INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

OPTIMIZED PRODUCT DEVELOPMENT BY MEANS OF CUSTOMIZED SIMULATION TOOLS - THEORY AND PRACTICE

Herbert Hinterleitner, Stefan Dierneder, Karl Ladner
Linz Center of Mechatronics GmbH, Altenbergerstrasse 69, 4040 Linz, Austria
{herbert.hinterleitner, stefan.dierneder, karl.ladner}@lcm.at

ABSTRACT

Simulation-Driven Product Development has become a key factor in achieving success in a highly competitive marketplace. Employing new simulation technologies in the earliest stages of design has become indispensable to reduce development cycles and to lower costs. However, the geometric complexity and advanced physics involved present some of the most challenging CAE problems facing engineers today. Market pressure to create innovative products in less time emphasizes the need to carry out more advanced simulations, faster than ever before. For this, a customization of the according simulation models and tools becomes more and more important. Of sure, the integrative design and customization is nothing really new and partly already content of engineers' daily work. But our experience has shown that until now, a really extensive integration and customization for product development only has been done for mathematical quite simple relationship. That is why one objective of this paper is also pointing out the reasonability of an extensive integrative product design with all its modeling and simulation possibilities and its customization for systems and products only can be described with extensive and non-linear models, too.

Keywords: Product and Systems Design, Design Methods and Tools

1 INTRODUCTION - THE DESIGN PROCESS IN GENERAL

Design in general is divided in a concept and embodiment definition step and a parameter specification step. Concept plus embodiment define a class of solutions spanned by varying the design parameters in their feasible range. New concepts or embodiments must be subject to a thorough development process to avoid too high risk of failure. A specific design problem in the framework of a given concept/embodiment then is an inverse problem. The requirements are given and a parameter combination has to be found to fulfill these requirements and, eventually, to solve an optimization problem. The design parameter functional requirement fulfillment relation should be a simple one. According to Nam P. Suh [1] it is mainly this simplicity that characterizes a successful concept. In case of the design of metal processing machines a huge number of parameters exist. Typically, in detail the number of parameters to be defined exceeds the number of requirements. Thus, parameters have to be grouped in so called lead parameters and dependent parameters. The set of lead parameters spans the required space of functional requirements; the dependent parameters are computed from the lead parameters by some design rules. These rules are partly heuristic ones, derived from experience. Basically, they would give place for some optimization, for instance for an optimization of production costs. But, optimizing with respect to a single criterion quite often worsens other properties, like robustness, or appropriateness for assembly or maintenance. Due to the multidisciplinary nature of the engineering work the activities of several departments couple to some extent. It has been discussed in [2], [3] and [4] how modular concepts help to cope with such a situation by reducing the complexity of the overall design process. In addition to these design related concepts, Simulation-Driven Product Development has become a second key factor in achieving success in a highly competitive marketplace. The geometric complexity and advanced physics involved present some of the most challenging CAE problems facing engineers today. Market pressure to create innovative products in less time emphasizes the need to carry out more advanced simulations, faster than ever before. This helps finding the best parameter setting for the best fulfillment of the given functional product requirements and consequently the special design requirements. For this, a customization of the according simulation models becomes more and more important. This brings more systematic and traceability into the whole design process what helps raising the product quality too.

1.1 Development and Benefit of Supportive Technologies

A lion's share of modern product development is concerned with product refinement. No really new technologies are involved, but some sort of optimization takes place. The objectives of such optimization are manifold: cost reduction, performance improvement, lead time reduction, increase of robustness, extension of the application range, both in qualitative and quantitative terms, energy consumption, less environmental harm, to mention only a few. Product optimization is never a strict mathematical optimization due to its multi-criteria nature. It is perceived as a decisive improvement leading to a product which is either superior to the competitors' products or at least very competitive within its intended product lifetime. Especially for products with make-to-order production cost saving by series production only is valid for components with multiple occurrence, the essential cost saving aspect of standardisation for this kind of production are lower design effort, lead time reduction, and lower error rate. Because of the complexity of the modern products this only can be supported by requirements oriented mathematical models, see also [5] and well designed simulation models.

2 CUSTOMIZED SIMULATION TOOL FOR A WIRE COILING MACHINE

In a first example, we had to investigate a special machine, invented for winding up large wire cables. This current existing machine often causes production failures due to mechanical damages, which come primary from undersizing. The producer did not consider the changing dynamic load on the device, even if some influencing system parameters were changing. To improve the design concept and to avoid these production failures, we had to investigate this very special and complex wire coiling process. Therefore our primary focus has been given on the very short period from clamping to tightening the wire, because in this phase, the wire cable and the coiling machine itself is loaded maximal.

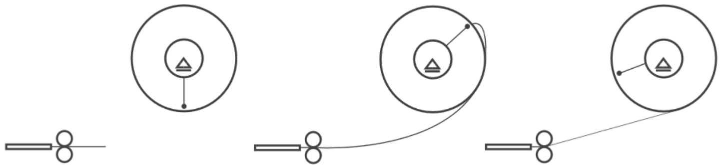

Figure 1: Coiling process of a wire cable

At the very beginning, the wire head moves to the coiling roll supported by a supply device, as shown in Figure 1. From the moment the wire head is automatically plugged to the coiling roll, the wire sags between the coiling roll and the supply device. The coiling roll now accelerates powerful, to prevent the system from building a big wire loop. Simultaneously, the wire moves with a constant velocity. According Figure 1 the wire has to be tightened strongly within the first turnaround of the roll.

2.1 Description of the Process

The intention of this work was to develop a calculation model, which describes the kinematical behaviour of this focused period with sufficient accuracy. The investigated process basically acts like a rotatory oscillator, but unfortunately it is not possible to describe it adequate by a simple linear analytical model. Complex physical effects (see Figure 2) have to be taken into account, calculated by both, analytical models and FE-analysis. Figure 2 shows these dominant physical effects which are as follows:

1. The free sagging wire. It can be described by an analytical model according to Feyrer K. [6]. Herewith, it is possible to gain a characteristic curve for the wire force depending on the wire sag.
2. The completely tightened wire. Its stiffness can be described like the stiffness of a tension bar.
3. The yieldingness of the steel construction. This can be determined from a FE-calculation.
4. The influence of the wire bending at the clamping point. A simple approach by using a plastic hinge [7] has been taken, to consider the complete plasticize of the wire cross section at the clamping point.
5. The size of the arisen wire loop determines the whole length of the wire, which has to be tightened.

6. The size of the friction area between the free sagging wire and the wire loop reduces the force on the wire loop itself (see Figure 2).

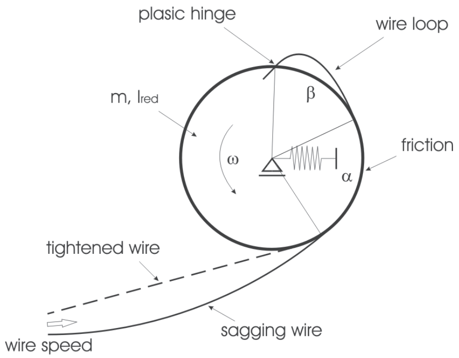

Figure 2: Physical effects

For modelling, simulating and analyzing this complex dynamic system, standard software packages have been used.

2.2 The Simulation model

As mentioned above, it was necessary to develop a complex numerical simulation model. Because of the above shown manifold non-linear physical effects, it is not possible to show the development of this simulation model in detail. The author has shown the mathematical modelling and the development of the simulation tool in [8]. But for a better understanding, a simple abstract model, illustrated in Figure 3, can be used.

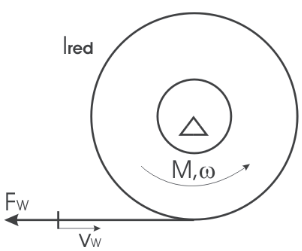

Figure 3: Dynamic model

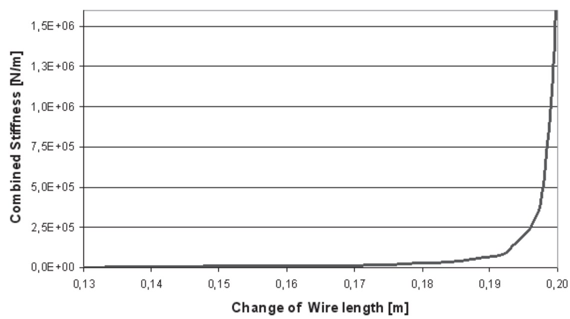

Figure 4: Characteristic system stiffness

The dynamic of the roll can be described under consideration of the drive torque and the gearbox by

$$I_{red} \cdot \ddot{\varphi} = M \cdot i - F_W \cdot r$$

where the wire force F_W is determined from a characteristic curve (see Figure 4) consisting of the non-linear effects 1, 2 and 3 as listed above. Furthermore, the difference in roll and wire movement ΔL can be calculated by

$$\Delta L = \int_{t_0}^{t} \left(\omega \cdot r - v_W\right) d\tau + \Delta L_0$$

because the wire is moved at its constant velocity v_w but the coiling roll has to accelerate to an circumferential speed higher the wire speed. These two equations have been integrated into the simulation structure below. Furthermore, a third substructure is shown in Figure 5, which calculates the mechanical equilibrium of the wire force in each time step, under consideration of the residual effects (4, 5 and 6), as listed above.

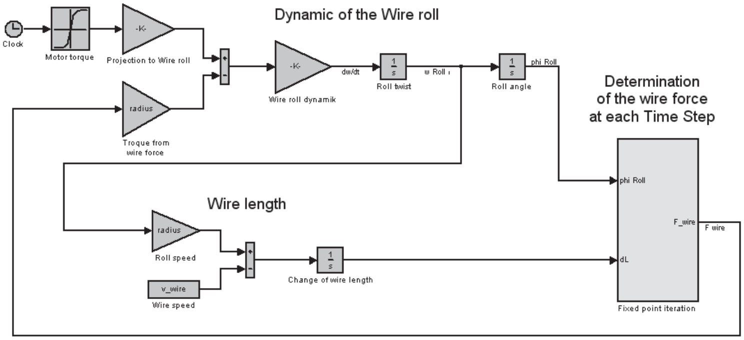

Figure 5: Simulation structure

For verification, we have compared the results to measuring data of an exemplary coiling process and we have found a very good accordance. In Figure 6 the circumferential speed of the roll and the constant wire speed are shown. In Figure 7 the simulation result is compared to the measuring data (represented by the dots). The maximal difference between the simulation result and the measuring data is about 10%. The buckling points in the curve shown in Figure 7 come from the rapid change of system stiffness, caused by the non-linear beaviour of the wire cable itself.

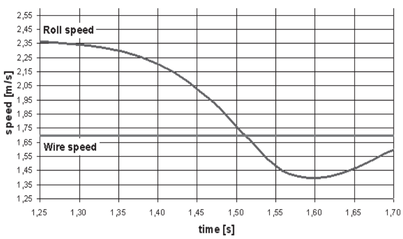

Figure 6: Measuring data

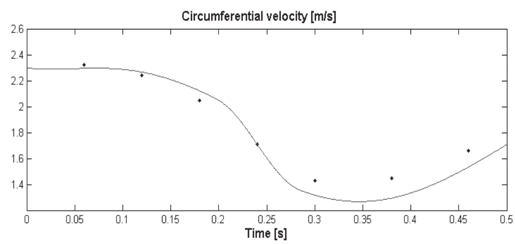

Figure 7: Simulation result

With this simulation model it is possible to calculate the occurring forces and to study different variants resp. configurations of geometry (e. g. different wire or roll dimensions, gear ratio, …), different materials or operating conditions like various wire speed, drive speed, and so on, and to compare all these different configurations among each other. A change of wire cable dimensions for example, causes a change of the dimensions of the coiling roll and perhaps the motor size and the gear ratio too.

2.3 Advantages and Disadvantages of such kind of Parametric Design respectively Product Family Design (see also [4] and [5])

The advantage of such a simulation model primary is the possibility to adapt and optimize a given mechanical configuration to special geometric or operating conditions and the customers' requirements. Furthermore, fast and sufficient precise information about the loads on each component is important for a safe mechanical dimensioning of the coiling machine. The disadvantages of that approach reads as follows: The current simulation model is not really user friendly and the user must be experienced in advanced mathematics and the usage of such mathematical software packages. Furthermore, such specialized software packages mostly have very high license fees and many small companies can not afford this R&D-staff and -costs. Therefore, the need for customized scientific design tools occur, which are able to consider complex physical effects, usable without having deep mathematical knowledge, encapsulated to avoid individual failures and best, free of extra charge too.

2.4 Development of an User-oriented Design Tool

Primary, the simulation system should consider the major influencing physical effects. It should allow to adapt the system to the given functional requirements best possible. Furthermore, additional design guidelines could be integrated into the simulation system. For example, the overall momentum of inertia has to be less than an assigned value, not to exceed the maximum allowed power consumption. In our case, the realisation of the customized design tool was done by transforming the mathematical simulation system to a stand-alone application and using standard software interfaces for data exchange. This stand-alone application is encapsulated and can be used by anyone without having deep and special mathematical experience and without extra software fee. The user can simply communicate with the encapsulated design tool via a customized user interface e. g. a standard spreadsheet program. He can now create different variants of a special design type within a given framework of functional requirements. He can easily compare the variants among each other, to find the best possible solution. In a further step, he can quickly gain manufacturing drawings from a parametric 3D-model of the coiling machine. And contemporary he has automatically created the complete technical documentation, which is absolutely necessary to fulfil legal engineering rules.

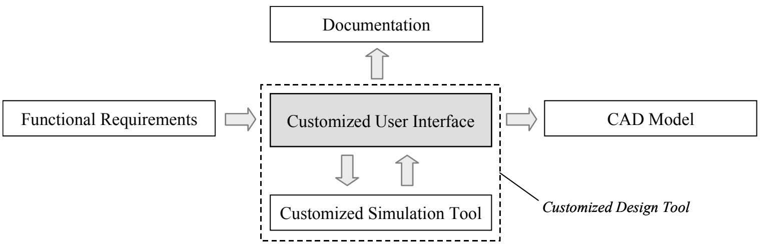

Figure 8: Principle of product development by means of supportive technologies

In our case, the investigation of the coiling process by means of this design tool, has shown a dominant influence on the arising forces if changing the wire dimensions or the wire material. Also the friction between the wire and the roll surface, which mainly depends on the wire material, as well as the velocity of the oncoming wire head, has a remarkable influence on the overall machine design as shown in Figure 9. In those cases the concerned mechanical parts must be completely new dimensioned.

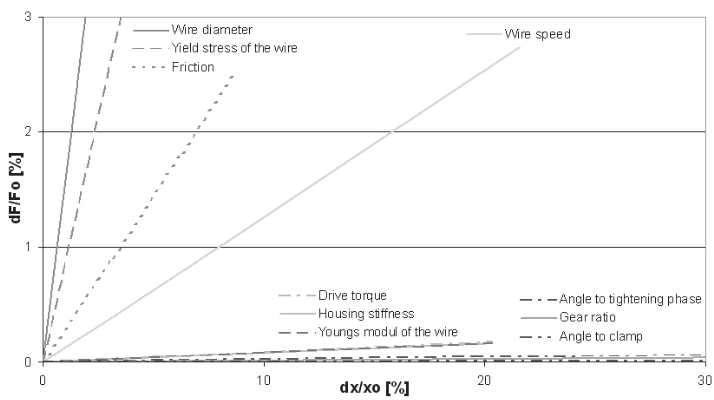

Figure 9: Effect of changing important system parameters

Otherwise the engineer can nearly free change the combination of electrical drive and gear box, as well as the operating conditions (rotation angles until clamping and tightening position), without changing the occuring loads. The geometry of the coiling roll can also be adjusted to the wire geometry (diameter and length) as long as the momentum of inertia remains constant. Hence, there are a lot of possibilities to customize and optimize the supporting equipment of the coiling machine. Additionally, because of the possibility of fast reply on parameter variations for setting up design variants, such design tools also help reducing the design costs, increasing the failsafe performance and improving the product quality and life time. Of course, the amount of work to develop and set up this customized design tools was high (it took about a year), but it now offers a lot of benefits as discussed so far. After this investigation the new coiling machine is decisively better dimensioned as its predecessor and at the same time the production costs are lower than before.

3 CUSTOMIZED SIMULATION TOOL FOR A HYDRAULIC PUMP

In this second example a design tool for self regulating variable displacement vane pumps has been developed. Therefore, the already existing mechanical device has to be described by a mathematical model, unlike in the first example, where the kinematical process has to be described. Self regulating pumps can deliver a constant pressure at different flow rates and they are used for automatic centralized lubrication in industry and automotive applications.

3.1 Principle of the self regulating variable displacement vane pump

The flow rate of the vane pump is adjusted by changing the eccentricity *e* as illustrated in Figure 10, and a hardware controller is used to feed back the current fluid pressure. The flow rate of the vane pump is directly proportional to the pump rotation speed and the eccentricity. If the pressure increases (e. g. caused by an increasing hydraulic resistance), the slide ring moves back against the eccentricity and the flow rate decreases. Otherwise, if the pressure decreases, the slide ring is being moved to higher eccentricities by a spring force.

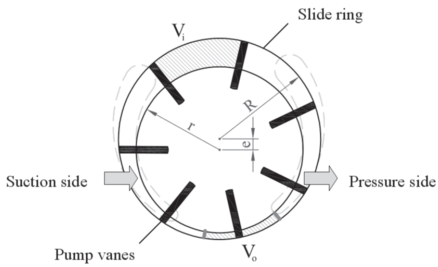

Figure 10: Vane pump scheme

Ivantysyn J. u. M. [9] and Murrenhoff H. [10] described such mechanical pressure control pumps, by the following basic equations. The flow rate Q delivered by the pump is proportional to the pump rotation speed ω, the eccentricity and the size factor k_p. It is given by

$$Q = k_p \cdot e \cdot \frac{\omega}{2 \cdot \pi} - \frac{2}{R_L} \cdot (p - p_U)$$

Usually a piping is installed between the pump and the valve to carry the lubricant or hydraulic oil. This piping acts like a hydraulic capacity and therefore, it must be considered in the simulation model. The difference between the flow rate delivered by the pump and the flow rate discharged through the valve determines the pressure build-up in the piping, which can be described by

$$\dot{p} = \frac{E}{V_{pip}} \cdot (Q - \frac{p - p_U}{R_h})$$

where E represents the fluid bulk modulus and R_L respectively R_h represent the hydraulic resistances.

3.2 The Simulation model

A dynamic simulation tool for the pump was built in a numerical simulation software package to customize and optimize the geometry of the pump to the given functional requirements according [1]. The simulation structure (see Figure 11) shows the basic equations, which have been mentioned above. The input parameters to the simulation are the pump geometry, the fluid parameters (e. g. hydraulic oil or water), the operating conditions (pump rotation speed) and the pump load. The most interesting output parameters are the pump pressure p, the control pressure p_R, the flow rate Q and the eccentricity e of the slide ring. The dynamic simulation model was first validated by a test bench with several vane pumps. Within the range of -50% to +50% of the original frame size, the simulation delivered accurate results. With this simulation model it is now easy to customize a wide range of vane pumps to very special customer requirements like pressure, flow rate or rotation speed. It is also possible to simulate the vane pump under constant pump rotation speed and variable pump load. This leads to the characteristic diagram of the pump according to Figure 12, which shows the results for a stepwise constant pump rotation speed from 500 to 3000rpm and an increasing pump load in each step. The obtained characteristic diagram shows the overall operating range of the designed vane pump.

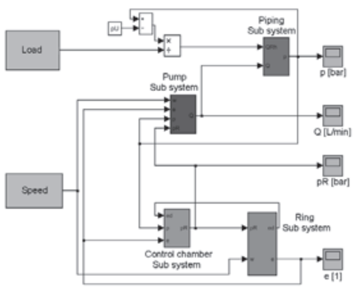

Figure 11: Simulation structure

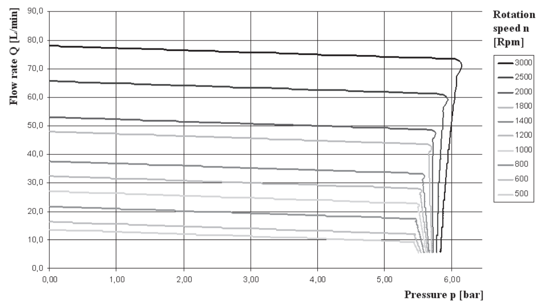

Figure 12: Characteristic diagram

3.3 Development of an User-oriented Design Tool

Like in the first given example, the simulation tool is described by a large amount of system parameters and the engineer must have a lot of special knowledge about using the simulation software, the theory which describes the vane pump and the physical coherences. Consequently, high effort in teaching the users is necessary. Furthermore, special software tools (including licence fees) and hardware equipment are necessary. Therefore, the dynamic simulation model was again transferred into an independent stand-alone application like done for the first example. It was again encapsulated and it communicates also via a standard user interface. Additionally, it directly communicates with a CAD system for the direct exchange of the required geometrical data. The used spreadsheet program provides an easy-to-use handling of all system parameters and a contemporary documentation of the calculations. So an engineer is able to use the tool after a short teaching time. He immediately can see the results of the simulation and he also gets additional information like the required installation space for the pump housing, the overall weight and some more important information. By the way, the technical documentation does not need additional work time. Finally, the engineer can now much faster create the adapted manufacturing drawings of the wanted pump variant, what directly reduces the development costs for the whole family of vane pumps within the given area of validity. The following figure illustrates the design steps of the development process described above.

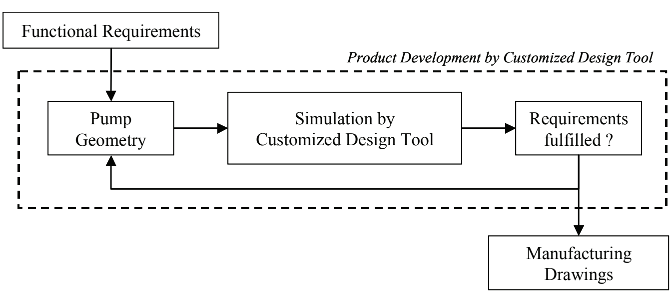

Figure 13: Optimized product development by customized design tools

In former times, it was unavoidable to build a prototype and to test it on a test bench after each design-loop. With the developed customized design tool, it is possible to design a new vane pump much faster and because of a better (deeper) product and process understanding often with increased product quality. Like also for the wire coiling example, the development of the simulation tool and the stand-alone application is expensive, but producing several prototypes and testing them for each customer specification is much more expensive and above all very time-consuming too.

4 CONCLUSION AND OUTLOOK

Summing up, it has been shown, that customized simulation tools combined with modern design methods contain a high cost savings and lead time reduction potential and improves product quality and also the consistency of project execution. Additionally, the tools contribute to a good documentation for both, the final product design and the overall design process with all its decisions and parameter settings especially for parametric design, where the lead parameters have to be suited best to adjust the concept to specific requirements and rules for deriving the dependent parameters substantial must be worked out. The results achieved so far will be extended to other systems and components which promise to be parameterised in an economic way. Currently, efforts are made for an advanced linking of the data flow between the used simulation tools and the different design and development processes done at different departments in a systematic and transparent manner without installing any hierarchy. This data flow concerns a huge set of parameters, which are coupled to some extent. The correct sequencing of work and decisions under ever shorter project execution time requires a real time forwarding of data and a documentation of all the decision processes.

REFERENCES

[1] Nam P. Suh, *The Principles of Design* (Oxford University Press, New York, 1990)

[2] R. Scheidl, S. Dierneder, K. Mörwald, *Computer Aided Conceptual Design by a Functional Decomposition Method for Process Oriented Heavy Machinery and its Relation to Mechatronization,* Lancaster International Workshop on Engineering Design - Computer Aided Conceptual Design Lancaster, UK, Proc. CACD'98, Eds.: A. Bradshaw and J. Counsell, Lancaster University, 1998

[3] S. Dierneder, R. Scheidl, *Modular Design – A Basis for the Successful Application of Mechatronics to Heavy Machinery,* Proceedings to 2003 ASME International Mechanical Engineering Congress and R&D Exposition, Washington, D. C. 2003

[4] S. Dierneder, C. Rudig, *Modern Plant Design with extended 3D Parametrics,* The 16th International Design Seminar, Kananaskis, Alberta, Canada, Proc. CIRP'06, Calgary, Canada, 2006

[5] S. Dierneder, R. Scheidl, *Conceptual Design, Functional Decomposition, Mathematic Modelling, and Perturbation Analysis,* Springer Lecture Notes in Computer Science 1798 - A Selection of Papers from the 7th International Workshop on Computer Aided Systems Theory and Technology 1999 – EuroCAST'99, Wien, Austria, Springer Lecture Notes in Computer Science – LNCS 1798, Eds.: F. Pichler, R. Moreno-Diaz, P. Kopacek (Springer Verlag, 1999)

[6] Feyrer K., *Drahtseile - Bemessung, Betrieb, Sicherheit* (Springer Verlag, Berlin, 1994)

[7] Young W.C., *ROARKS's Formulas for stress & strain, 6th Edition* (McGraw-Hill Inc., 1989)

[8] Hinterleitner H., Grieshofer O., *Investigation of the Non-Linear Behaviour of a Dynamic Wire Coiling Process*, Proceedings of IASTED 2009 - Modelling, Identification and Control, Innsbruck, Austria 2009

[9] Ivantysyn J. u. M., *Hydrostatische Pumpen und Motoren* (Vogel Verlag, Würzburg, 1993)

[10] Murrenhoff H., *Grundlagen der Fluidtechnik - Teil 1Hydraulik* (Verlag Shaker, Aachen, 2005)

ACKNOWLEDGEMENT

The authors gratefully acknowledge the sponsoring of this work by the "Austrian Center of Competence in Mechatronics" in the framework of the COMET program of the Austrian government. This program is funded by the Austrian government, the province Upper Austria and the Scientific Partners especially the Johannes Kepler University Linz.