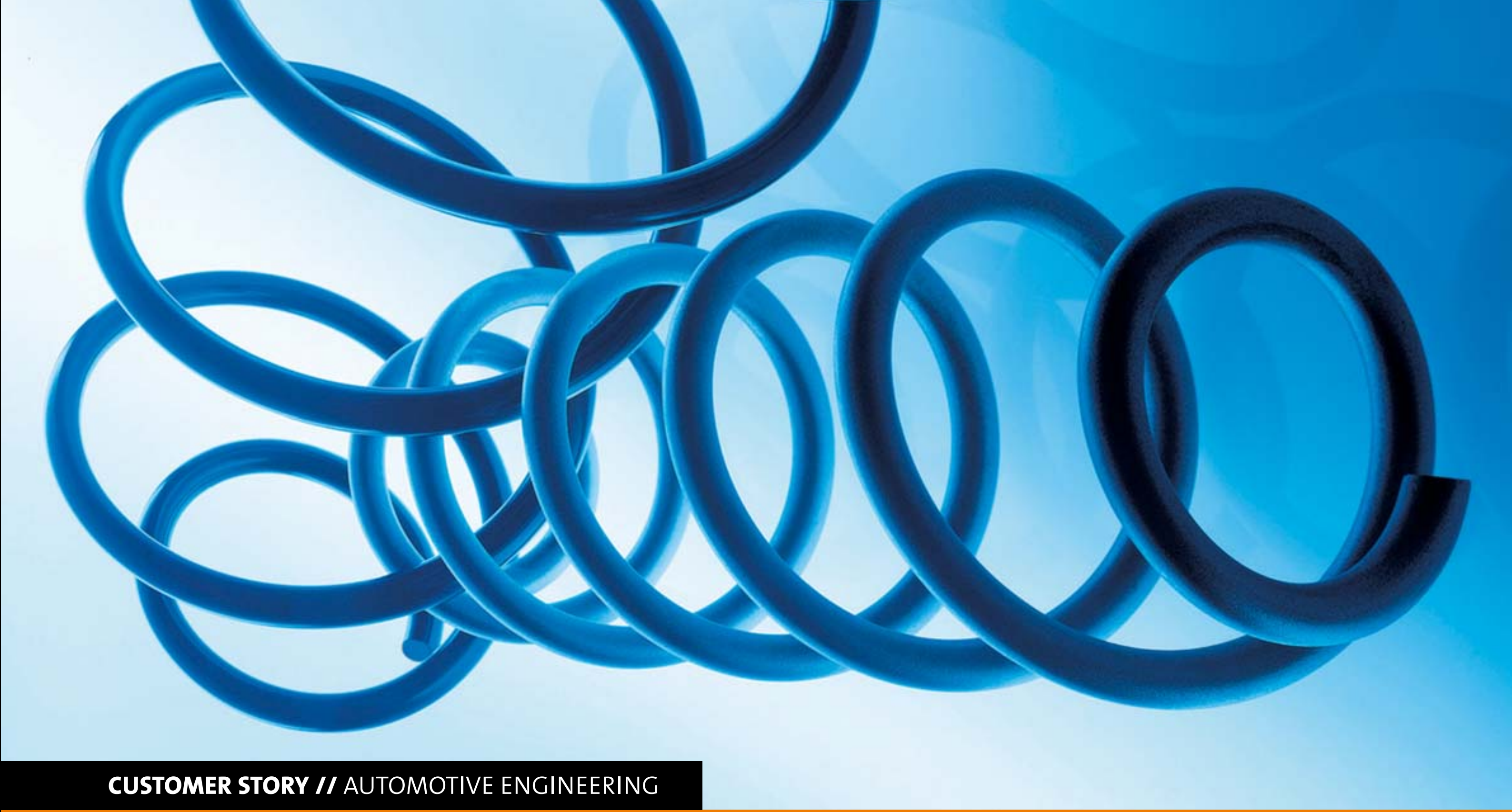

AUTOMATED DESIGN AND OPTIMIZATION OF SUSPENSION COIL SPRINGS

At Mubea, FEA methods and optiSLang are applied for an automated design of coil springs with subsequent optimization procedure to fulfill all boundary conditions and lifetime requirements.

Introduction

The Mubea Group is a world leading manufacturer of complex automotive components that reduce vehicle weight and contribute to an improved environmental performance by reduced CO_2 emission. Suspension components represent a large proportion of the company's portfolio and revenue. The chassis components also include coil springs, which will be explained in the following.

Task of a suspension coil spring

The current density of traffic requires motor vehicles that are safe and comfortable to allow the driver to concentrate fully on the traffic during short and long distance rides. Therefore, not only intuitive designs, manageability, cost-effectiveness and fault-free operation, but also the demands for a high level of comfort and driving safety are of central importance.

The fulfillment of these requirements call for the involvement of resilient and damping components between the chassis and the vehicle body. On the one hand, these components must largely absorb road-induced impacts and vibrations and, on the other hand, must consistently ensure sufficient traction control of the wheels.

Helical compression springs as resilient components are particularly suitable because:

- their compact design enables a space-saving installation in subframes or on the wishbones
- they can be combined with the damper to a unit (simple strut and McPherson strut)
- they show linear or even progressive characteristics
- their production is economical and inexpensive
- their operation is practically maintenance-free

In today's automobiles, in addition to the helical compression springs, often stabilizers are installed for supporting both one-sided and double-sided deflection of the wheels. Stabilizers essentially serve to reduce the rolling of the vehicle body when cornering, while helical compression springs primarily ensure a proper pitch response and ground clearance of the body.

Types of force transmission

For the positioning and force transmission, the design of the spring end coils are of crucial importance. Coil springs are usually installed inside or outside of their struts with

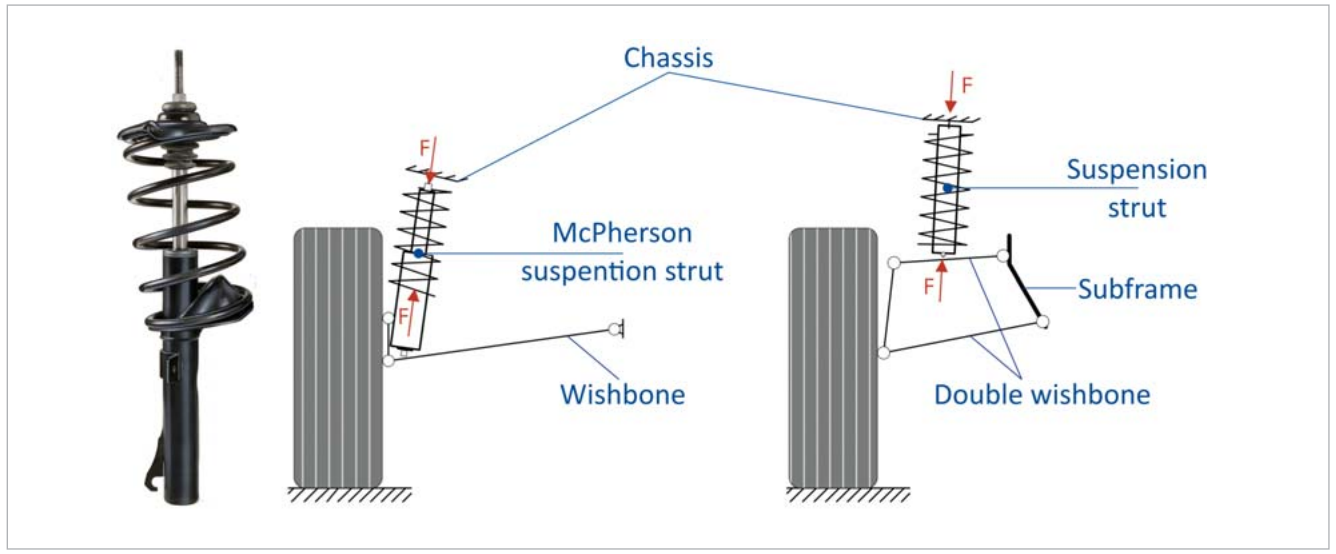

Fig. 1: Spring arrangement around the damper

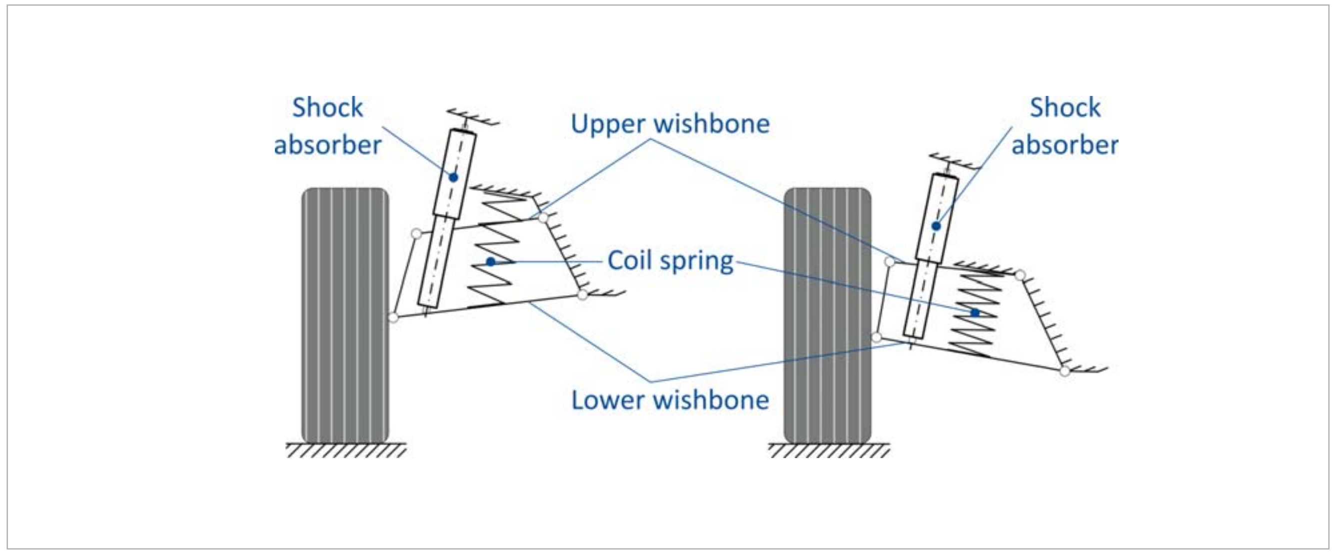

Fig 2: Spring arrangement on a wishbone: decompressed (left) and compressed (right)

an angle range up to about 270° to support a centric force transmission. The support is either constructed on flat or pitch-profiled spring seats. These are usually made of sheet metal or rubber parts that are adapted to the end coil.

The force transmission can be basically classified into two different types. The more simple technique is to guide linearly the end coil of the spring toward each other with parallel aligned struts and without any lateral offset. This variant is still interesting today because it allows a simple dimensioning of cylindrical helical compression springs (see: DIN 13906-1).

Two examples of the first type of load transmission are shown in Fig. 1. The spring is arranged around the damper forming a unit. One end is fitted to the other without lateral offset. This enables a practically free deflection of a cylindrical spring regarding bending-moment and lateral force with evenly distributed coil stress.

In many applications, however, the end coils are guided toward each other using non-parallel aligned struts with curved spatial orientation or with lateral offset. When dimensioning helical compression springs, simple methods have to be replaced by Finite Elements Analysis (FEA). Two examples of the second type of force transmission are shown in Fig. 2.

The spring is mounted on the lower wishbone and the spring end is guided along a space curve. As a result, the cylindrical spring is unevenly deformed and, in addition, moment and transverse forces are acting at both spring ends. The consequence is an uneven stress distribution in the coils and a distortion of the spring body.

Analytical dimensioning

The calculation of coil springs is based on the equations given in the standard sheet DIN EN 13906-1. The following basic formulas are taken from this standard sheet and describe the relationships between the most important characteristic values: spring rate R, spring force F, shear modulus G, wire

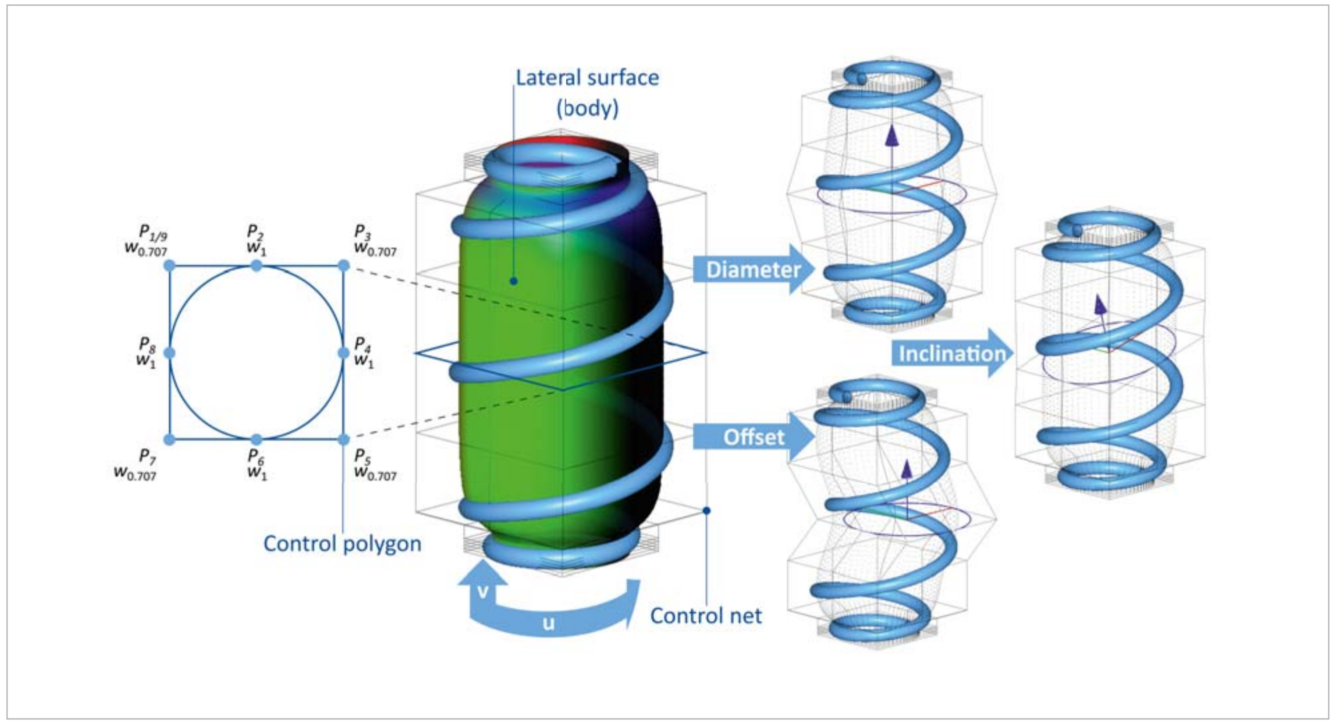

Fig. 3: Generation and variation of the lateral surface

diameter d, number of coils n, mean coil diameter D, spring deflection s and the resulting shear stress τ. These values are essential in the calculation of simple cylindrical coil springs:

Spring Force $$F = \frac{G}{8} \cdot \left(\frac{d^4 s}{D^3 n}\right) \tag{1}$$

Spring Rate $$R = \frac{G}{8} \cdot \left(\frac{d^4}{D^3 n}\right) \tag{2}$$

Shear Stress $$\tau = \frac{8}{\pi} \cdot \left(\frac{D}{d^3}\right) \cdot F \tag{3}$$

However, this approach is only suitable in a special case of force transmission for cylindrical coil springs (see paragraph type of force transmission). Therefore, this approach can only be applied for the preliminary dimensioning of a modern coil spring.

Parameterization

The use of FEA in the dimensioning and especially in the optimization of the geometry requires a parameterized model of the coil spring. In the course of time, engineers at Mubea have developed different parameterization approaches or applications for coil spring modeling. They support the product developer in the definition of the free, unloaded coil spring geometry as well as in the setting of boundary conditions. Furthermore, they enable the generation and evaluation of the FE simulation model.

One application has been especially developed for optimization and an automated design of the coil spring geometry.

GRASP Designer

The GRASP (Graphical Spring) Designer is based on the Helix definition, which is a curve that winds around the barrel of a cylinder at a constant pitch. Similarly, with this parameterization approach, the coil spring modeling is subdivided into the modeling of a lateral surface (body) and a curve ([multiply] unwinding). With regard to C- or S-shaped coil springs, the demand on the designer is to develop more or less complex bodies and spring coils while using a manageable number of parameters. One reason to choose the mathematical construct of the NURBS (Non-Uniform Rational B-Splines) as an extension of the B-splines to describe the body and the coiling was its ability to map perfectly circular curves.

The body is defined by a closed NURBS surface, which consists of control points. The control points of a NURBS surface represent the control mesh. The surface itself is defined by u in peripheral direction (the coil spring) and v in the height direction. u and v are defined in the interval [0, 1]. The degree of the NURBS surface in v is variable.

The coiling is defined by a NURBS curve. The control points of a NURBS curve represent a control polygon. The curve itself is defined by u in the interval [0, 1]. The degree of the NURBS curve is variable.

Lateral surface

The control mesh describes the lateral surface and consists of series-connected control polygons with the resulting circular curve. For a circular cross-section, each control polygon must be aligned in peripheral direction u of the shape as shown in Fig. 3 and has to represent a second degree.

In the design process or in the subsequent optimization, not the control points of the polygon or the cross section are directly varied, but the surrogate variables that represent the individual cross sections.

These surrogate values for describing a body cross-section are:
- diameter,
- displacement and
- inclination angle.

The introduction of these surrogate values is not only advantageous for a more intuitive processing of the coil spring body, but also ensures a significant reduction of the (optimization) parameters.

Coiling

A variable number of control points define the multiple coiling of the coil spring on the body or in the uv-plane of the lateral surface. The resulting control polygon is defined on the interval [0, number of coils n] in u-direction of the lateral surface and on the interval [0, 1] in v-direction.

Here, the first and last control point is fixed in (0, 0) or (n, 1), while all other points are freely displaceable in the uv-plane. The local influence of a control point on the axial spring geometry depends on the degree of the NURBS curve (see Fig. 4).

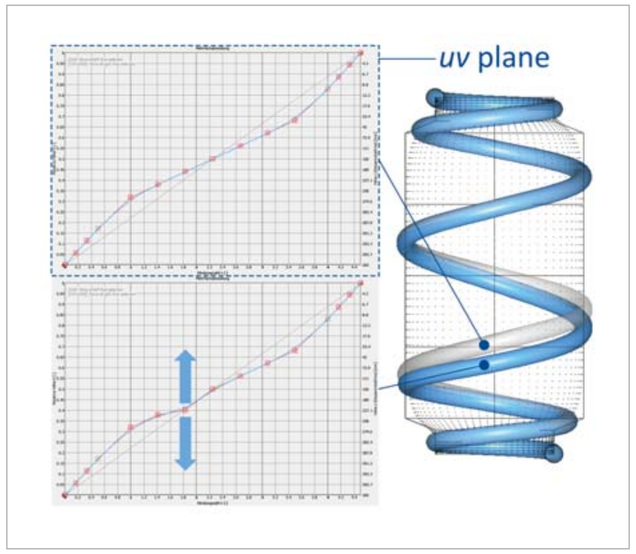

Fig. 4: Generation and variation of the coiling in the uv-plane

Simulation Model

For the numerical simulation a parameterized FE model of the coil spring is used. The simulation is done in ANSYS Mechanical APDL (ANSYS Parametric Design Language). In this case, it is a static, geometrically non-linear calculation using quadratic elements and an elastic material model.

Optimization Model

The aim of the optimization is to create a coil spring design with the required mechanical characteristics while complying with all boundary conditions and lifetime requirements. Since there are critical requirements and boundary conditions, this can be difficult to accomplish. Therefore, and to support particularly the project engineers, optimization methods are applied in the design process. An OPX file is created from GRASP on the basis of a reference design to generate the optiSLang project via the OPX interface.

In principle, an analytically generated cylindrical reference geometry is used for the automated design replacing a numerical pre-dimensioning. Due to the large number of parameters, the application of an EA optimization algorithm is required. Investigations of the existing types of mutation have shown that for the present optimization problem the constraint adaptive option has proven to be particularly stable and efficient.

Objective Function and Constraints

Coil springs are exposed to static and dynamic loads. The maximum statically permissible load is reached at maximum deflection L_{Jounce}. The assessment of the static load is based on the shear stress $\tau_{max} = \tau_{Jounce}$.

In addition to the constraint not to exceed the defined stress limit, the primary objective is to homogenize the static stress as much as possible over a considered coil area of the coil spring. Thus, an equal distribution of material stress is achieved. For this purpose, the variance of the static load is minimized.

If explicit constraints using inequalities were applied, the analyses showed a negative effect on the objective history and the quality of results, or on the stability of the automated design methodology. For this reason, all constraints included in the objective function to be minimized are defined as penalty terms. For an inequality

$$L_i \geq R_i \tag{4}$$

the penalty term P_i is

$$P_i = \frac{w_i}{2} \cdot [\text{sign}(R_i - L_i) + 1] \cdot [|L_i| + 1]^{k_i} \tag{5}$$

with weighting w_i and exponent k_i

This definition includes a step function that zeroes the penalty term as soon as the originally formulated constraint inequality is fulfilled. The weighting as well as the exponent can be used to adjust the magnitude of the penalty term and, thus, its priority within the objective function. Here, the weighting mode of the penalty terms considers a violation of constraints more than an improvement of the original objective function. Therefore, it can be ensured that the optimization algorithm primarily fulfills all constraints.

For a scattering objective value C standardized to the tolerance interval, the constraints can be defined as follows:

$$\frac{C_{tol} - |C_{target} - C|}{2 \cdot |C_{tol}|} \geq 0 \tag{6}$$

For the alternative definition as a penalty term this would result in:

$$C_{penalty} = \frac{w_C}{2} \cdot \left[\text{sign}\left(0 - \frac{C_{tol} - |C_{target} - C|}{2 \cdot |C_{tol}|}\right) + 1\right] \cdot \left[\left|\frac{C_{tol} - |C_{target} - C|}{2 \cdot |C_{tol}|}\right| + 1\right]^{k_C} \tag{7}$$

At this point, the following constraints are taken into account in the design of the coil spring:

- Maximum permissible limit stress
- (Nominal) supporting force Fz (± Tol.) of the coil spring at design length L_{Design} (length when installed at empty vehicle weight)
- (Nominal) spring rate R (± Tol.) in the range of $L_{Design} \pm \Delta L$
- (Nominal) piercing points $PP_{x|y,top|bottom}$ (±Tol.) at L_{Design} (Intersection of the resulting force with the upper or lower plane through spring ends)
- Minimum distance between coils
- Maximum permissible gap / clearance between coil spring ends and seat
- Design space

The space design verification is carried out on the basis of STLs. Here a separate inner and outer design space is required (see Fig. 5). Several sections are generated through the deformed coil spring and the design space STLs. Each section forms two surfaces based on the STLs. For each axial spring section, the minimum distance to the respective cut surface is determined. If the axial spring section is outside the cut surface, the minimum distance is given a negative sign, which represents a space violation corresponding to the requirement of a distance ≥ 0. The first and last half coil of the coil spring is usually excluded from the design space verification.

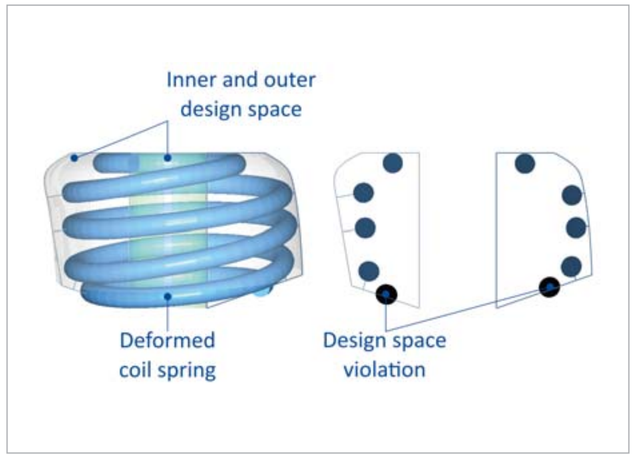

Fig. 5: Inner and outer design space limits (left) and section through design limits and coil spring (right)

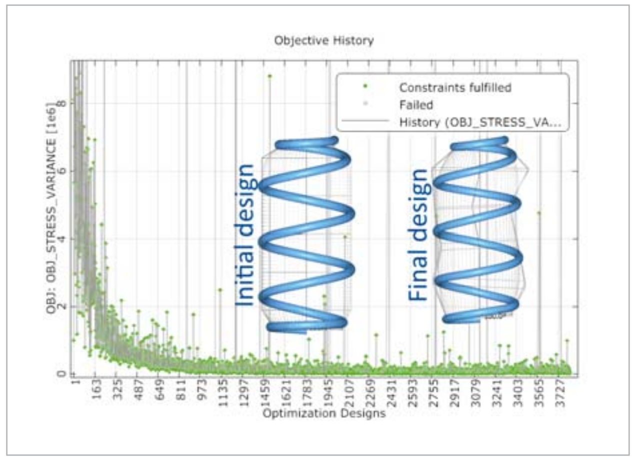

Fig. 6: Initial cylindrical coil spring design and final geometry

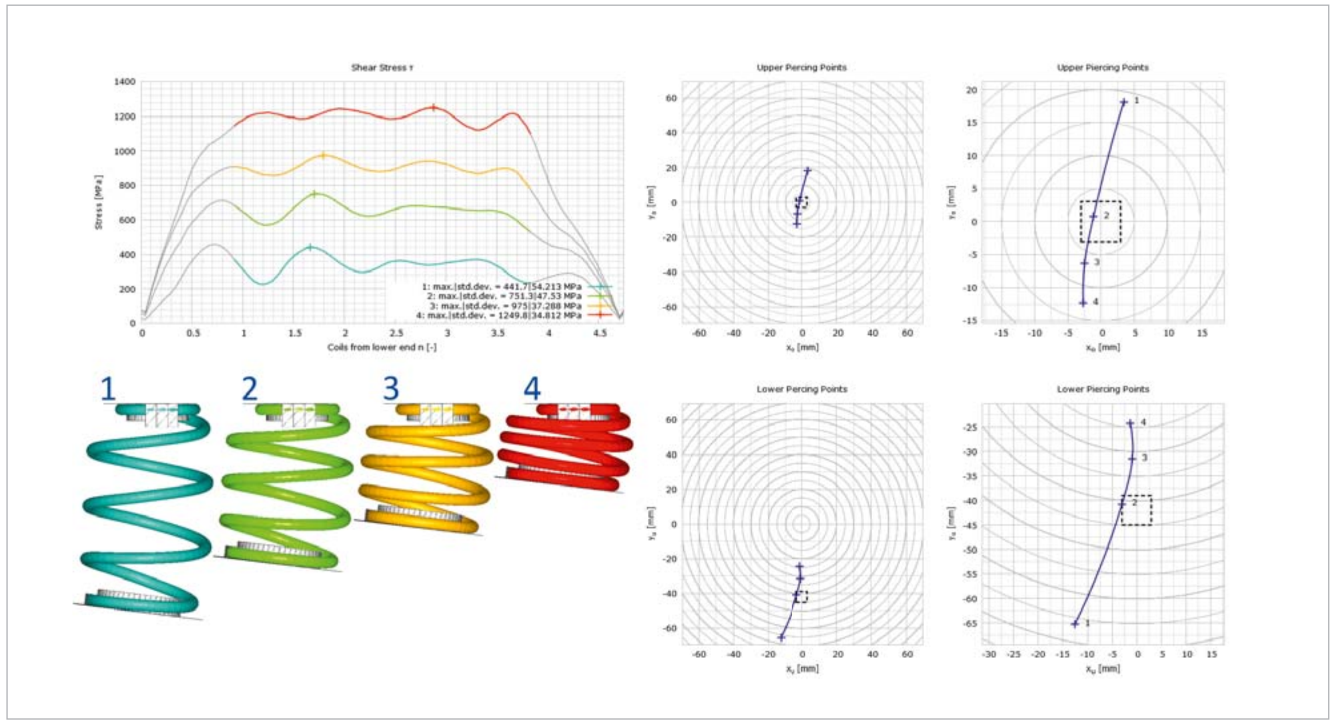

Fig. 7: Shear stress curve (left) and piercing points (right) in different compression states

Results and Conclusion

The result of an exemplary automated coil spring design with optiSLang is shown in Fig. 6 (see previous page).

A cylindrical coil spring based on an analytical pre-dimensioning was used as the initial design. The final optimized design could already be determined after running only 4000 variants. It has to be noted that the history of the objective function showed a steady and rapid improvement. This is due to the use of constraints as penalty terms in the objective function and is representative of all previous coil spring designs generated with optiSLang. The abort criterion is usually reached between 4000 and 6000 designs.

Fig. 7 (see previous page) shows selected results of the final design. On the left side, the shear stress curves are shown in different compression states for the considered coil area. The red shear stress curve corresponds to the maximum deflection and was, as required, sufficiently smoothed.

On the right side of the figure, the piercing points can be seen in evenly scaled and detailed views. There the required piercing points for compression step 2 are located within the given tolerances.

As a conclusion, it can be stated that the automated design using optiSLang is very practicable. The automated engineering procedure not only convinces with high-quality results, it also provides meaningful results, which would be difficult to achieve with manual designing. The greatest advantage of automated dimensioning is the homogenization of the stresses. Otherwise, this would be a major challenge while using manual designing procedures.

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