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Reaching Zero-Defect Manufacturing by Compensation of Dimensional Deviations in the Manufacturing of Rotating Hollow Parts

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Abstract

In many sectors such as the aerospace industry, the manufacturing of rotating components is based on multi-stage production systems to achieve the complex requirements of high quality products. Even in the presence of Industry 4.0 and the increasing connectivity, these systems are very prone to failure due to the high level of potential influences of both the system and the products, ultimately leading to defects. The project “ForZDM”, funded by the EU under Horizon2020, envisions reducing scrap rate by avoiding and compensating defects at an early stage thus guaranteeing a high quality product. This paper presents an approach using an existing manufacturing line to compensate the dimensional deviations of an inner contour of a turbine shaft at an early stage. Based on measurements of the inner contour, a new rotation axis for the subsequent manufacturing processes is calculated in order to avoid unbalances at the end-of-line control. Different algorithms are developed and integrated in a web-based application to find an optimal rotation axis under consideration of the to-be-manufactured outer contour in an operator-friendly usage on the shop floor. The application is connected with the measurement system and the subsequent CNC machine which enables automatic execution and data transfer.

Keywords: manufacturing process; zero-defect manufacturing; error compensation; unbalance; multi-stage; downstream compensation

1. Introduction

An improved value chain corresponds to higher company turnover which is decisive for the success of every company [6]. Turnover can be improved through the zero-defect manufacturing approach, which focuses on reducing scrap and rework time, particularly in multi-stage manufacturing systems. In complex production systems, however, scrap is often generated due to a high number of complex processes with unknown influences and a multitude of unavoidable production uncertainties. Especially in the case of rotating hollow parts, errors include geometric deviations that often only become apparent at a very late state of production or even only during the final check for unbalances. In the worst case, a component with errors introduced at an early stage is processed in the normal production flow and is only being detected as scrap at the end-of-line (EOL) check. Reiff et al. deal with the compensation of deviations based on the distortion of axle shafts after the forging process [9] however, to the best of the authors' knowledge, no other solutions can be found in the literature, in particular when considering hollow shafts.

In light of recent developments leading to greater availability and affordability of sensors, data acquisition systems and computer networks, the competitive nature of today's industry is forcing it to implement modern and sustainable methods. The increasing use of sensors and networked machines further leads to continuous generation of large amounts of data, which theoretically enables early detection of errors. The EU project “ForZDM”, part of the Horizon2020 cluster, aims at making the unused potential of multi-stage production systems transparent and available on this basis [2]. The challenge is to prevent the occurrence of errors or, in case of unavoidable errors

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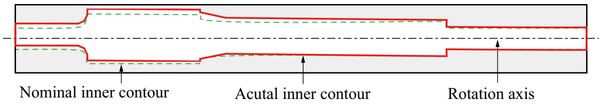
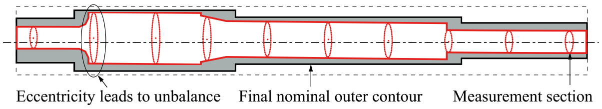
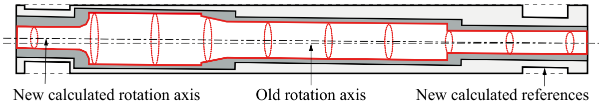


(a) Introduced defect due to an unsymmetrical inner contour.



(b) Part without optimization.



(c) Optimized rotation axis.

Fig. 1: Based on the introduced defect (a), a comparison of the resulting product after manufacturing with (b) and without (c) optimization.

which are detected by inter-stationary analysis, to compensate these in downstream production steps. In combination with a dynamic production and process planning, cost and time intensive rework and scrap can be avoided [1].

Besides comprehensive measurement and acquisition of machine, process, and product data, an essential part of this approach lies in evaluating correlation analysis and comparison of the actual and target state of the component along its production. In the geometric context, this process is presented as Part Variation Modeling [3, 4]. Part variations, which have an influence on the part quality, are modelled and used for an event-based prediction of the future part quality. The exact modelling of the target state for each station provides the basis for interpretation of the actual state on the one hand and, if necessary, to compensate for errors by downstream strategies [8]. This approach can also be applied to the compensation of dimensional deviations. Based on the results of Reiff et al. [9], this paper presents further methods using a turbine shaft in order to also enable the compensation of hollow rotating components in conventional multi-stage production systems by using simple measurement techniques. The developed architecture and the underlying methodology can be applied to a variety of components regardless of their geometric character and to various manufacturing processes.

This paper is structured as follows: Section 2 describes the fundamentals of the concept as well as a simplified production of turbine shafts and identified problems in the context of the industrial use case. Section 3 presents the methodology developed for optimizing the system using an adaptive grinding strategy. In Section 4, the developed algorithms are compared and validated on basis of measurements from the industrial use case. Section 5 summarizes and critically examines the results and describes the future work.

2. Fundamentals

If an error occurs in an early stage of a multi-stage production system, it can remain initially undetected and propagate through subsequent processes, leading to EOL rejects or extensive rework. In many cases, the identification of deviations due to special processes or object geometries relates to high demands on the measuring system, which is why it is often omitted. In the production of the inner contour of a turbine shaft for example, it is barely possible to integrate coterminous measuring technology and process control in the shaft. However, this prevents the actual ForZDM-approach from identifying errors early on. The sooner the error identification can be performed, the easier it is to use the capabilities of the production system to correct for errors and save resources that would otherwise be spent on machining a part that is already faulty. Frequent measurements of the part are therefore necessary to detect deviations from the target geometry [5].

Rotation-symmetric parts are used in many different sectors, ForZDM focuses on two uses cases: production of turbine shafts for use in the aerospace industry and production of wheel and axle sets for the railway industry. Both sectors imply high quality and safety requirements which have to be met by the production. Defects that occur in a multi-stage production system can be divided into geometrical and dimensional deviations. This paper deals with the compensation of deviations which can occur during the production of the inner contour of turbine shafts. The turbine is a slim component up to 3 m in length, having an inner contour adapted to the outer contour stemming from lightweight design requirements. Once the inner contour has been manufactured, the component is clamped in the downstream station for machining the outer contour.

The component passes through several stations and processes until the outer contour meets the requirements. Depending on the type, the component passes through 30 to 40 processes, resulting in an average total manufacturing time of 60 h to 90 h. However, in order to be able to deliver the component to the customer, it has to pass an EOL control where it is checked for surface defects, external dimensions, and unbalances. Even if the part has a perfect outer contour with all dimensions within their tolerances, it does not imply a perfectly balanced part. This can be caused by material defects, such as blowholes, or geometrical deviations between the outer and inner contour caused by process-related inaccuracies or errors (the former defect can be excluded by preliminary analysis). If an unbalance is identified at the EOL checks, rework of up to 15 h is necessary, that is up to 25 % of the original manufacturing process time. This time can be substantially reduced with the proposed approach.

Dimensional and geometrical deviations during production of the inner contour has been identified to be the greatest contributor to resulting unbalances. As shown in Fig. 1(a), deviations from the nominal geometry occur due to high process forces and complex machining processes of the inner contour, composed of several individual cylinders. The centers of the inner contour are not on a straight line neither collinear with the axis of rotation of the outer contour, depicted in Fig. 1(b).

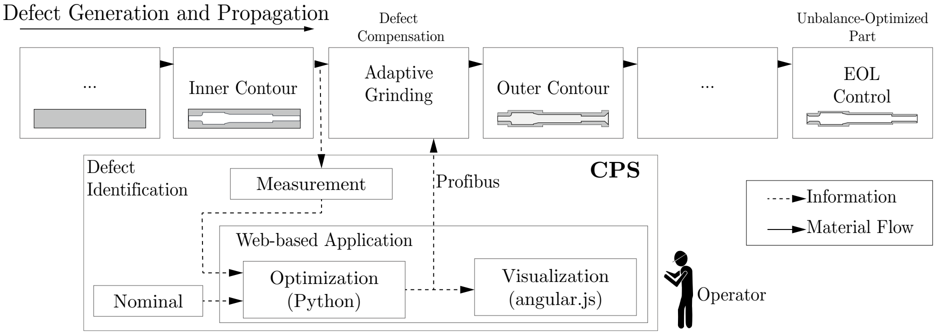


Fig. 2: Schematic representation of the integration of the developed CPS into the existing multi-stage manufacturing system.

Further processing without compensation of the deviation would result in a defective end product with high imbalances (see Fig. 1(b)). To prevent this problem and to achieve zero-defect manufacturing, an optimal positioning of reference points on the part must be determined on basis of the optimization of target values derived form the actual and nominal geometry. ForZDM provides a newly developed measurement system that allows the acquisition of the actual geometry of the inner contour (cf. Fig. 1(b)). The presented strategy for intelligent adaptation of the references considers the target geometry of the final product at an early stage of the manufacturing process. It is possible to predict the quality of the final product and to manufacture the newly identified reference surfaces (see Fig. 1(c)), which are used for downstream machining of the outer contour in another computer numerical control (CNC) machine.

3. Adaptive Grinding Methodology

The so-called *Adaptive Grinding Methodology* is based on a defined chain of actions and interfaces with the overall goal to optimize the references for the machining of the outer contour for individual products with respect to the expected unbalance. All of these actions are embedded in the existing manufacturing processes.

Figure 2 schematically illustrates the architecture of the Adaptive Grinding solution based on the main components, which are described in the following in detail. The main component of the architecture is the optimization core written in Python and deployed as browser-based web-app using the web framework Django. This design decision enables access from external devices and is easy to maintain. The calculated results are visualized in a front end developed in Angular. Thereby, the operator can easily evaluate the current state of the part and results obtained from the optimization core. The calculated correction values are directly sent to the machine control via Profibus. Subsequently, the machine can autonomously perform the necessary compensation actions. Following will be the introduction of the measurement system.

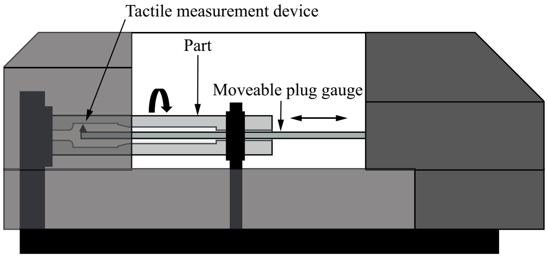


Fig. 3: Measurement setup on the CNC machine.

3.1. Measurement

The task of the measurement system is to capture the actual inner contour. The measurement device is integrated as machine tool on a CNC machine already installed in the shop floor. The device is a tactile measuring system attached to a 3 m long carbon plug gauge with wireless communication to the machine control.

The part to be measured comes directly from the manufacturing of the inner contour and is clamped and referenced in the machine as shown in Fig. 3. The operator starts the measurement and the gauge enters the part to measure the internal contour in this case on eleven predefined sections—this number of measurement sections is flexible. As the number of measurements increases, the actual geometry of the part can be reproduced more precisely. As soon as the tool reaches the first section, the gauge is moved in z-direction until the tactile measuring head and the surface come in contact. Subsequently, the product is rotated for 360°. From these data, the run-out measurements are calculated and used to determine the geometry as well as the deviation of the section from the actual axis of rotation of the component. The measurement values are stored in a central database to provide fast access for other systems.

3.2. Parametric Model

Since the optimization methods described in the following section require the nominal geometry of the product, an exchange of the relevant information is necessary. For this purpose, an algorithm was developed which reconstructs the nominal product on the basis of tabularized values. These values are provided for the inner and outer contour and describe the respective radius over a defined path. Using this information and the condition that the product only consists out of cylinders or cones, the complete three-dimensional model can be virtually generated.

3.3. Analysis and Optimization

The optimization aims at finding the best axis i.e., the symmetry axis of the outer contour. The optimized axis is subsequently used as the reference to clamp the part, containing the imperfect inner contour, in the machine for manufacturing the outer contour. Since one of the essential requirements for the shafts are low unbalances, the developed goal functions, described in the following, try to optimize these or related parameters. For this purpose, multiple, partly interrelated goal functions were set up taken from [7, 10].

In principle, unbalances of a rigid rotor can be described by the resulting unbalance $\vec{U}_r$ and couple unbalance $\vec{P}_r$, as represented in Fig. 4. For simplification, the rotor can be divided into single disc-shaped sections k for which the resulting unbalance reads

$$\vec{U}_r = \sum_{k=1}^{N} \vec{U}_k\,, \tag{1}$$

with single unbalance $\vec{U}_k$ of the k-th rotor section as

$$\vec{U}_k = m_k \vec{r}_k\,, \tag{2}$$

and m_k the mass of the unbalance, and $\vec{r}_k$ the distance between the mass of the unbalance and the rotation axis.

The single couple unbalance $\vec{P}_k$ is dependent on a defined reference plane R and can be calculated as vector product of the distance $\vec{l}_k$ (distance between measurement plane R and the unbalance $\vec{U}_k$) and the single unbalance $\vec{U}_k$ reading

$$\vec{P}_k = \vec{U}_k \times \vec{l}_k\,. \tag{3}$$

With Eq. (3), the resulting couple unbalance reads

$$\vec{P}_r = \sum_{k=1}^{N} \vec{P}_k\,. \tag{4}$$

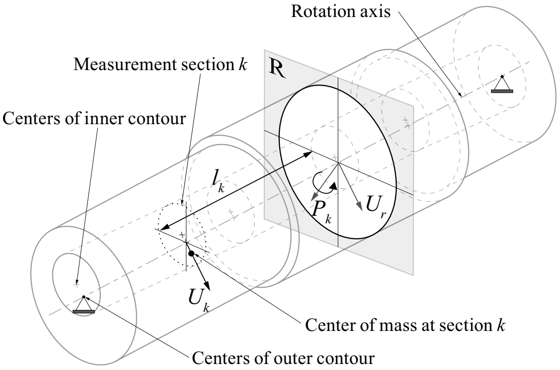


Fig. 4: Principle representation of a hollow shaft and the related unbalances based on [10]. Unbalance vector $\vec{U}_k$ represents the static unbalance in measurement section k. Resulting static unbalance vector $\vec{U}_r$ presents the resulting unbalance of all single unbalances $\vec{U}_k$. Plane R is used as reference for the couple unbalance $\vec{P}_k$.

In the following, seven goal functions for the optimization of the rotation axis are presented. Each optimization problem is formulated in the proximal and distal offset of the new line of rotation with respect to the original geometric center of the outer contour. That is, the free parameters

$$\boldsymbol{\theta} = \left[x_{\text{start}},\, y_{\text{start}},\, x_{\text{end}},\, y_{\text{end}}\right]^{\top}, \tag{5}$$

are the input to every optimization method, which represent the x and y displacement of the rotation axis on the start $(\cdot)_{\text{start}}$ and end plane $(\cdot)_{\text{end}}$, respectively.

3.3.1. Minimization of Distance Between Centers of Inner and Outer Contour

The approach of the first optimization method is based on the theory that the center of mass of a disc-shaped rotor must be on the axis of rotation so that the static unbalance $\vec{U}$ according to Eq. (2) is zero. In this case, the axis of rotation is the center axis of the outer contour i.e., the variable to be optimized. The cost function tries to minimize the distances from the center axis to the centers of mass of the measurement sections.

With a_k being the distance between the center of the inner contour and the center axis of the outer contour in measurement section k, N being the number of measurement planes, the cost function reads

$$\min f_{\text{dist in/out}}(\boldsymbol{\theta}) = \min\left|\sum_{k=1}^{N} a_k\right|. \tag{6}$$

This approach is comparable to the linear regression in three-dimensional space and aims at minimizing the amount of each measurement sections' individual static unbalance.

3.3.2. Weighted Minimization of the Distance Between Centers of Inner and Outer Contour

This approach extends the first cost function by weighting the calculated distances given the area A_k of each measurement section k yielding better approximation of the static unbalance. This leads to the weighted minimization function

$$\min f_{\text{wghtd dist i/o}}(\boldsymbol{\theta}) = \min \left| \sum_{k=1}^{N} A_k\, a_k \right| . \tag{7}$$

Area A_k is calculated by $A_k = \pi \left(r_{\text{outer}}^2 - r_{\text{inner}}^2 \right)$, with r_{inner} the radius of the inner contour and r_{outer} the radius of the outer contour. By the weighting used in this method, distances in sections with a bigger area will have more influence on the optimization. Thus, the expected resulting unbalance is reduced.

3.3.3. Minimization of Absolute Static Unbalance

This method tries to minimize the static unbalance of the individual measurement sections directly. For this purpose, the static unbalance of each measurement plane k are calculated as shown in Eq. (2) within the cost function as

$$\min f_{\text{abs unbal}}(\boldsymbol{\theta}) = \min \sum_{k=1}^{N} \|\vec{U}_k\| . \tag{8}$$

However, the effective directions of the single static unbalances are not considered in this method. This can lead to the individual unbalance vectors being minimized but the resulting unbalance, as defined in Eq. (1), remaining non-negligibly large.

3.3.4. Minimization of Resulting Static Unbalance

This cost function minimizes the sum of the static unbalances of each measurement section. In comparison to Eq. (8), single unbalances can compensate each other depending on their effective direction. However, it should be noted that the individual static unbalances may be increased due to mutual compensation. For this optimization method, the cost function reads

$$\min f_{\text{res unbal}}(\boldsymbol{\theta}) = \min \left| \sum_{k=1}^{N} \vec{U}_k \right| = \min \left| \vec{U}_r \right| . \tag{9}$$

According to Eq. (3), this also results in a reduction of the resulting coupled unbalance.

3.3.5. Minimization of Absolute Static and Resulting Static Unbalance

This method combines the goal functions from Eq. (8) and Eq. (9). The resulting unbalance $\vec{U}_r$ and the sum of the static unbalances $\vec{U}_k$ are normalized to have an equal influence.The normalization is performed by dividing the initial unbalance values. In addition, introduced weighting factors c_1 and c_2 can be used to define the ratio of each criterion's influence. The cost function correspondingly reads

$$\min f_{\text{stat+res unbal}}(\boldsymbol{\theta}) = \min \left(c_1 \frac{\left\|\vec{U}_r\right\|}{\left\|\vec{U}_{r,\text{initial}}\right\|} + c_2 \frac{\sum\limits_{k=1}^{N} \left\|\vec{U}_k\right\|}{\sum\limits_{k=1}^{N} \left\|\vec{U}_{k,\text{initial}}\right\|} \right) . \tag{10}$$

3.3.6. Minimization of Resulting Couple Unbalance

The minimization of the resulting couple unbalance is based on Eq. (3). In this case, two reference planes R_1 and R_2 have to be defined to determine the couple unbalances. The positions of the reference planes have a major impact on the optimization. Typically, the reference planes should be positioned in the later bearing points of the shaft. The goal functions is as follows

$$\min f_{\text{abs cpl unbal}}(\boldsymbol{\theta}) = \min \left(\sum_{k=1}^{N} \frac{\left\|\vec{P}_{k,1}\right\| + \left\|\vec{P}_{k,2}\right\|}{2} \right) . \tag{11}$$

3.3.7. Minimization of Resulting Static and Resulting Couple Unbalance

Similar to Section 3.3.5, this method combines two aspects. The first part contains the normalized resulting static unbalance while the second part describes the vector sum of the resulting coupled unbalances in the reference planes R_1 and R_2. The resulting coupled unbalance can be calculated according to Eq. (4), yielding the final custom function

$$\begin{aligned} \min f_{\text{stat+cpl unbal}}(\boldsymbol{\theta}) = \min \Bigg(& c_1 \frac{\left\|\vec{U}_R\right\|}{\left\|\vec{U}_{R_{\text{init}}}\right\|} + \ldots \\ & + c_2 \frac{\left\|\vec{P}_{R_1} + \vec{P}_{R_2}\right\|}{\left\|\vec{P}_{R_{1,\text{init}}} + \vec{P}_{R_{2,\text{init}}}\right\|} \Bigg) . \end{aligned} \tag{12}$$

4. Preliminary Results

We assess reduction of the unbalance using the algorithms presented in Section 3.3 by means of a real-world example of a single 1800 mm long shaft. Over the length of the shaft, 11 measurement planes are used to obtain data of the inner contour (cf. Section 3.1). Then, each of Eqs. (6) to (12) are used for finding an optimal displacement to orient the shaft in the manufacturing process of the outer contour. By this technique, ultimately, the final unbalance should be reduced to a minimum since rotation axes of inner and outer contour are properly aligned.

Table 1: Comparison of different optimization results of a measured shaft taken from the production. It is apparent that different goal functions yield different optimality measures.

Goal Function	Sum of all distances between outer and inner contour centers 1/mm	Sum of absolute static unbalances 1/(kg m)	Sum of vectorial addition static unbalances 1/(kg m)	Sum of absolute moment unbalances $1/(\mathrm{kg\,m^2})$	Sum of vectorial addition moment unbalances $1/(\mathrm{kg\,m^2})$
before optimization		6.638	4.656	3.961	3.864
$f_{\text{dist i/o}}$ Eqn. (6)	**0.240**	5.020	1.372	1.999	0.443
$f_{\text{wghtd dist i/o}}$ Eqn. (7)	**0.240**	5.049	1.391	1.992	0.549
$f_{\text{abs unbal}}$ Eqn. (8)	**0.240**	**5.008**	1.114	2.021	**0.363**
$f_{\text{res unbal}}$ Eqn. (9)	1.839	37.125	0.055	19.101	18.615
$f_{\text{stat+res unbal}}$ Eqn. (10)	0.944	19.152	0.110	9.375	9.039
$f_{\text{abs cpl unbal}}$ Eqn. (11)	0.254	5.278	2.160	**1.923**	0.905
$f_{\text{stat+cpl unbal}}$ Eqn. (12)	1.318	26.652	**0.042**	13.440	13.030

Section 3.3 shows physical meaningless quantities of the unbalance as calculated per the optimization function itself in the columns. That is, the rotation axis displacement $\boldsymbol{\theta}$ (cf. Eq. (5)) obtained from the optimization is used in conjunction with the respective goal function to calculate the values shown in the table. The first row shows the shaft's original unbalance as calculated per each column as means of reference. It is apparent that most methods reduce the unbalance, however, in some cases the resulting unbalance measure is increasing. This may be the case due to interpolation between the measurement sections which impedes the results obtained from calculating the unbalance.

Further investigation into choosing a generally valid unbalance measure needs to be taken since the variation of the results is rather large. However Eq. (8) shows the most promising and consistent results for various unbalance measures.

5. Conclusions

The presented Adaptive Grinding methodology aims at achieving a more economical production of turbine shafts through the intelligent alignment of the axis of rotation after the often erroneous manufacturing of the inner contour. For this purpose, approaches of zero-defect manufacturing were realized in an industrial use case and integrated into the process chain in the form of a cyber-physical system. In order to compensate the resulting unbalance caused by the manufacturing of the inner contour, both the nominal description of the product and the actual geometry are taken into account. Different goal functions for the optimization of the reference axis are presented and discussed.

In future work, the developed algorithms must be validated in long-term experiments. Special attention will be paid to the accuracy and efficiency of the presented optimization functions.

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