Cable Dynamics and Fatigue Analysis for Digital Mock-Up in Vehicle Industry

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Abstract

Numerical simulation has become an important aspect of modern industrial production processes. Very early in the process chain - even before first prototypes are built - simulation is used for digital mock-up in order to discover potential problems and to improve certain components and their assembling.
In our work, we focus on the simulation of highly flexible components like cables and hoses, which is a challenging task in vehicle industry. Nowadays, complex harnesses with kilometers of cables can be found in every vehicle and the amount even increases for electric drivelines and hybrid cars. Especially for cables of safety-relevant equipment, high loads and contacts with high friction should be avoided, already during the assembling but also later in regular usage.
We present the essential steps of a dynamic cable simulation and a subsequent comparative load data analysis. The latter allows to efficiently compare many different cable configurations in order to identify the best one in the sense of damage.

Keywords: Cosserat rod, dynamic simulation, load data analysis

1. Introduction

In modern vehicle industry, virtual product development is continuously growing. Numerical simulation is used for digital mock-up of certain components or the complete system, in order do detect potential problems at very early stages of the product development. Thus, the number of iterations and prototypes can be reduced significantly, saving time and money. However, physically correct and thus reliable simulation results are needed.
In this work, we will focus on the simulation of highly flexible structures like cables and hoses. Nowadays, complex harnesses are assembled in every car with kilometers of different cables, many of them belonging to safety-relevant equipment. Moreover, the amount of cables even increases for electric drivelines and hybrid cars. Thus, their simulation is an important aspect in the early digital mock-up, such that harmful loads or contact with high friction can be avoided.
Thinking about the numerical simulation of such highly flexible structures, on the first view a computationally very expensive transient finite element analysis seems to be indispensable. A common approach to reduce the computational costs is a modal reduction followed by superposition of modes. However, this approach is only valid for linear, i.e. very small deformations, which in general is not fulfilled for cables and hoses.
Therefore, an alternative methodology was developed at Fraunhofer ITWM and Fraunhofer Chalmers Centre, based on formulations from geometrically nonlinear beam theory and a discretization motivated from discrete differential geometry. This approach competes with finite element models concerning accuracy, but nevertheless is real-time capable (see e.g. [1]).
For quasi-static simulations, i.e. very slow motions where inertia can be neglected, our software *IPS Cable Simulation* already offers the possibility to simulate flexible components interactively. It is available as commercial software tool and has found a wide range of industrial applications in the last years, especially in the context of design and assembly (some examples can be found here [2]). Nevertheless, when it comes to fast excitations with high frequencies, inertia effects can not be neglected and dynamic simulation of cables is absolutely essential.
Figure 1 shows an application scenario of an engine compartment with a flexible hose (left) and the motion volume from both quasistatic and dynamic simulation (right) resulting from the same engine motion input. The motion volumes are hardly distinguishable, however, the corresponding forces show differences. Due to the inertial effects, the amplitudes of forces and moments in the dynamic simulation are greater than in the quasistatic case (see Figure 2). Strongest relative differences appear for the torsion moment, while absolute changes are comparable to the ones of the bending moment.

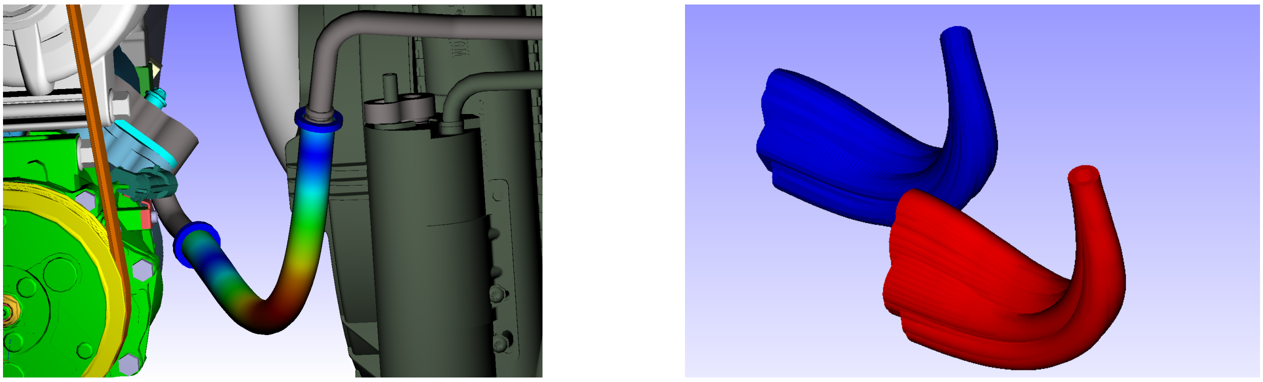

Figure 1: Left: Engine compartment with hose, color-coded with its bending moment. Right: Motion volume of quasistatic (blue) and dynamic (red) simulation.

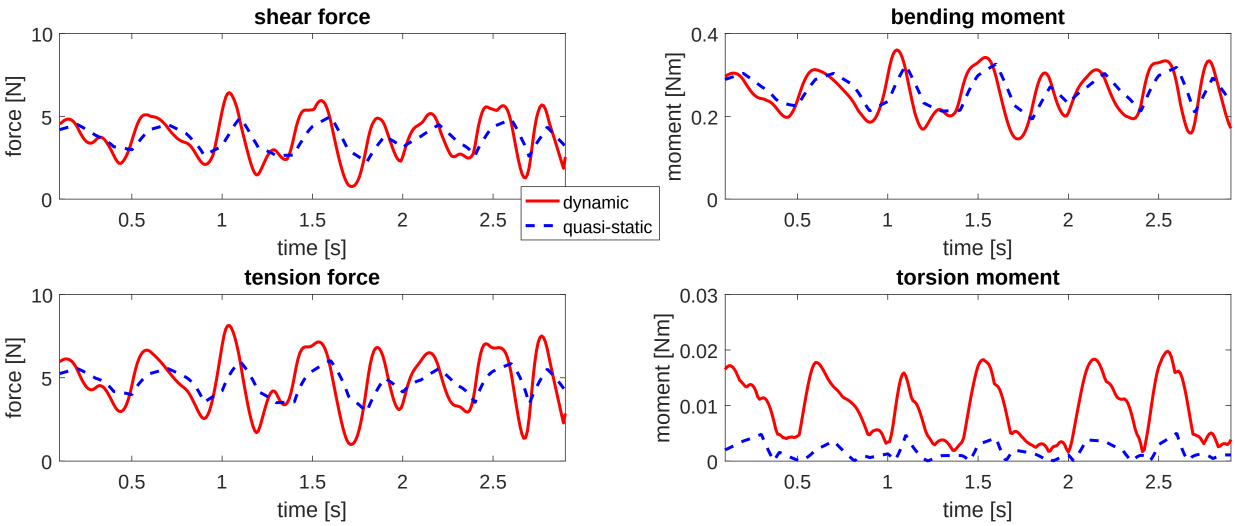

Figure 2: Comparison of simulation results: The maximum values along the cable of shear force, tension force, bending moment and torsion moment are plotted over time for quasistatic (dashed) and dynamic (solid) cable simulation.

In total, this underlines the need for dynamic simulations when fast excitations are applied and forces and moments are relevant, as it is the case for a subsequent fatigue analysis.

The paper is structured as follows. In Section 2 we briefly discuss the theory of the cable model. Moreover, we demonstrate the essential steps of a dynamic cable simulation, based on our quasistatic simulation software *IPS Cable Simulation*. How the results, i.e. forces and moments, of both the quasistatic and the dynamic simulation can be used in a fatigue analysis is shown in Section 3. Here, we present an efficient comparative load data analysis, which is especially tailored for the damage assessment of cables and hoses. Section 4 contains an application example and, finally, we summarize the main aspects and give a short outlook in Section 5.

2. Dynamic Cable Simulation

To achieve fast and accurate dynamic simulation, the cable is formulated as geometrically exact Cosserat rod, which allows rather rough discretization on a staggered grid (cf. Figure 3) and still leads to robust and realistic results. More precisely, the translatory degrees of freedom $x_n \in \mathbb{R}^3$ are defined in the nodes with corresponding arc length s_n, $n = 0, \ldots, N$, while the rotatory degrees of freedom, given as unit quaternions $p_{n-\frac{1}{2}} \in \mathbb{R}^4$ with $\|p_{n-\frac{1}{2}}\| = 1$, are defined on the edge midpoints. The edge length is defined as $\Delta s_{n-\frac{1}{2}} = s_n - s_{n-1}$ and the distance from adjacent edge midpoints

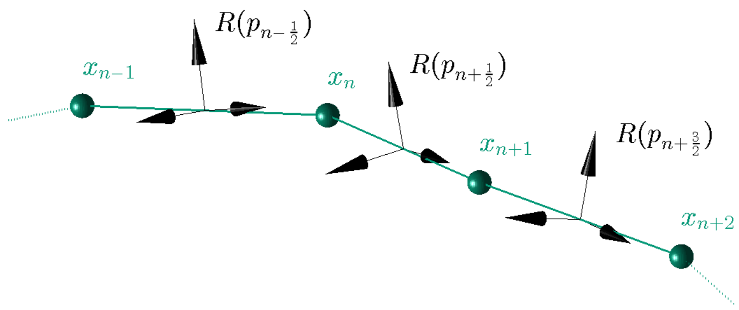

Figure 3: Staggered grid discretization of a geometrically exact Cosserat rod.

is given as $\delta s_n = \frac{\Delta s_{n+\frac{1}{2}} + \Delta s_{n-\frac{1}{2}}}{2}$. With this discrete setting, we can formulate the strains

$$\Gamma_{n-\frac{1}{2}}(x_{n-1}, p_{n-\frac{1}{2}}, x_n) = R(p_{n-\frac{1}{2}})^T \frac{x_n - x_{n-1}}{\Delta s_{n-\frac{1}{2}}} - e^3 \quad \in \mathbb{R}^3 \tag{1}$$

and the curvatures

$$K_n(p_{n-\frac{1}{2}}, p_{n+\frac{1}{2}}) = \frac{2}{\delta s_n} \frac{Im(\bar{p}_{n-\frac{1}{2}} p_{n+\frac{1}{2}})}{Re(\bar{p}_{n-\frac{1}{2}} p_{n+\frac{1}{2}})} \quad \in \mathbb{R}^3 \tag{2}$$

along the cable and finally state the elastic energy as

$$\mathscr{V} = \frac{1}{2} \sum_{n=1}^{N} \Delta s_{n-\frac{1}{2}} \Gamma_{n-\frac{1}{2}}^T C^\Gamma \Gamma_{n-\frac{1}{2}} + \frac{1}{2} \sum_{n=0}^{N} \delta s_n K_n^T C^K K_n \quad \in \mathbb{R}_{\geq 0}. \tag{3}$$

The matrices $C^\Gamma \in \mathbb{R}^{3\times 3}$ and $C^K \in \mathbb{R}^{3\times 3}$ are diagonal and contain the effective stiffnesses of the cable. The dissipation energy $\mathscr{D} \in \mathbb{R}_{\geq 0}$ is formulated accordingly, with strain rates $\dot{\Gamma}_{n-\frac{1}{2}} \in \mathbb{R}^3$, curvature rates $\dot{K}_n \in \mathbb{R}^3$ and damping coefficient matrices $C^{\dot{\Gamma}} \in \mathbb{R}^{3\times 3}$ and $C^{\dot{K}} \in \mathbb{R}^{3\times 3}$. Moreover, for the kinetic energy it holds

$$\mathscr{T} = \frac{\rho A}{2} \sum_{n=0}^{N} \delta s_n \|\dot{x}_n\|^2 + \frac{\rho}{2} \sum_{n=1}^{N} \Delta s_{n-\frac{1}{2}} \dot{p}_{n-\frac{1}{2}}^T \left(4Q(p_{n-\frac{1}{2}}) I Q(p_{n-\frac{1}{2}})^T\right) \dot{p}_{n-\frac{1}{2}} \quad \in \mathbb{R}_{\geq 0}, \tag{4}$$

where $Q(p_{n-\frac{1}{2}})$ is a matrix which acts like a quaternion product with $p_{n-\frac{1}{2}}$ from the left.

From the Lagrangian $\mathscr{L} = \mathscr{T} - \mathscr{V} - \mathscr{D}$ we can derive the Newton-Euler equations. The Newton equations for the nodes x_n are given as

$$m_n \ddot{x}_n = f_n^x(x_{n-1}, p_{n-\frac{1}{2}}, x_n, p_{n+\frac{1}{2}}, x_{n+1}) \tag{5}$$

with mass $m_n = \delta s_n \rho A \in \mathbb{R}_{\geq 0}$. The Euler equations for quaternions $p_{n-\frac{1}{2}}$ on the edge midpoints are the index-3-DAEs

$$\mu_{n-\frac{1}{2}} \ddot{p}_{n-\frac{1}{2}} = f_{n-\frac{1}{2}}^p(p_{n-\frac{3}{2}}, x_{n-1}, p_{n-\frac{1}{2}}, x_n, p_{n+\frac{1}{2}}) - p_{n-\frac{1}{2}} \lambda_{n-\frac{1}{2}} \tag{6a}$$

$$0 = \frac{1}{2}\left(\|p_{n-\frac{1}{2}}\|^2 - 1\right) \tag{6b}$$

with quaternion mass $\mu_{n-\frac{1}{2}} = \Delta s_{n-\frac{1}{2}} \rho 4 Q(p_{n-\frac{1}{2}}) I Q(p_{n-\frac{1}{2}})^T \in \mathbb{R}^{4\times 4}$.
The right hand sides $f_n^x \in \mathbb{R}^3$ and $f_{n-\frac{1}{2}}^p \in \mathbb{R}^4$ include viscoelastic contributions from bending, torsion, tension and shearing. Its dependencies as given in (5) and (6a) guaranty a band structured Jacobian and, consequently, the resulting system can be solved efficiently. More details on the cable model can be found in [3].

To run a dynamic cable simulation, the initial steps are similar to a quasistatic simulation. As usually, the scene with rigid bodies and flexible cables and hoses, as well as their geometric and material properties, is created directly in *IPS*. Also, the single modules for pre-processing (generating the signals), the actual dynamic simulation and the post-processing (load data analysis) are called from *IPS* (see Figure 4 on the left).

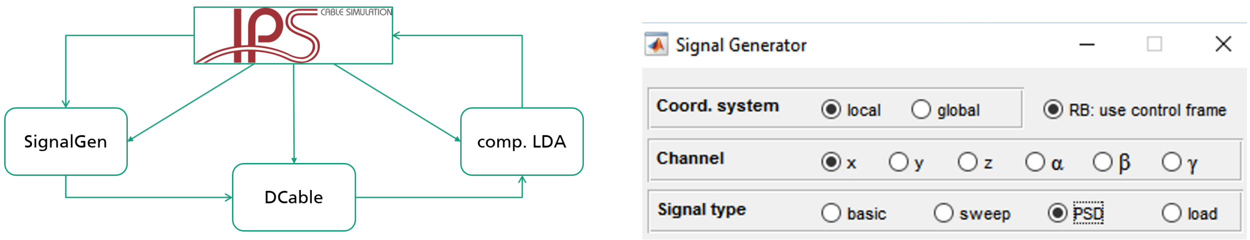

Figure 4: Left: Module overview with *IPS Cable Simulation* as central software tool and the modules *Signal Generator*, *Dynamic Cable Simulation* and the *comparative Load Data Analysis*. Right: Initial mask of the *Signal Generator* with user choice of the coordinate system, the channel and the signal type.

First, the excitation needs to be defined. This is done via the *Signal Generator*, which provides several masks for the signal input (cf. Figure 4 on the right). Besides two rather academical signal types (basic sine-signals and a sweep signal), it is possible to define a PSD (power spectral density), such that the generated signal inherits this characteristic, or one can load arbitrary signals, e.g. from real measurements.
When this is done, the actual dynamic simulation can be started. All geometric and material properties are transfered to the cable dynamics module, together with an additional material characteristic: the damping coefficients. Since, a quasistatic simulation does not require damping coefficients, they must be defined at this point. By default, a critical damping is estimated and used for the dynamic simulation, but can be adjusted by the user if necessary.
Whether the simulation results can be obtained in real-time, depends on the complexity of the scene (number of cables) and, in particular, on the frequency of the excitations. The time step sizes of the numerical integration is dominated by the time discretization of the input signal, which is very fine for high frequency input (e.g. 10^{-5}s). However, for one single cable and a moderate input signal (with time step size $\sim 10^{-3}$s), also for the dynamic case the simulation is real-time capable.
Once the simulation is finished, the motion of the cable can be regarded and a motion volume can be created. For instance, these volumes can be used to analyze the allocated construction space.

3. Fatigue Analysis

The simulation results of both the quasistatic or the dynamic case serve as input for a fatigue analysis of the cable. Below, we describe a very efficient and especially tailored method for the damage assessment of cables and hoses, where we distinguish two approaches.
On the one hand, we already provide a *comparative load data analysis (LDA)* [4]. This method computes pseudo-damage values on the cable surface which do not predict the absolute lifetime of a component, but allow to compare several configurations to find the best one in the sense of damage. It consists of typical steps of a LDA (detailed discussions can be found, e.g., in [5]). On the other hand, there is also a request for absolute predictions. However, this would require individual *Wöhler* measurements of the specific cable and, thus, is much more cumbersome. In the following, we will consider the comparative LDA (see Figure 5) and only give an outlook on absolute predictions.

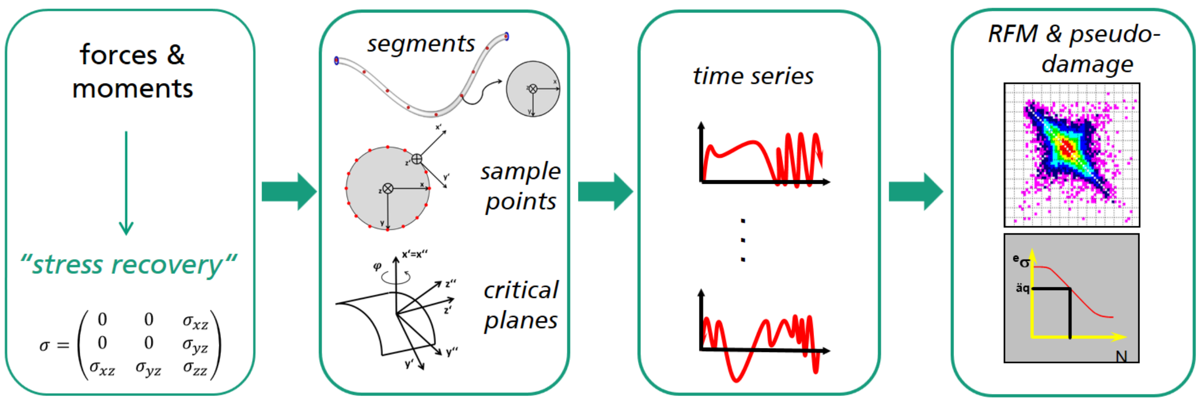

Figure 5: Overview of the steps in the comparative load data analysis: stress recovery, generating one-dimensional comparison stress and pseudo-damage calculation.

The first step of the comparative LDA is the stress recovery from generated simulation results (cf. Figure 5, left), i.e. from the time series of forces and moments along the cable $F(t,s) \in \mathbb{R}^3$ and $M(t,s) \in \mathbb{R}^3$. The stress tensor $\sigma \in \mathbb{R}^{3\times 3}$ can be computed depending on these forces and cross section coordinates $\xi_x \in \mathbb{R}$ and $\xi_y \in \mathbb{R}$ as

$$\sigma_{ij}(t,s,\xi_x,\xi_y) = \sum_{k=1}^{3} \left[F^k(t,s)\Phi_{ij}^k(\xi_x,\xi_y) + M^k(t,s)\Psi_{ij}^k(\xi_x,\xi_y) \right], \tag{7}$$

where Φ and Ψ are cross section specific warping functions.
Next, a one-dimensional comparison stress must be derived for the subsequent damage assessment (cf. Figure 5, middle). To this end, the stress tensor is considered in discrete cross sections along the cable. In these cross sections, the stress tensor is evaluated in discrete sample points on the cable surface. For instance, for a sample point on a circular cross section at arc length s_n with cross section radius r and sample point position specified by the angle γ, we get

$$\sigma_{ij}(t,s_n,r\cos(\gamma),r\sin(\gamma)) = \sum_{k=1}^{3} \left[F^k(t,s_n)\Phi_{ij}^k(r\cos(\gamma),r\sin(\gamma)) + M^k(t,s_n)\Psi_{ij}^k(r\cos(\gamma),r\sin(\gamma)) \right] \tag{8}$$

and receive a time series for the stress tensor in this point.
Finally, in the critical plane approach a set of potential crack directions on the cable surface is used to deduce a scalar quantity from the stress tensor. Like this, many one-dimensional comparison stress time series are generated. In fact, for a usual discretization of the cable the number of time series is approximately

$$(\#\text{cross sections}) \times (\#\text{sample points}) \times (\#\text{critical planes}) \approx 2000$$

and we exploit the special structure of the stress recovery formula to gain efficiency in their evaluation.
Now, these scalar load quantities serve as input for the rainflow counting and the pseudo damage calculation (cf. Figure 5, right). Their computation can easily be parallelized, since the time series are mutually independent.
The rainflow counting provides a histogram of amplitudes, which indicates the number of cycles n_i for certain amplitudes ΔS_i. From this, the accumulated damage can be calculated using the Palmgren-Miner rule

$$D = \sum_i D_i = \sum_i \frac{n_i}{N_i}, \tag{9}$$

where N_i is the number of cycles to failure. In principal, N_i can be deduced from Wöhler parameters α and k by

$$N_i = \alpha \cdot (\Delta S_i)^{-k}. \tag{10}$$

In most cases these Wöhler parameters are unknown for individual cables. Thus, fixed default values are used here and only allow the calculation of pseudo-damage, which does not necessarily predict the absolute lifetime correctly. Nevertheless, many configuration variants – e.g. cable length, position of mounting clips, etc. – can be compared in a fast and easy manner to find the best one concerning damage.

4. Application example

To illustrate the above described methods and its benefits, an application example is presented in this section. In this example, two mounting variants of a cable are compared concerning damage. Figure 6 shows the two variants, where the rectangle highlights the variation: a shifted mounting point.

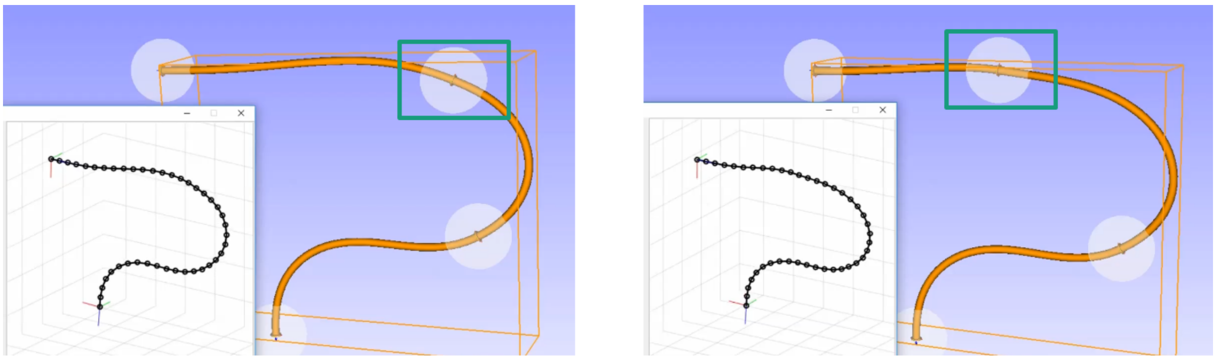

Figure 6: Two mounting variants of cable with four mounting clips. The upper right mounting clip (highlighted by the rectangle) is shifted between the two variants.

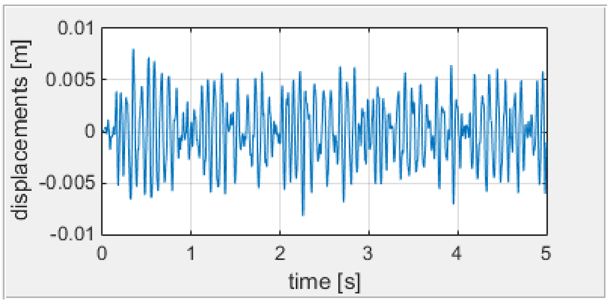

Figure 7: Excitation of the mounting clips, generated by defining its PSD.

Both variants of the dynamic simulation are excited with the same input signal, generated by defining its PSD (see Figure 7). The physical time of the excitation is 5 seconds and also the simulation needs approximately 5 seconds to complete. After that, the simulation results can be used in the comparative LDA.
Even without parallelization, the comparative LDA takes less than three minutes for one variant. The results are shown in Figure 8, where the pseudo-damage is color-coded. In the left variant, the upper left mounting shows the highest pseudo-damage with a value slightly above 250. In the right variant, two spots stand out: the upper left mounting and the lower right mounting. A closer look shows pseudo-damage values slightly above 100 for both spots. Consequently, the right mounting variant should be preferred in order to minimize the cable damage.
Due to the high efficiency, this comparison can be performed within minutes, allows to analyze many configuration variants in short time and enables a comfortable virtual product development without building prototypes.

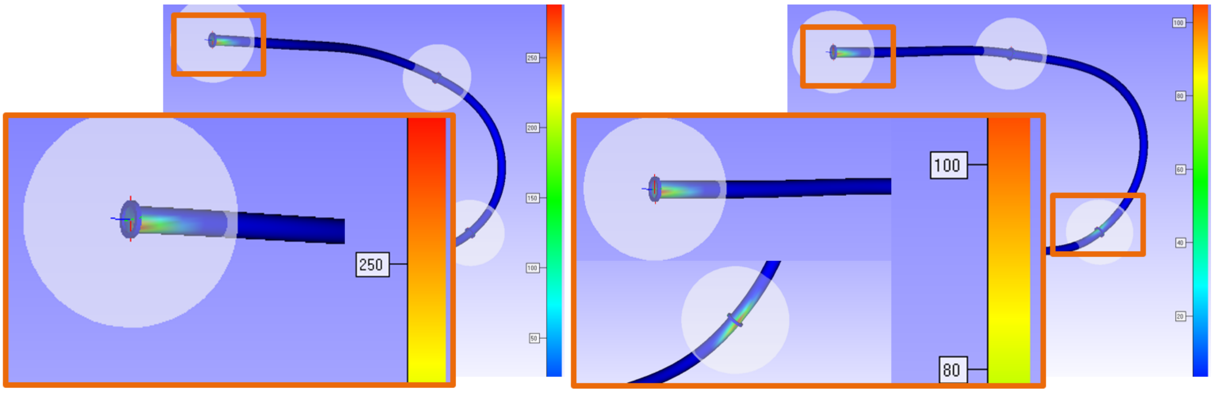

Figure 8: Results of a comparative LDA of two mounting variants. The right variant shows less damage and should be preferred.

5. Conclusion

In this paper, we presented a powerful tool for the virtual product development in vehicle industry, especially tailored for the digital mock-up of cables and hoses. A highly efficient – but at the same time physically correct – dynamic cable simulation provides forces and moments, which serve as input for a subsequent fatigue analysis. The comparative LDA allows a comfortable comparison of configuration variants in order to find the best one in the sense of damage, although absolute lifetime predictions are not yet qualified.
For absolute lifetime predictions, Wöhler measurements are required, which provide the actual number of cycles to failure. Thus, for individual applications absolute predictions are attainable, if the default Wöhler parameters used above are substituted by a measured Wöhler curve.

Acknowledgments

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