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Division V

ANALYTICAL AND NUMERICAL INVESTIGATION OF RING SPRING DAMPERS IN SEISMIC DESIGN

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ABSTRACT

The application of ring spring dampers in seismic design and strengthening of engineering structures is less or even not investigated. Ring spring dampers are extremely robust, heat-resistant, and durable. In addition, ring springs are mostly maintenance-free and used in mechanical engineering with maintenance intervals of up to 50 years. With an innovative design, they combine self-centering characteristics with high seismic energy absorption capacity. The preloading feature introduces a typical flag-shaped force-deformation hysteresis curve, which can absorb seismic energy in a structure very efficiently independent of deformation velocity (non-viscous damping). Due to these properties, a structure with ring spring dampers can withstand seismic loads with little or even no damage. The springs themselves also remain free of damage.

The objective of the present work is to give an overview of the behavior of ring spring dampers. The properties, calculation, and effective damping are discussed.

INTRODUCTION

Ring spring dampers are not widely investigated by civil engineers, several perspectives have to be explored such as the damping effect. One of their features is high heat resistance and durability. High performance of the ring spring dampers can be reached by implementing the concept of self-centering in the design method. Therefore, it is possible to develop low-damage and high-performance systems with self-centering capabilities as an alternative to conventional systems (Issa 2018). The aim is to ensure that the occupancy of the building is maintained right after the earthquake, and therefore only the elastic structural behavior is exploited. The advantage is a high level of reliability, which is particularly important in the nuclear field.

PROPERTIES

Ring springs, also known as friction springs, are made of steel material that can withstand cyclic loads. They are composed of outer and inner rings, each with conical surfaces. The springs can be loaded axially and, as a result, the outer rings expand in diameter while the inner rings are compressed. Since the deformation of the rings is elastic, the friction forces are so high that the restoring force is 66 % percent less than the deformation force. Figure 1 shows the typical flag-shaped load-deformation curve. The area with an orange background represents the hysteretic damping D_{rel}. A direct correlation can be introduced between the max force $F_{\max}$ and the restoring force F_{R} which is presented in the next formula.

$$F_{\mathrm{R}} = (1 - D_{rel})\, F_{\max} \tag{1}$$

The frictional damping D also depends on the lubrication, so in addition to the standard value of 66 %, damping values of 55 %, 45 %, and 35 % are also possible. The sliding surfaces are lubricated ex-factory and, in general, relubrication during operation is not necessary.

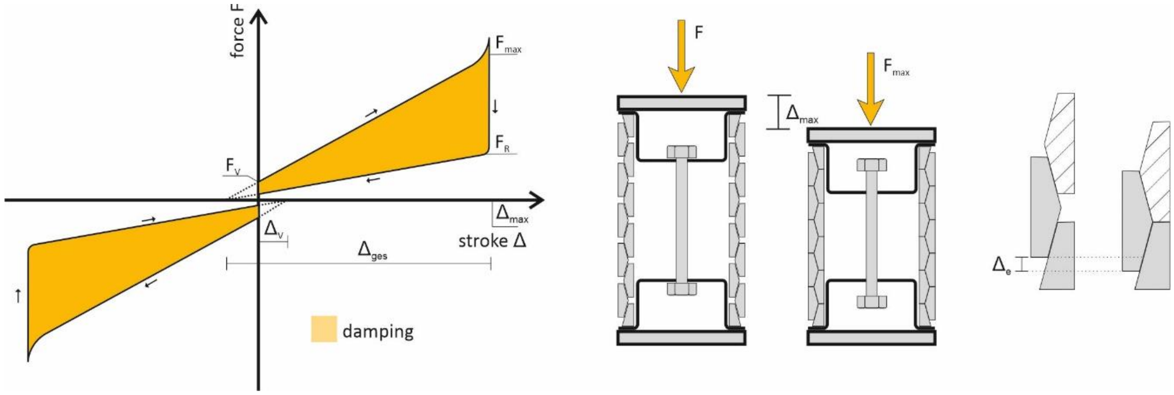

Figure 1. Design and typical load-deformation curve of a ring spring (Helm, L., Sadegh-Azar, H., Jahnel, L., Jandrey, H. 2022)

As the rings themselves are not fixed, the spring must be preloaded to secure its position. This must be at least 5 to 10 % of the final force and can also be increased to up to 60 % if required. The preload displacement Δ_V is calculated from the total stroke Δ_{ges} and the preload force F_V:

$$\Delta_V = \frac{F_V}{F_{max}} \Delta_{ges} \tag{2}$$

The available stroke is determined by the number of rings. The stroke results from the relative displacement of two rings Δ_e and this unit is defined as one element e. The total stroke can be calculated as follows:

$$\Delta_{ges} = e\, \Delta_e \tag{3}$$

Considering the preload, the usable stroke results from:

$$\Delta_{max} = \Delta_{ges} - \Delta_V \tag{4}$$

Although the springs themselves can only absorb compressive forces, a tension spring element can be created by appropriate design. A possible solution is shown in figure 2. (Ringfeder; Jahnel, L., Cole, E. M. 2015)

After exceeding the maximum stroke, the spring is in the block state in which it is still able to carry greater loads but behaves like a stiff element. When the load is reduced, the spring returns to its initial position and remains fully operational. This results in a high level of safety because the greatest transmissible static force is limited by the design and not by the ring springs. Ring springs are currently employed in the mechanical engineering sector for absorbing and dissipating high kinetic energies even though their properties also offer great advantages in earthquake engineering. They can withstand many cycles, are reusable, and are suitable for continuous use. As a result, they are always ready for use, even in the event of an aftershock or clustered seismicity. Furthermore, if a ring in a friction spring assembly were to break, the spring would still be functional and the maximum transmissible load would be maintained.

However, the use of the ring spring is also extended to the mechanical engineering field with maintenance intervals of up to 50 years (Sadegh-Azar, H., Goldschmidt, K., Jahnel, L. 2019). The ring springs are not only robust to cyclic loading, but they are also favorable in case of fire and maintain their function until the critical temperature is reached (Wiebe, L. D. A. 2015). Another advantage is their self-centering capability after an earthquake event whereby permanent deformations are prevented.

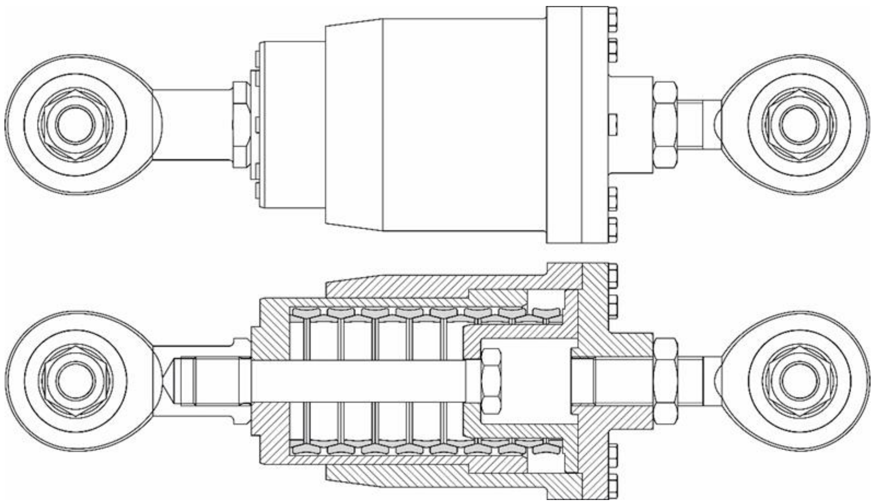

Figure 2. Design of a double-acting ring spring: tension and compression

Figure 3. Load-deformation measurement of a double-acting ring spring

A measurement is shown in figure 3. The expected hysteresis curve is reliably reproduced by the experiment. The hysteresis is generally independent of the loading velocity (Ringfeder), which is to be investigated with further experiments at the university.

FORCES IN THE SPRING

For the sake of comparison between the ring spring and other springs, the same amount of resistance can be achieved with fewer materials. The generated stresses are distributed equally over the cross-section. To better understand the ring spring, the stress in the rings will be determined in the following. (Meissner, M., Schorcht, H., Kletzin, U. 2015)

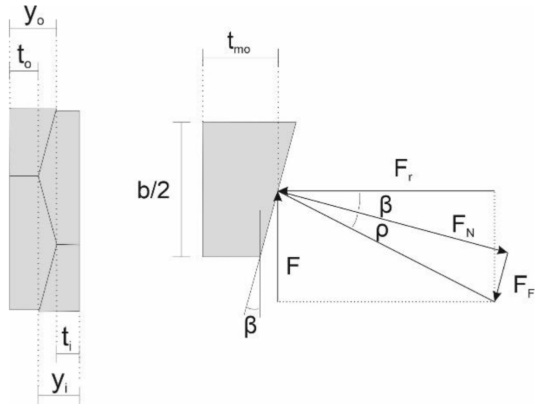

Figure 4. Forces on one element (Meissner, M., Schorcht, H., Kletzin, U. 2015)

The geometry of the rings is defined by the parameters t_o, t_i, y_o, y_i, b and β. The average thickness of the outer rings t_{om} is calculated with

$$t_{om} = \frac{t_o + y_o}{2} \tag{5}$$

Accordingly, the average thickness of the inner rings t_{im} can be determined. The thickness of the outer and inner rings can be adjusted to the material-specific relationship between the compressive and tensile strength.

$$t_{im} = \frac{t_i + y_i}{2} \tag{6}$$

The stress σ_o in the rings can be determined based on Barlow's formula. A half outer ring is considered (figure 4). The radial force F_r acts in the area of the contact surface between the inner and outer ring.

$$\sigma_o = \frac{F_r}{\pi\, t_{om}\, b} \tag{7}$$

The radial force is calculated according to the triangle of forces with the angle of friction ρ, the inclination of the rings β, and the spring force F. A distinction must be made between loading ($F_{r,l}$) and unloading ($F_{r,ul}$) of the spring. This affects the direction of the frictional force F_F.

$$F_{r,l} = \frac{F}{\tan(\beta + \rho)} \tag{8}$$

$$F_{r,ul} = \frac{F}{\tan(\beta - \rho)} \tag{9}$$

In the following, only the loading is considered. Finally, the stress of the outer rings can be calculated.

$$\sigma_o = \frac{F_r}{\pi\, t_{om}\, b \tan(\beta + \rho)} \tag{10}$$

The tension of the inner rings is calculated accordingly.

$$\sigma_i = -\frac{F_r}{\pi\, t_{im}\, b \tan(\beta+\rho)} \tag{11}$$

EFFECTIVE DAMPING

Ring springs have damping of approximately 66 %. However, this value refers to the amount of the restoring force and thus describes the hysteresis or the force-deformation curve. For oscillatory systems, the degree of damping, also known as Lehr's damping coefficient, is commonly used. Despite this value being defined for linear vibration equations with viscous damping, an analogous value can be determined. For this purpose, the logarithmic decrement or the hysteresis curve can be used to quantify the damping for a better characterization of the vibration behavior.

Figure 5 shows the work done over the displacement without preload. Here, W_S is the work of stiffness and W_D is the work of damping. From their ratio, the degree of damping can be estimated.

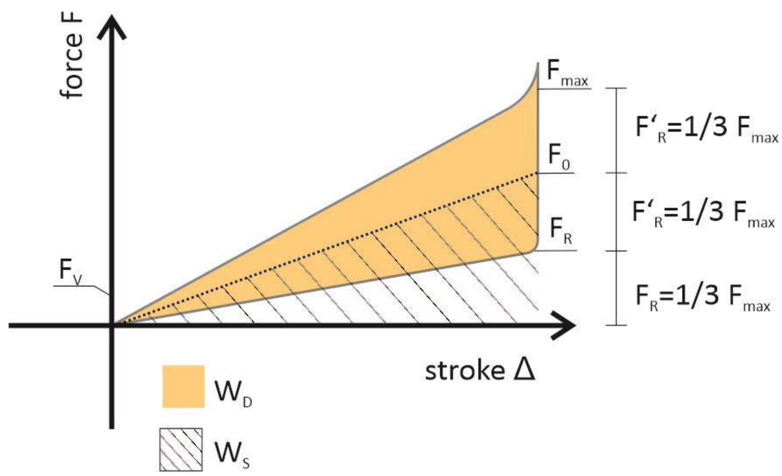

Figure 5. Work done, W_S work of stiffness, W_D work of damping (Helm, L., Sadegh-Azar, H., Jahnel, L., Jandrey, H. 2022)

$$\xi = \frac{2\,W_D}{4\pi\,W_S} = \frac{2\,\frac{2}{3}\Delta}{4\pi\,\frac{2}{3}\Delta} = \frac{1}{2\pi} \approx 16\ \% \tag{12}$$

This simple consideration results in approximately 16 %, though the preload cannot be counted for this approach. In an alternative analytical approach, the vibration amplitudes are calculated. The logarithmic decrement subsequently provides the damping factor through the reduction of the amplitudes. Initially, the range of the preload is calculated. In this case, the constant spring force $-F$ is assumed for small displacements. The mass m starts at the displacement Δ_0 and is now accelerated to the maximum velocity v by the constant spring force. The new amplitude $\Delta_{0,5}$ can then be calculated based on this.

$$v = \sqrt{\frac{2}{3}\frac{F}{m}\Delta_0} \tag{13}$$

$$\Delta_{0,5} = \frac{v^2}{2}\frac{m}{F} = \frac{1}{3}\Delta_0 \tag{14}$$

$$\delta = 2\ln\left(\frac{\Delta_0}{\frac{1}{3}\Delta_0}\right) = 2\ln(3) \tag{15}$$

$$\xi = \frac{2\ln(3)}{\sqrt{4\pi^2+(2\ln(3))^2}} \approx 33\ \% \tag{16}$$

This results in significantly higher damping of 33 %. The same procedure is now used to calculate friction springs without preload and the spring force is hence considered to be linear.

$$v = \Delta_0 \omega \sin(\omega t) = \Delta_0 \sqrt{\frac{\frac{1}{3}K_{RL}}{m}} \tag{17}$$

$$\Delta_{0,5} = \frac{v}{\omega \sin(\omega t)} = \sqrt{\frac{1}{3}}\Delta_0 \tag{18}$$

$$\delta = 2\ln\left(\frac{\Delta_0}{\sqrt{\frac{1}{3}}\Delta_0}\right) = 2\ln(\sqrt{3}) \tag{19}$$

$$\xi = \frac{2\ln(\sqrt{3})}{\sqrt{4\pi^2+(2\ln(\sqrt{3}))^2}} \approx 17\ \% \tag{20}$$

This approach provides damping of 17 % and corresponds approximately to the calculation with the work done. The damping is between 17 % and 33 % depending on the preload. This correlation will now be investigated in more detail. For this purpose, a single degree of freedom system without stiffness is assumed. The free vibration is calculated numerically. With the maximum amplitudes and the logarithmic decrement, the damping can be determined. The investigation has shown that, unlike linear systems, the damping changes over the deflection. Furthermore, the initial stiffness has an influence. The results are shown separately for the preload and the initial stiffness in figure 6 and figure 7.

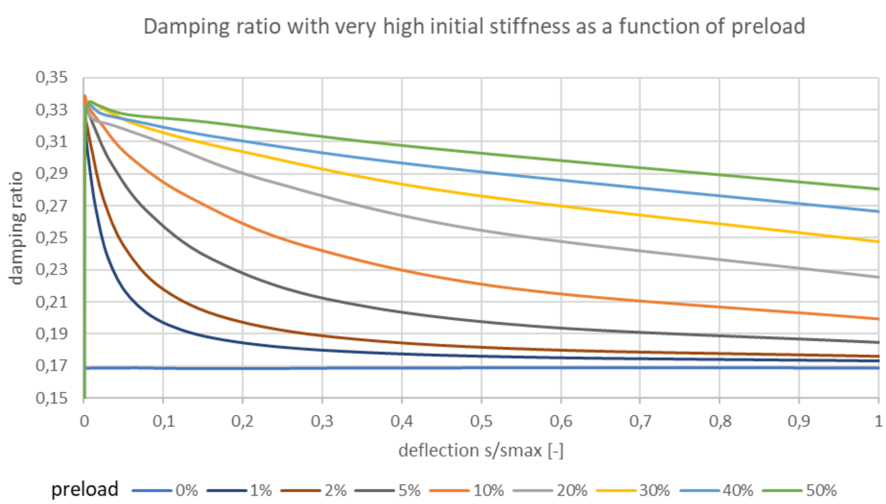

Figure 6. Damping ratio as a function of preload (Helm, L., Sadegh-Azar, H., Jahnel, L., Jandrey, H. 2022)

In a system without preload, a damping factor of just under 17 % is achieved. As soon as a small preload is present, damping of approx. 33 % is observed for small displacements, which drops rapidly for larger displacements. In this case, the initial stiffness, which is assumed to be very high here, is decisive. If the preload is increased up to 10 %, 20 %, which is the relevant range for practical applications, then damping of 20 % to 33 % is possible. With increasing preload, larger displacements approach higher damping.

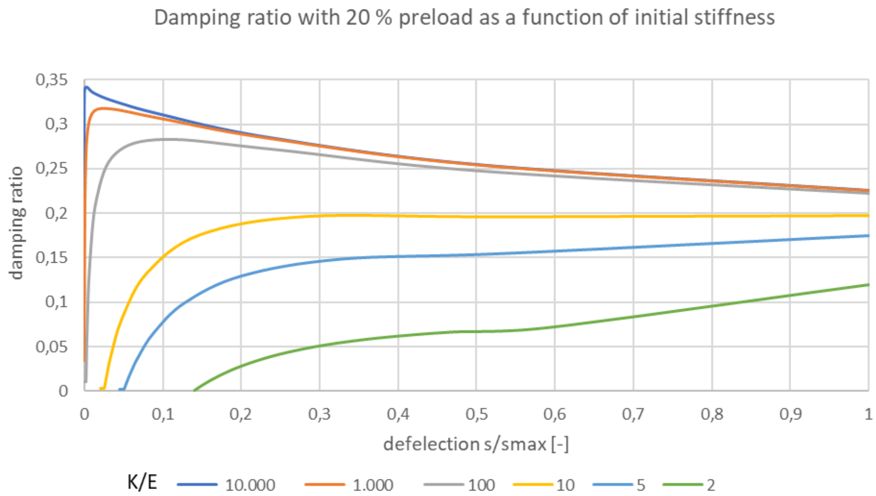

Figure 7: Damping ratio as a function of initial stiffness (Helm, L., Sadegh-Azar, H., Jahnel, L., Jandrey, H. 2022)

The initial stiffness K is specified in relation to the tangent stiffness E at loading. It can be seen that a smaller initial stiffness reduces the damping and especially for small displacements the effect is very large.

DYNAMIC MAGNIFICATION

A magnification function describes the response of a structure under harmonic loading or in this case under harmonic base excitation. It shows how robustly a system behaves at different frequencies. The harmonic base excitation $\Delta_g(t)$ is defined as

$$\Delta_g(t) = \Delta_{\mathrm{g},0} \sin \omega_{\mathrm{p}} t. \tag{21}$$

In this case $\Delta_{\mathrm{g},0}$ is the amplitude and ω_p the frequency. The magnification function V_d results from $\Delta_{g,0}$ and the largest displacement Δ_{max} of a structure due to the harmonic base excitation $\Delta_g(t)$, whereby only the steady-state response is considered here.

$$V_d = \frac{\Delta_{max}}{\Delta_{g,0}} \tag{22}$$

For an elastic Single-Degree-of-Freedom system with a viscous damping ξ, the magnification function can be derived from the equation of motion and calculated as follow.

$$V_d = \sqrt{\frac{1+(2\xi\beta)^2}{(1-\beta^2)^2+(2\xi\beta)^2}} \tag{23}$$

Here β is the ratio of the excitation frequency to the natural frequency and a factor of $V_d = 10{,}05$ results in a damping ratio of 5 % in resonance. Such a system is now additionally braced and analyzed with ring springs. In this case, the ring springs are dimensioned in such a way that the natural frequency is doubled and, simplified, no preload is taken into account. For this system, the solution must be found numerically. The results are shown in figure 8.

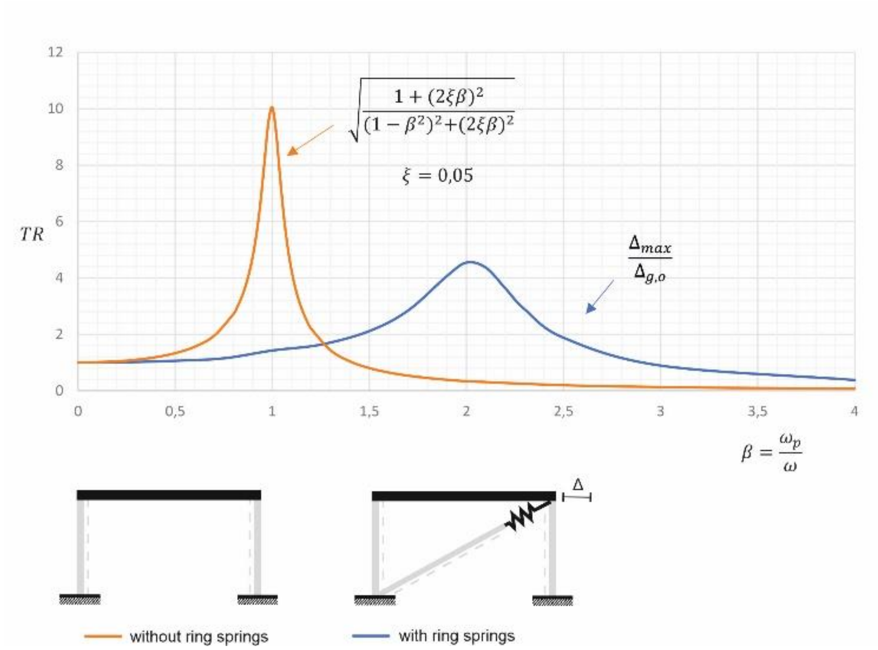

Figure 8. Magnification function of a system with and without ring springs (Helm, L., Sadegh-Azar, H., Jahnel, L., Jandrey, H. 2022)

Due to the higher damping of the ring springs, the magnification factor in resonance could be reduced to $V_d = 4{,}54$, which corresponds to a damping ratio of 11 %.

SUMMARY

This paper gives an overview of the ring spring behavior. Implementing the ring spring damper as one of the energy dissipation devices is not very well investigated by the structural engineers, one of the features, which distinguishes the ring spring damper among the other dampers, is the ability to maintain under function with high resistance after the cracking of rings. The stresses are distributed equally over the cross-section. The advantage of these springs is that they can absorb a large amount of impact energy in a structure, independently of deformation velocity. The investigation shows that the damping is approximately 16 % up to 33 % considering the preload. Therefore, a system with ring spring dampers has significantly reduced magnification factor.

It is possible to develop low-damage and high-performance systems with self-centering capabilities as an alternative to conventional systems (Issa 2018). The aim is to ensure that the function is maintained even immediately after the earthquake, and therefore only the elastic structural behavior is exploited. The advantage is a high level of reliability, which is particularly important in the nuclear field.

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