdot 2 \cdot \pi \cdot H / \ln(r_i/r_f)) \tag{7}
\]

- the force that causes deformation \( f_c \) when compressing the plate

\[
P_c = f_c \cdot E \cdot A / \alpha = f \cdot \sin(\alpha) \cdot E \cdot A / d \tag{8}
\]

The force \( P \) which axially loads the rubber piece is the result of the shear and compression forces \( P = P_f \cdot \cos(\alpha) + P_c \cdot \sin(\alpha) \) and, with the values of this force, results:

\[
P = f \cdot \left[ \frac{G \cdot 2 \cdot \pi \cdot H}{\ln(r_i/r_f)} \cdot \cos^2(\alpha) + \frac{E \cdot A}{\alpha} \cdot \sin^2(\alpha) \right] \tag{9}
\]

This results in the axial rigidity of the rubber conical air
\[
\frac{P}{f} = \frac{G \cdot 2 \cdot \pi \cdot H}{\ln(r_1/r_2)} \cdot \cos^2(\alpha) + \frac{E \cdot A}{\alpha} \cdot \sin^2(\alpha)
\]  

(10)

If the conical spring is made up of several concentric bushings, the stiffness of each bush is determined, depending on the geometric dimensions, and is summed up as a series-loaded arc battery. Conical rubber springs have a particularly widespread use in the construction of rolling stock because, in addition to the advantages of good use of the rubber (shear and compression), they are easy to achieve because the metal fittings can be made by simple technologies (rolling, cupping, turning) and also the vulcanization molds have the majority of turning processes.

The shape and dimensions of the tapered rubber bearings make them usable in a very wide range, from components for suspension of aggregates (compressors, traction motors) to primary or secondary suspension components for vehicles.

The high deformability in the transverse direction of the conical springs makes it possible to use them in the central suspension for the bogies without the oscillating crosspiece, the upper reinforcement being fixed to the chassis body of the wagon, and the lower arm to the bogie frame, the relative bogie-bogie rotation being assumed by the transverse deformability of the spring.

The transverse stiffness and modulus of deformation of such an element used in the central suspension is shown in Figure 7.

![Figure 7. Deformation mode and characteristics of a secondary suspension conical spring.](image)

4. Conclusions
The paper presents the main features of the rubber elements and the specificity of their use as suspension springs on railway vehicles. It is thus shown that these springs when the transverse deformation capacity can be used in the center suspension of the vehicles without the need for an oscillating crosspiece.

In addition to the cross-sectional ratio, these springs also provide good sound insulation for the bodywork.

In the paper there are also elements of design of this type of spring according to the recommendations of the International Union of Railways (UIC).

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