OPTIMIZATION OF IN-PLANE COMPACTION OF A BRAIDED LAYER

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Abstract

Over-braiding has become a significant manufacturing technology for producing braided preforms in low costs and high volumes for fiber reinforced plastics (FRP). However, there is still potential to improve the mechanical properties, thus, to decrease the weight of the composites. This can be done by reducing in-plane compaction of a braided layer by spreading fibers in the braiding process. Thus, the reduced in-plane compaction will increase mechanical properties of the final part.

The in-plane compaction describes compression of a braided textile layer in its plane. Low in-plane compaction results in decreased ondulation, which in turn increases mechanical properties of the final component. The in-plane compaction is not yet measurable online. However, it can be described during the set-up of the machine by the cover factor that can be measured online.

A preliminary research has shown a nonlinear behavior of the cover factor over the vibration frequency of the braiding ring. Individual maxima and minima of the cover factor over the vibration frequency are clearly identified. In order to minimize the in-plane compaction, a corresponding method was developed within the scope of this research work by measuring the cover factor during the set-up process.

1. Introduction

In order to follow positive trend of global demand for carbon fibers [1], manufacturing companies in high-wage countries such as Germany are increasingly confronted with increasing demands in order to maintain their competitiveness against emerging low-wage countries. On the one hand, companies have to choose between individual production (scope), which involves high unit costs, and mass production (scale). On the other hand, they try to reduce unit costs by means of complex planning tools and highly automated production plants (planning orientation) compared to a robust, value oriented and adaptable process chain (value orientation). However, companies in high-wage countries are increasingly confronted with volatile and global markets with short innovation cycles, cost pressure and expensive resources. In order to withstand this competitive pressure, they must find an optimum between the two dichotomies (scope/scale and planning/value orientation). The two dichotomies are referred to in production engineering as the polylemma of production (Figure 1.2). [2 - 4]

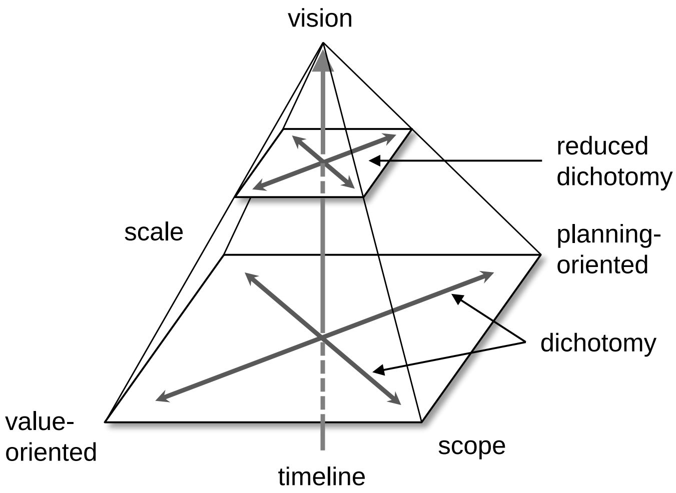

Figure 1. Polylemma of Production [4]

The resolution of these two dichotomies offers manufacturing companies in high-wage countries the opportunity to keep their competitiveness in the increasingly rapid global competition. Adaptive and flexible manufacturing systems are being developed to solve this conflict. If new product requirements arise in today's processes or if the process conditions change, the machine operator adapts the machine parameters to the requirements. The modifications are based on parameter tables, empirical experiments or subjective expertise of the production staff. Iterative adjustments of the machine parameters are often necessary. Time-consuming preliminary tests are carried out to determine the processing parameters for new products. During preliminary testing, no products are manufactured leading to financial losses. In order to meet the required tolerances faster, production is monitored and optimized on an abstract level. Instead of the machine level, the process level is considered. Additional measurements and control loops are therefore required. Model-based self-optimization (MBSO) is an essential concept that deals with this conceptual formulation. The following research hypothesis describes the approach of MBSO. [5]

„MBSO enables a robust and reproducible process control of manufacturing processes under constraints of variable requirements and boundary conditions. MBSO will increase the product quality and process efficiency.“ [5]

According to Adelt et al. [6] self-optimizing systems are defined by the following recurring execution of the actions:

- continuous analysis of the current situation,
- determination of the objectives and
- adaptation of the system behavior to achieve the goals.

The hypothesis for self-optimization has already been investigated in several studies or already implemented. For example, cognitive systems are developed to control robots [7, 8]. In communication networks, self-optimization is implemented on robot systems for their missions in disaster scenarios [9 - 11]. Another example for self-optimization in mechatronic systems is the system design itself of e.g. control module of rail vehicles [12 - 14].

Further examples for the application of MBSO are the self-optimizing assembly of large shell-shaped components such as shells of an aircraft fuselage [15], self-optimizing control of article-related material disposition in procurement [16], automated laser resonator alignment [17]. Further examples can be found in [5]. Gloy et al. implemented the MBSO approach in textile technology for the first time on a weaving machine [18]. The concept for self-optimization of the weaving process is based on the four following steps:

- design of experiments,
- execution of the test,
- modeling and
- determination of the optimum [18].

The first step involves planning the experiment. The result is a test design consisting of various machine setting parameters. According to this experimental design, the tests are carried out in the second step. Here, all test points are passed through and the warp yarn tensile force is measured. This is followed by modeling. Several models are created. The models are designed to predict the warp tension depending on the setting parameters. Finally, the setting parameters are determined in which the warp yarn tensile force is optimal with regard to the specified quality criteria. [18]. Self-optimization is also being investigated in the braiding process within the Excellence Initiative. Some results are discussed in this paper. The approach to design the MBSO for braiding is based on the same modeling methodology designed in [5].

2. Potential for Optimization

Birkenfeld and Mitwalsky have shown that reducing in-plane compaction or increasing the coverage by spreading fibers in the braiding process can significantly increase mechanical properties. [19, 20] It is based on the process window defined by Birkenfeld [19]. The in-plane compaction can be understood as illustrated in Fig. 2.

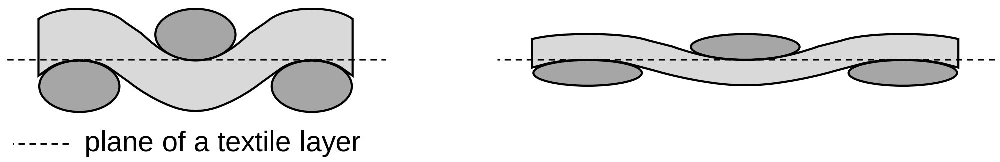

Figure 2. High (left) and low (right) compaction in the plane

The in-plane compaction describes the compression of a braided textile layer in its plane. Low compaction results in decreased ondulation, which in turn increases mechanical properties of the final component. The in-plane compaction is not yet measurable online. However, it can be described during the set-up of the machine by the cover factor that can be measured online via camera sensor and image processing.

3. Methodology for Modeling of Manufacturing Processes

In order to fulfill the hypothesis introduced in chapter 1, a methodic procedure is required to implement the required MBSO. As part of the Excellence Initiative of RWTH Aachen University methodical approach was developed that enables the gradual implementation of an MBSO for production processes. [5]

In most cases, the MO system is based on so-called metamodels. Metamodels describe the correlation between input and output parameters of the technical system in a simplified, mathematical form. When using metamodels, particular attention must be paid to their prediction quality. For this reason, a nine step methodology for developing metamodels was designed. This methodology was evaluated using different manufacturing processes [5].

The nine steps of the methodology are as follows:

1. definition of the process and model requirements
2. selection of parameters
3. determination of the process domain
4. selection of the data source
5. generation of the test design and design
6. generating the data
7. selection of model class and structure
8. implementing the model
9. determining the model quality

4. Implementation of the Methodology on Over-braiding

After defining the process and the model requirements for the braiding process, one process parameter is selected to optimize the in-plane compaction. Here, the shaking frequency of the shaking mechanism of the braiding ring has a significant influence on spreading of the fibers. However, compaction cannot be measured yet to find optimal shaking frequency. Instead, the cover factor of a braid can be measured with good contrast to the background. Thus, it will be used during the optimization process due to its correlation to the in-plane compaction. Cover factor is usually set to maximum of 100 % for the final component. Subsequently, it will be measured before the braiding process or during the set-up of the process to find the optimal frequency. Since both parameters, cover factor and in-plane compaction, are improved by spreading, the following conclusion will be taken into account:

> *Increasing the cover factor during set-up process may result in a lower in-plane compaction of a braided layer.*

This allows compacting to be optimized indirectly via the cover factor during the set-up process. This means that the coverage forms the data source for the metamodel. The cover factor can already be determined by means of image processing systems as already implemented in [21] using a gray value method.

Creating a metamodel requires relatively large amount of measurement data. Since manual data acquisition during the test execution greatly increases the effort, a graphical user interface in LabVIEW from National Instruments Corporation, Austin, TX, USA was set up for this purpose. The interface is based on a process flow that supports the user during the optimization process by collecting data and independently forming a model and finally deriving an optimal operating point for the shaking mechanism. In addition, in the background of the interface a method for determining the model quality is implemented. This allows the model to be evaluated.

The data collected and modeled via the nine steps discussed in a chapter before are shown in figure 3. Here, a polynomial formula of sixth grade was exemplarily used to show the potential of the optimization process. The domain was set from 12 Hz to 18,75 Hz. In this domain best spreading was achieved, thus, more data was collected in the same range to design a proper metamodel. It can be seen that there are certain maxima and minima in the diagram. To the end of the x-axis, or frequency range, the disturbances grow and even decrease. The maximum cover factor was found at a frequency of 15,5 Hz while disturbances decrease. In the worst case, a difference between the maximum and minimum coverage of at least 5 % is achieved regarding the small domain from 12 Hz to 18,75 Hz. Regarding the whole domain from 0 Hz the difference in this set-up is even higher.

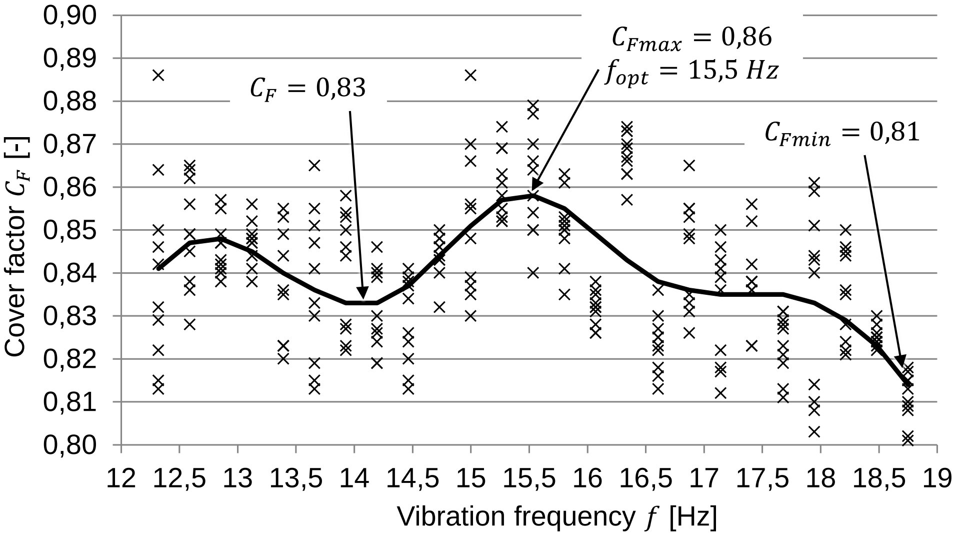

Figure 3. Polynomial metamodel of sixth grade of cover factor over vibration frequency

5. Results

The gained metamodel has shown its potential to find optimal frequency for the over-braiding process. Now, it can be implemented into the MBSO of a braiding process. Before the optimization process can be started, the machine has to be prepared. Here, simple cylindrical mandrel geometry will be used. The number of fibers and pattern of the braid will be set, to achieve coverage between 60 and 90 % to be measureable via image processing system online. Thus, there should be good contrast between fibers and mandrel.

After the experiment preparation the optimization process will be started. The optimization process consists of four steps. In the first step a test design is created. Here, the user enters the data such as material used into a graphical user interface. Other values such as the threshold value of the grayscale method are autonomously determined by the system. The data is then generated in the second step. During the testing procedure the user is assisted by the graphical user interface. The test is followed by an automatic evaluation of the metamodel and the output of the optimum frequency of the vibration mechanism.

With the optimum frequency, the process can now be finally set up and braid production with optimum in-plane compaction can be started. The whole concept of the self-optimization process can be seen in figure 4.

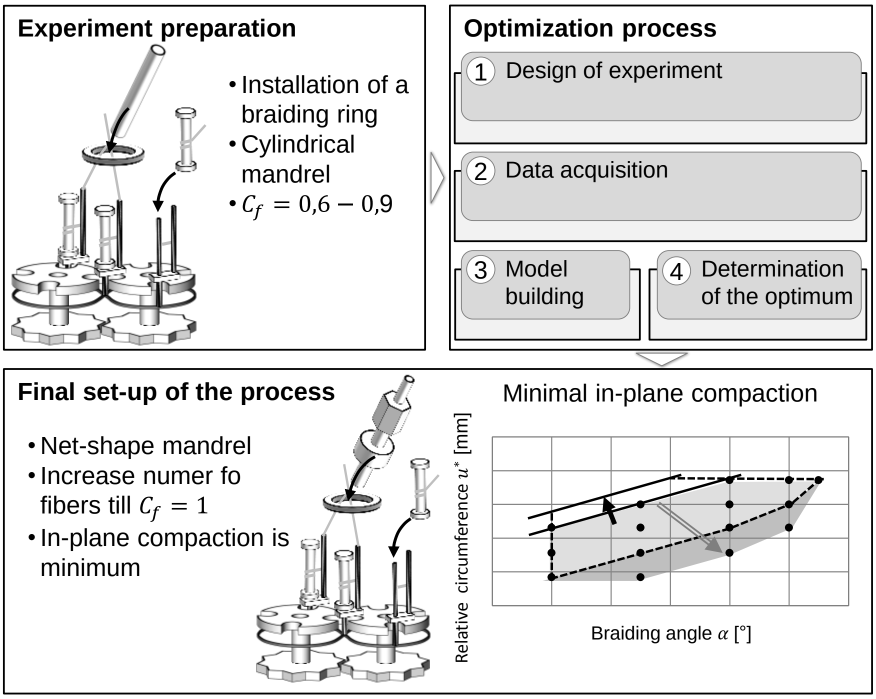

Figure 4. Concept of an optimization process during set-up in an over-braiding process

6. Conclusion and Outlook

In addition to growing environmental awareness, companies in high-wage countries have to choose between individual production (scope), which involves high unit costs and growing demand on quality, and mass production (scale). In today's processes, the machine parameters are adapted to the new requirements by a machine operator due to new product requirements or changed process conditions. The modifications are based on parameter tables, empirical experiments, subjective expertise or iterative adaptation of the machining parameters. Time-consuming preliminary tests are carried out to determine the processing parameters for new products.

Thus, the goal of this work was to lay the foundation for resolving the dilemma between scale and scope in a braiding process. An approach to solve this dilemma was a development and implementation of metamodels on measured data during set-up of the braiding process to improve in-plane compaction of a braided layer. The metamodel was then implemented into a concept of a model-based self-optimization of an over-braiding process.

MBSO makes it possible to increase the quality of a preform with minimum effort. Here, high quality is described by minimum in-plane compaction and thus minimum thickness and undulation of a braided layer of a preform. The compacting is optimized indirectly via the degree of coverage during the set-up process. The one-dimensional metamodel makes it possible to increase the cover factor in this example by at least 5 %. To further increase the quality, the concept of MBSO should be expanded to a multi-dimensional metamodel. This will make it possible to include further external parameters such as humidity, friction or fiber damage, thus, further optimize the process and make it operable during the process. It is also conceivable to implement the concept on different braiding ring concepts.

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References

[1] T. Kraus, M. Kühnel and E. Witten. Composites-Marktbericht 2016 : *Martentwicklungen, Trends, Ausblicke und Herausforderungen.* Frankfurt am Main; Augsburg: AVK - Industrievereinigung Verstärkte Kunststoffe; Carbon Composites, 2016, URL: https://www.carbon-composites.eu/media/2448/marktbericht_2016_ccev-avk.pdf
[2] C. Brecher, D. Özdemir and A. R. Weber. *Integrative Production Technology : Theory and Application.* In: C. Brecher and D. Özdemir (Ed.): Integrative production technology : theory and applications. Cham, Switzerland: Springer, 2017, P. 1 - 17.
[3] C. Brecher and D. Özdemir. *Introduction.* In: Brecher, C. (Hrsg.): Advances in Production Technology. Cham: Springer International Publishing, 2015, 1 - 8.
[4] C. Brecher, S, Jeschke, G. Schuh et al. *Integrative Produktionstechnik für Hochlohnländer.* In: Brecher, C. (Ed.): Integrative Produktionstechnik für Hochlohnländer. Berlin, Heidelberg: Springer, 2011, P. 17 - 81.
[5] F. Klocke, D. Abel, T. Gries et al. *Self-optimizing Production Technologies.* In: Brecher, C.; Özdemir, D. (Hrsg.): Integrative production technology : theory and applications. Cham, Switzerland: Springer, 2017, P. 745 - 877.
[6] P. Adelt, J. Donoth, J. Gausemeier et al. *Selbstoptimierende Systeme des Maschinenbaus : Definitionen, Anwendungen, Konzepte.* Paderborn: Heinz-Nixdorf-Institut, 2009.
[7] A. Bannat, F. Wallhoff, G. Rigoll et al. *Towards Optimal Worker Assistance: A Framework for Adaptive Selection and Presentation of Assembly Instructions.* In: Pagello, E.; Zhou, C.; Menegatti, E. (Hrsg.): Proceedings of the 1st International Workshop on Cognition for Technical Systems, Cotesys 2008, München Technische Universität, 2008.
[8] T. Laue and T. Röfer. *Getting Upright: Migrating Concepts and Software from Four-Legged to Humanoid Soccer Robots.* Proceedings fo the Workshop on Humanoid Soccer Robots of the 2006 IEEE-RAS International conference on Humanoid robots, Genoa, Italy, December 4, 2006, P. 32 - 39.
[9] R. Schmitt, C. Brecher, B. Corves et al. *Selbstoptimierende Produktionssysteme.* In: Brecher, C. (Hrsg.): Integrative Produktionstechnik für Hochlohnländer. Berlin, Heidelberg: Springer, 2011, P. 747 - 1057.
[10] S. T. Witt. *Integrierte Simulation von Maschine, Werkstück und spanendem Fertigungsprozess.* Aachen: Shaker, 2007.
[11] M. Litoiu, M. Woodside and T. Zheng. *Hierarchical model-based autonomic control of software systems.* DEAS 2005 : Workshop on the Design and Evolution of Autonomic Application Software, 2005.
[12] J. Gausemeier, P. Iwanek, M. Vaßholz et al. *Selbstoptimierung im Maschinen- und Anlagenbau.* Industriemanagement (2014), H. 6, P. 55–58.
[13] J. Gausemeier, U. Frank, A. Schmidt et al. *Towards a Design Methodology for Self-optimizing Systems.* In: H. A. ElMaraghy, W. H. Elmaraghy, W. H. (Ed.): Advances in design. London: Springer, 2006, P. 61 - 71.
[14] J. Gausemeier. *Von der Mechatronik zur Selbstoptimierung - Herausforderungen an die domänenübergreifende Zusammenarbeit.* Produktdaten-Journal 12 (2005), H. 1, P. 50-23.
[15] M. Janßen. *Selbstoptimierende Montage schalenförmiger Großbauteile mit rekonfigurierbaren Handhabungssystemen.* Aachen: Apprimus Verl., 2015, Zugl.: Aachen, Techn. Hochsch., Diss., 2015.
[16] F. Bauhoff. *Selbstoptimierende Regelung der artikelbezogenen Materialdisposition in der Beschaffung.* Aachen: Apprimus-Verl., 2013, Zugl.: Aachen, Techn. Hochsch., Diss., 2013.

[17] C. Brecher, R. Schmitt, P. Loosen et al. *Self-optimizing approach for automated laser resonator alignment.* Optics and Lasers in Engineering 50 (2012), H. 2, P. 287–292.
[18] Y.-S. Gloy. *Modellbasierte Selbstoptimierung des Webprozesses.*Aachen: Shaker, 2013, Zugl. Aachen, Techn. Hochsch., Diss., 2012.
[19] K. Birkefeld. *Virtuelle Optimierung von Geflecht-Preforms unter Berücksichtigung von Fertigungsaspekten.* München: Dr. Hut, 2013, Zugl.: Stuttgart, Univ. Diss., 2013, URL: https://elib.uni-stuttgart.de/bitstream/11682/3943/1/Birkefeld_online_22102013.pdf.
[20] M. Mitwalsky. *Strategien zur Steigerung der Variabilität bei der Herstellung von geflochtenen Hohlbauteilen.* München: Verlag Dr. Hut, 2016, Zugl.: München, Techn. Univ., Diss., 2015, URL: http://mediatum.ub.tum.de/download/1244755/1244755.pdf.
[21] F. Heieck, F. Hermann, P. Middendorf et al. *Influence of the cover factor of 2D biaxial and triaxial braided carbon composites on their in-plane mechanical properties.* Composite Structures 163 (2017), P. 114 - 122.