Extension spring design on a new level

In the IGF research project 22762 BR (01/2023–09/2025), the team led by Ulf Kletzin at TU Ilmenau, together with the Association of the German Spring Industry (VDFI) and numerous member companies, developed new approaches and methods for extension spring design.

Fig. 1a: Selection of loops investigated in the project (from left to right): half German loop, English loop, and German side loop (C. Otto). *© TU Ilmenau*

The objective was to determine both existing stresses that have so far not been calculable and previously unknown permissible stresses, and to consolidate these into strength verification calculations and diagrams.

Key characteristics of extension springs

In manufacturing extension springs, the spring steel wire is either coiled around a mandrel or the wire is wound to the spring body. The coils typically lie directly against each other to achieve the shortest possible installed length. The wire is pretorsioned so that the spring already exhibits an initial tension force F_0 at its free length. The spring force is adjusted by pulling on the spring ends. The tensile load must be introduced into the spring body in an appropriate manner. For this purpose, numerous end configurations have become established, including screw-in fittings, half or full German loops, and English loops (Fig. 1). As a result of the forming process, heat treatments, and further optional manufacturing steps such as shot peening or surface, a complex residual stress state develops in the wire.

Limitations of DIN EN 13906-2

For the design of cylindrical extension springs, the mathematical relationships specified in DIN EN 13906-2 [1] form the essential basis. However, there are significant shortcomings due to missing approaches and insufficient information. This limits the ability to meaningfully describe and assess the complex interactions, such as spatial complexity, superposition of several stress types and manufacturing influences.

For extension springs, several critical regions must be verified in the dynamic and/or static strength verification, depending on the type of load introduction (Fig. 2 according to the standard, with additions shown in red). For common loop ends, these include, in addition to the spring body FK, the loop A itself and, in particular, the transition region B from the spring body to the loop. In the transition, normal and shear stresses are superimposed. Moreover, this region is subjected to severe plastic deformation (residual stresses, tool contact effects), and the bending radius is very small (notch effect, stress concentration).

According to the standard, extension spring design is carried out using the equation $\tau = 0.45 \cdot R_m$ by determining the allowable shear stress in the spring body τ as a function of the tensile strength R_m of the wire. Normal stresses are not considered at all.

Unlike compression springs, the allowable stresses cannot be taken from fatigue-strength diagrams (see [2], [3]) because no comparable charts exist for extension springs. Beyond a reference to the “peculiar shape”, the standard also provides no recommendations for a calculation-based verification for the various loop geometries. Instead, it merely recommends performing “fatigue life tests under the actual operating conditions”.

There are no generally applicable formulas for determining the existing stresses in the loop-to-body transition, since these de-

Fig. 1b: Examples of extension springs with different load-introduction options. *© TU Ilmenau*

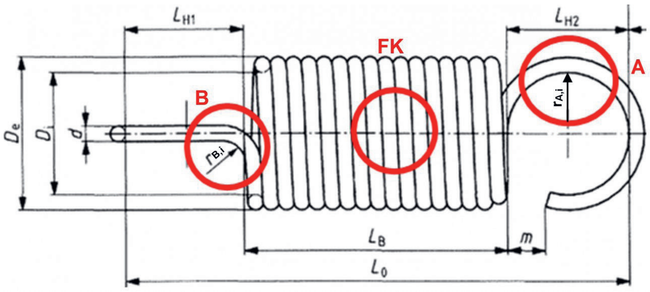


Fig. 2: Failure-critical regions (red) in extension springs (here: half and full German loop) based on [1]*© TU Ilmenau*

pend on numerous parameters (loop orientation and position, spring parameters). Consequently, numerical analyses had to be used. For the spring body, the same equations as for compression springs are applied. As a result, a standardized and, in particular, SME-suitable calculation-based design of extension springs has so far been significantly hindered in many respects, or even impossible.

New strength assessments

The FKM Guideline "Springs" [4], to whose development the research group made a significant contribution, forms the basis of the proposed solution approach. Using this guideline, the degree of utilization a_{BK} is to be determined at the failure-critical locations. With the aid of the guideline, locally bearable stress amplitudes for a given mean stress are calculated while taking various influencing factors into account (surface roughness, highly stressed surface area, dimensions, etc.). A safety concept converts the bearable stresses into permissible stresses, regarding the survival probability P_s and the level of trust of the database C(x). In addition, the research project developed several approaches for determining the existing local stress components and for incorporating them into the verification procedure.

Alongside the theoretical considerations, a comprehensive experimental program was carried out. Fig. 3 shows a test configuration at our resonance testing machine. Additionally, the static characteristic values of the wires and springs and, in particular, the experimental determination of bearable stresses in cyclic tests were documented, which enabled validation of the calculations.

Example strength verification and diagrams for the half German loop

The half German loop is one of the most established loop geometries. However, an analytical description of the existing stresses in the loop-to-body transition B is difficult. The concept for determining and simplifying the existing stress state is presented here.

Owing to its compact design, the extension spring with a half German loop is particularly suitable for small installation spaces. Often, the transition radius in region B is very small, which leads to a significant increase in stress. Not only does the small bending radius r complicate the assessment of the half German loop: another challenge is the direct superposition of bending stresses, coming from the loop (A), and shear stresses, coming from the spring body (FK), with varying proportions, depending on the location at the transition path. In addition, region A and region B can move very close to one another (cf. Fig. 2) or merge smoothly into each other for low loop heights. Fig. 4 illustrates how strongly the formation of the critical stress distribution depends on the spring geometry and especially on the loop height L_H.

An FE parameter study was carried out using ANSYS. This made it possible to establish a scalable relationship between the nominal shear stresses in the spring body and the equivalent (van Mises) stresses at loop A or in the critical transition region B, described by a new transfer factor K_T. A major advantage of this approach is that regions A and B, which were found to be critical in alternation depending on the geometry, are combined. This allows a normal-stress verification to be performed jointly for A+B for this loop geometry and compared with the critical permissible stress. Table 1 provides a clear overview of how existing stresses (left) and permissible stresses (right) must be determined for each critical location and consolidated into the strength verification (bottom).

Conclusion and outlook

The primary objective of this work was to take the design of extension springs to a new level. The new verification methods were intended to be as straightforward to use as the established Goodman diagrams for compression springs and to be directly applicable to standard extension springs by incorporating a meaningful safety factor into the stresses. Where required, the level of safety can also be adapted to specific requirements. Practical workflows will be provided to users in form of comprehensive tables for the different loop types.

We are pleased to be able to provide the industry with accurate yet easy-to-apply tools through this research project. Our stated

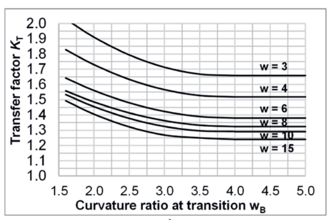
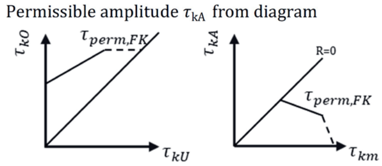
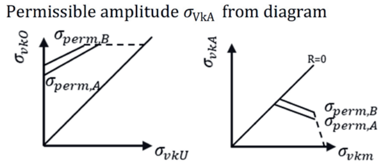
Existing stresses	Permissible stresses
1. Spring body FK $\tau_{k1,2} = k_t \cdot \tau_{1,2}$ with $k_t = (w + 0{,}5)/(w - 0{,}75)$ $\tau_1 = \frac{8 \cdot F_1 \cdot D}{\pi \cdot d^3}$ $\tau_2 = \frac{8 \cdot F_2 \cdot D}{\pi \cdot d^3}$ $\tau_{km} = (\tau_{k2} + \tau_{k1})/2$ $\tau_{kh} = \tau_{k2} - \tau_{k1}$ $\tau_{ka} = \tau_{kh}/2$ 2. Critical areas A+B $\sigma_{Vk1,2} = K_T \cdot \sqrt{3} \cdot \tau_{1,2}$  with $w_B = \frac{2r_B}{d} = \frac{2(r + d/2)}{d}$ (see Fig. 2) $\sigma_{Vkm} = (\sigma_{Vk1} + \sigma_{Vk2})/2$ $\sigma_{Vkh} = \sigma_{Vk2} - \sigma_{Vk1}$ $\sigma_{Vka} = \sigma_{Vkh}/2$	1. Spring body FK Permissible amplitude τ_{kA} from diagram  2. Critical areas A+B Permissible amplitude σ_{VkA} from diagram  $w_B < 4\,? \rightarrow \sigma_{perm,B}$ $w_B \geq 4\,? \rightarrow \sigma_{perm,A}$ k_t stress correction factor $F_{1,2}$ force at working points r inner radius at loop transition r_B radius of centerline at loop transition d wire diameter D mean spring diameter τ_{km} ; σ_{Vkm} local mean stress τ_{kh} ; σ_{Vkh} local stress range τ_{ka} ; σ_{Vka} local stress amplitude
Strength verifications	
1. Spring body FK $a_{BK,\tau} = \frac{\tau_{ka}}{\tau_{kA}}$ $(\tau_{ka} \leq \tau_{kA}$ or $\tau_{kh} \leq \tau_{kH})$ 2. Critical areas A+B $a_{BK,\sigma} = \frac{\sigma_{Vka}}{\sigma_{VkA}}$ $(\sigma_{Vka} \leq \sigma_{VkA}$ or $\sigma_{Vkh} \leq \sigma_{VkH})$	
The fatigue strength verifications are valid for $a_{BK,\tau} \leq 1$ and $a_{BK,\sigma} \leq 1$.	

Table 1: Simplified fatigue strength verification for extension springs with a half German loop. *© TU Ilmenau*

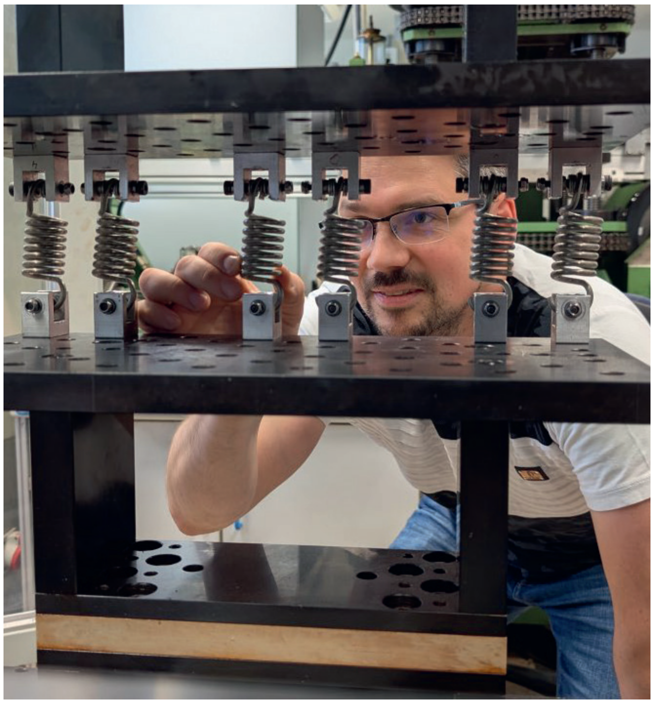


Fig. 3: Example of a failure check of a test configuration for determining cyclic fatigue strength (M. Petrich). *© TU Ilmenau*

aim is, analogous to the predecessor project on compression springs (IGF 19693 BR [5]), to integrate the approaches and results into the FKM Guideline "Springs" and into a revision of DIN EN 13906-2.

Acknowledgements

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References

[1] CEN European Committee for Standardization. Cylindrical helical springs made from round wire and bar - Calculation and design: Part 2: Extension springs. 2nd ed.(13906); 2013.

[2] CEN European Committee for Standardization. Cylindrical helical springs made from round wire and bar - Calculation and design: Part 1: Compression springs. 1st ed.(13906); 2013.

[3] Petrich, M.; Kletzin, U.: Practical fatigue strength diagrams for compression springs based on the FKM-Guideline "Analytic Strength Assessment for Springs". International Journal of Fatigue 2024; 183:108273. https://doi.org/10.1016/j.ijfatigue.2024.108273.

[4] FKM Forschungskuratorium Maschinenbau e.V. (ed.). Rechnerischer Festigkeitsnachweis für Federn und Federelemente: FKM-Richtlinie für Federn und Federelemente. 2nd ed. Frankfurt am Main: VDMA-Verlag; 2023.

[5] Petrich, M.; Kletzin, U.: Erneuerung der Dauerfestigkeitsschaubilder für kaltgeformte Schraubendruckfedern in DIN EN 13906-1 mit methodisch rechnerischer Herangehensweise: Abschlussbericht zum Forschungsvorhaben IGF 19693 BR. Ilmenau; 2021.

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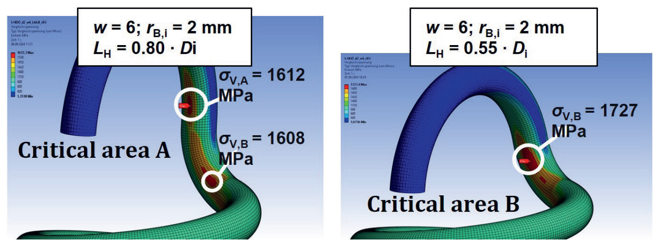

Fig. 4: Height of loop L_H influencing the location of the stress concentration area at a German loop. *© TU Ilmenau*

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