Simulation of wiring harnesses and hoses for product design and manufacturing

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Abstract

In this paper a physically accurate real time cable simulation is presented and validated. The simulation method is fully integrated in Virtual Reality, which increases the usability and the sense for physical realism. The influence of predeformation, non-homogeneous cross sections and different taping of the bundles will be analyzed and compared to the simulation. The simulation is validated with respect to the physical behavior of real cables and bundles. Material properties like stiffness and density are measured of every specimen. To avoid further expensive measurements, a way to determine bending and torsional stiffness numerically with the knowledge of the cross section is presented and analyzed.

1. Introduction

Since the construction and building of real mock-ups is costly and time-consuming, the proportion of virtual simulation in the product life cycle grows. Today e.g. visibility, reachability and ergonomic questions can be dealt with long before the first real mock-up is constructed. The knowledge about the accuracy of the utilized simulation tool is indispensable for the substitution of mock-ups by virtual prototyping. The motion and behavior of stiff objects can already be dealt with high performance.

Concerning flexible parts, the usage of simulation is not very common since the tools usually lack accuracy, usability or real-time performance. Non-physical representations like splines dominate today's digital work with cables and hoses. This provides the user with real-time interaction, but the physical behavior is disregarded. In order to contrast with these approaches, a simulation tool has to demonstrate its physical correctness. To prove accuracy, one needs the real material parameters of a real complex cable bundle and compare the simulation results with reality.

The focus of previous publications was concentrated on the real-time solution and collision handling [5], the dynamic behavior [2], and the mathematical background of the approach [8, 9, 5, 2]. In this paper, the accuracy of the system is tested and compared with reality. Therefore, real use case setups and advanced trial setups are taken into account.

2. Related Work

Publications dealing with the simulation of flexible objects can be classified depending on the research progress. The first step is the approach itself with few optimizations [4, 8, 18]. If the idea is promising, the next goal is to obtain real-time performance for smaller segments and small examinations of the accuracy are done [14, 3, 17]. Now the simulation is embedded into some virtual environment, where additional functionality, usability and features are applied without great additions to the simulation core [7, 9]. After that is successfully done, a product is developed out of this approach. Selling this product means to be confronted with the customers' demands for interaction, integration and their use cases [5, 2]. To replace step by step physical mock-ups with virtual simulation, a high credibility of the simulation tool is needed which leads to the next step: the proof of concept, which is dealt with in this paper.

Most publications concerning simulation of cables and hoses include sections where the accuracy of the approach is embraced, but none of them prove their correctness expressively.

Theetten [16, 17] presents his work on geometrically exact dynamic splines and follows the ideas of [15, 10, 11]. Here the comparison has been made between the simulation and the theoretical solution of the elliptic equations. Several loads are applied to a 4 meter cantilever beam and the bending behavior of the presented approach (GEDS) is computed. No numbers are given, only a visual comparison and depictions like "'close"' and "'accurate"' with relation to the number of control points.

The idea of Schotte [14], based on [13, 12, 1], is the modification of a mass-spring system, where forces are replaced by impulses. The accuracy of this iterative model depends of the value of the distance condition $D_{\max}$. If $D_{\max}$ is set to a large value, the computation is fast, but the accuracy is low and vice versa. Unfortunately Schotte makes no validation of the results and only mentions the accuracy increases if $D_{\max}$ is reduced.

The approach of Grégoire and Schömer [3] is iterative as well and it is mentioned that several algorithms are used for the best solution in position and energy. If a certain threshold is reached, the simulation finishes with this solution. A comparison to reality is made with one use case, a brake hose. No accuracy numbers are given, only a visual impression and the description "‘good fitting"'. The determination of the material properties is done empirically. Grégoire and Schömer mention the problem of predeformation and supplementary torsion and relegate to construction tolerances.

Linn et al. [7] present an approach based on Kirchhoff's geometrical exact theory which is approximately solved by energy minimization using a nonlinear conjugate gradients method. It is mentioned that the algorithm is integrated in a software package and the real-time capability is comparable to [3]. The accuracy is neither mentioned nor proved.

3. Idea of Comparison

In this paper, the published approach of a high accurate real time simulation of cables (*fleXengine*) [8, 5, 2] is compared with real cable setups. Since dynamic effects are difficult to measure, the first step ist to take the quasistatic behavior of our simulation tool into account. This is equivalent to the constraint that the system is at equilibrium after each time step and the energy is minimized.

In the virtual scene, the accuracy of a cable simulation system can only be judged by the users' sense of plausibility and experience. For many applications, this solution with real-time interaction is already feasible and leads to a reduction of prototypes. For further credibility, the accuracy of the simulation system has to be proved. In most cases, the comparison was made with numerical solutions [17] or simple curvature in reality (unpublished internal work). Complex curvature, gravity and torsional effects are not yet taken into account.

Therefore we composed and constructed a testing setup for complex cable and hose shapes (see fig. 1). Variable setups and torsions can be applied to the specimen up to a length of 1000 mm. The position and orientation of both sides is freely adjustable and on one side torsional forces can be applied and measured. The cable specimen are braided cables from $1mm^2$ to $10mm^2$, the bundle specimen homogeneous and composite bundles with different taping like spiral taped, half taped, conduit and full taped. A hand held laser scanner digitizes the shape without influencing it at very high precision (0.1 mm resolution). The digital shape is then imported in the simulation system and the centerline is extracted. The simulation system is embedded into the Visual Decision Platform developed by IC:IDO GmbH[1]. The software is able to replace rigid geometry which represents a cable or hose with a flexible object. The algorithm is able to reconstruct the round shape of the specimen very precisely, even if the laser scan is highly fragmented. Thus the scanned object is replaced by a simulated object with a high number of supporting points (handles) to fit the original shape with very high precision. The internal procedure of this algorithm is confidential, the accuracy of this method is seen in figure 4.

The next step is the determination of material properties of the real cable. Therefore the specimen is measured for stiffness (Young's Modulus) and density. The stiffness is determined by measuring the force that is needed to bend a defined length of the specimen for a given displacement. The stiffness measured by tensile test differs much from the bending test, which is due to the complex inner structure: a braided wire behaves in bending far softer than in the tensile test, where it behaves almost like a rod. Thus the tensile stiffness is up to 100 times higher. Since in most cases the simulation is build to simulate bending behavior and shapes, the bending stiffness is the parameter of choice. Density is measured with a pycnometer. Additionally, inner and outer diameter and the length of the specimen are measured.

With the scanned shape of the specimen and the material properties, the simulation can be performed. The end positions of the scanned shape are taken and the tangents are measured. The end positions, the tangents, the diameters, the length, the material properties and the knowledge about the direction of gravity are used as input parameters of the simulation. Since the positions are taken out of the laser scan, the optimal case would now be a high match of the scanned and the simulated shape. The centerlines are extracted and compared with NX[2] to measure the deviations with μm precision. The maximum deviation between the centerlines in relation with the length of the specimen is defined as the error of the analysis.

4. Precomputation of Material Properties

To increase the expressiveness of the comparison, the real material properties have to be measured. This leads to several difficulties in the daily use of the tool.

1. **Knowledge of components** In early construction stages, a rough routing of the cable is needed. The knowledge of the final components is still dependent of the later usage of the bundle. Without the final construction idea, the bundle cannot be build and measured.

[1] www.icido.com
[2] http://www.ugsplm.de/produkte/nx/

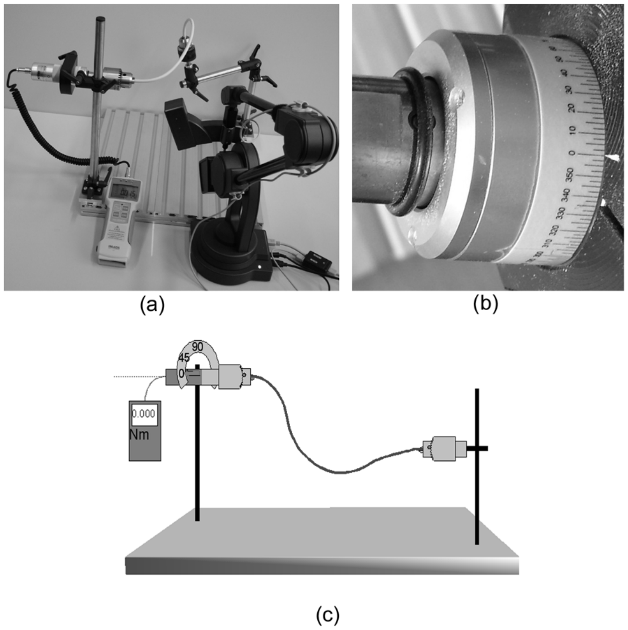

Figure 1. The test setup for any possible combination of bending and torsion (a) with measurement system and scale for torque (b). The applied or risen torsion force can be read on the newton meter and related to the degree of rotation (c).

2. **Variants** In the same product, the components of a cable bundle differ depending of the fitting. The bundle can contain e.g. three aerial cables or six or additional sensor cables for e.g. inflation status. Thus, plenty of variants have to be measured.

3. **Need of accuracy** Not every part of a flexible component is critical regarding the shape. Motion, critical obstacles and construction issues have to be handled with high accuracy. If the environment is uncritical, a 90%-solution might be adequate.

4. **Cost-Benefit** The measurements are costly and the construction of the cable takes critical time.

These considerations lead to the question if there is a faster and cheaper way for some use cases, where e.g. a 90%-solution is adequate. Therefore investigations have been made to compute the material parameters of a bundle with only the knowledge of the components. The material properties of the components have to be measured as well, but their number is more limited than the combinations. For the single strands and their isolations the properties are known and filed in a material database.

Known from beam theory [6], the bending stiffness (B) is given by the Young's Module (E) and the moment of inertia of area (I) by

$$B = EI.$$

I is defined as

$$I = \frac{1}{4}\pi(R_1^4 - R_2^4),$$

where R_1 is the outer diameter and R_2 the inner one regarding a hose. Since R_2 is zero for cables, the equation for the bending stiffness reduces to

$$B = \frac{1}{4}\pi E R^4.$$

This equation is valid for homogeneous and circular cross sections. For composite cross sections, the center of bending is no longer the center of the bundle since it is dependent of the material distribution. Thus two main axes of inertia are defined, which represent the minimum and the maximum bending stress (see fig. 2, (a)). The cross sections are composed in an editor, where each color represents a defined stiffness (see fig. 2, (b)). These directions are obtained via the computation of the eigenvalues of the bending stiffness matrix

$$B_{ij} = \begin{pmatrix} B_{xx} & B_{xy} \\ B_{yx} & B_{yy} \end{pmatrix}, \quad (1)$$

which is computed by

$$B_{ij} = \int E(\vec{s})(s - s_0)_i (s - s_0)_j df. \quad (2)$$

s and s_0 are given in cross section coordinates. The moments of inertia are related to the center of bending which differs from the center of the bundle s_0 and leads to the offset $s - s_0$.

For coaxial cross sections eqn 2 can be transfered to polar coordinates and can be rewritten as

$$B = \int \pi r E_r r^2 dr. \quad (3)$$

This leads to the known and proved analytical solution for coaxial cross sections (see fig. 2, (c))

$$B = \sum_i \frac{1}{4} E_i \pi (R_{1i}^4 - R_{2i}^4). \quad (4)$$

The torsional stiffness is described with the shear modulus μ. For composite cross sections, μ is no longer constant but dependent on the position $\mu(x, y)$. Thus μ is partially differenced and with the auxiliary function χ (see [6]), and the substitutions $\omega(x, y) = \mu\chi$ and $\alpha(x, y) = \frac{1}{\mu}$ we have

$$\frac{\partial}{\partial x}\left(\alpha \frac{\partial \omega}{\partial x}\right) + \frac{\partial}{\partial y}\left(\alpha \frac{\partial \omega}{\partial y}\right) = -1. \quad (5)$$

By taking into account the boundary conditions for the edge handling ($\omega = 0$), the torsional stiffness C can be computed

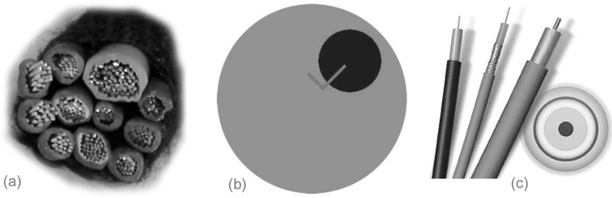

Figure 2. A typical cross section of a bundle (a) and the eigenvalues with maximum and minimum bending stiffness visualized by the length of the vector (b). Typical coaxial cables (c).

via the elastic torsional energy. For round inhomogeneous cross section we obtain

$$C = 4 \int \left(\alpha(x, y) \cdot (\nabla \omega(x, y))^2 \right) df. \tag{6}$$

For coaxial cables, the substitution and auxiliary function from eqn 5 depend only on the radius r of the cross section. Thus the equation is reformulated with the Laplace operator for twodimensional polar coordinates as

$$\frac{d}{dr} \left(\alpha \frac{d\omega}{dr} \right) + \frac{1}{r} \left(\alpha \frac{d\omega}{dr} \right) = -1. \tag{7}$$

With the substitution $\lambda = \alpha(d\omega/dr)$ the equation becomes an ordinary differential equation of first order and can be written as

$$\lambda' + \frac{1}{r} \lambda = -1. \tag{8}$$

The solution $\lambda = -\frac{1}{2} r$ is inserted in eqn 6 and leads to the equation for torsional stiffness of coaxial cables

$$C = \frac{1}{2} \pi \sum_i \mu_i (R_{i1}^4 - R_{i2}^4). \tag{9}$$

5. Results

The cable and bundle specimen are chosen from frequently exerted use cases. This increases the expressiveness of the tests since the results can be compared to the real prototype. 72 measurements are performed with the setups shown in figure 5 with and without torsion. The setup is build with least predeformation possible, though preformed behavior is common in manual bundle fabrication and transportation. The steps of the comparison are demonstrated in figure 4. The error is defined as the maximum deviation in relation to the length of the specimen (100%). The results are shown in figure 5.

The measurements of the stiffness are done with several bending tests of the same sort of cable or bundle. They are monitored and a graph is drawn with the force in relation to the bending distance. This graph is a hysteresis and no straight line. This means that even for small deflections, the behavior of the specimen is not purely elastic. Additionally, the bundles showed the behavior of inner displacements and friction.

The computation of the material properties shown in section 4 is mathematically correct. Deviances occur due to the plastic behavior of the real specimen, whereas in the equations plasticity is neglected. Furthermore, effects like the taping and friction are not taken into account which leads to deviances as well. This explains the discrepancies of the measurement of a specimen and the computed value, which differ about the factor of two. The computation and measurements of two bending stiffnesses showed small variances depending of the bending direction. E.g. for the bundle shown in figure 2, the maximum measured bending stiffness is 0,034158 Nm^2 and the minimum 0,028351 Nm^2.

The measured shape of the composite bundles lead to the assumption that the effects of different bending stiffnesses depending on the bending direction are negligible. Due to internal twist and the small differences in the values, the shape behaves like a homogeneous or coaxial specimen.

6. Conclusion

The results show the very high accuracy of the simulation in VR with an average precision higher than 99% for the 72 tests. The bending and torsion of cables and bundles is simulated physically correct. The main source of error are material variances due to manual fabrication which lead to preformed object behavior. The accuracy is much higher than the constraints usually given by the client, so the simulation is able to replace physical mock-ups. During the tests, much knowledge about measurement and material properties was gathered and with these experiences, further tests can be performed very efficiently.

In this paper it is shown that the material distribution leads to differing bending stiffnesses and that the center of gravity changes in the cross section. Concerning the simulation, we proved that this effect nullifies in reality, because the distribution changes over the length of the specimen due to internal twist. This behavior is another demonstration of the validity of the approach: one bundle, one material.

In the approach of computing the bending and torsional stiffness with the knowledge of the cross section and the component parts, further physical issues have to be taken into account. Elastic-plastic effects, the inner friction and the way of taping have high influence on the combined

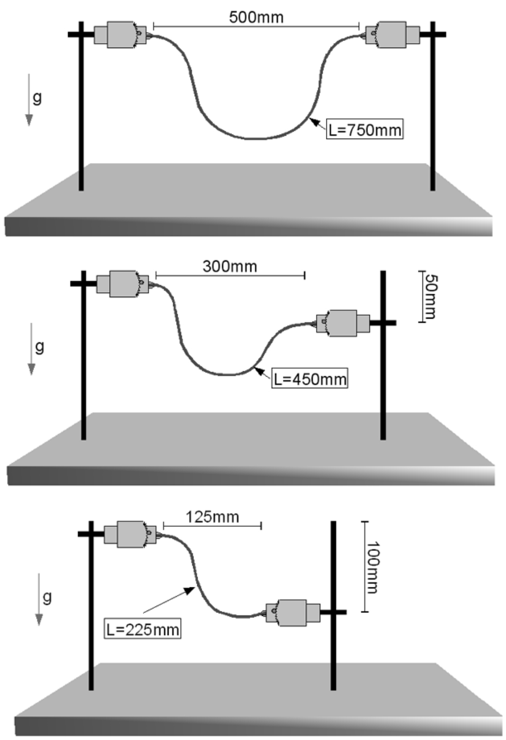

Figure 3. Three setups used for the validation. The test were performed with no torsion and 45° or 90° torsion.

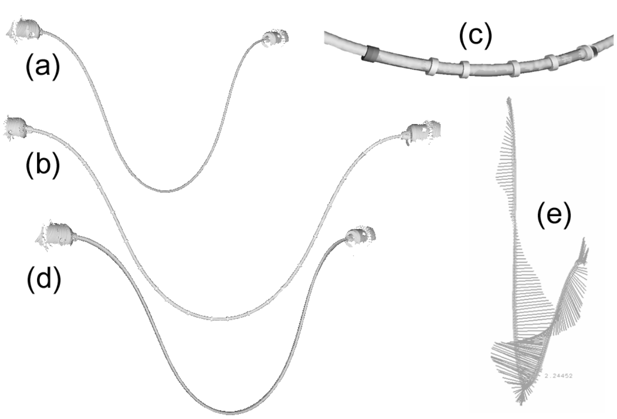

Figure 4. The laser scan of the specimen (a), the reconstruction of the centerline of the specimen (b, c), the simulation result (d) and the comparison with NX.

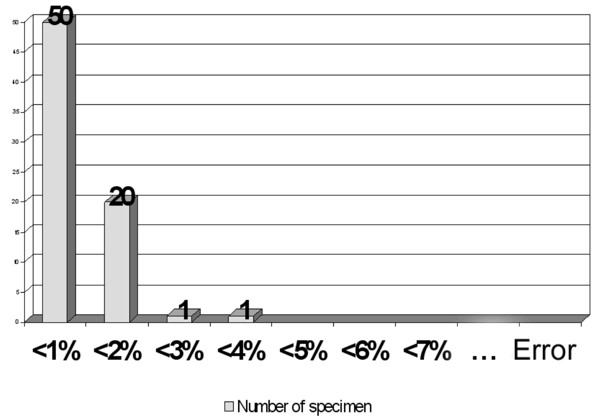

Figure 5. From 72 specimen, the error of 50 test is below 1%. The main source of error (3% and 4%) is related to predeformation. This proves the high accuracy of the simulation and the correctness of the measurement of the material properties.

properties of the specimen. This sector will be of high interest for further research projects.

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