Mastering Uncertain Operating Conditions in the Development of Complex Machine Elements by Validation Under Dynamic Superimposed Operating Conditions

Thiemo Germann^(✉) , Daniel M. Martin , Christian Kubik , and Peter Groche

Institut für Produktionstechnik und Umformmaschine, Technische Universität Darmstadt,
Otto-Berndt-Str. 2, 64287 Darmstadt, Germany

{germann,daniel.martin,kubik,groche}@ptu.tu-darmstadt.de

Abstract. Machine elements produced in large quantities undergo several development cycles and can be adapted from generation to generation. Thus, experiences from real operation can be taken into account in further development. This is not possible for innovative investment goods such as special purpose machines, as these are usually individual items. Therefore, functionality and quality of newly developed components must be assured by previous investigations.

Conventional methods are inadequate at this point, as they cannot represent the actual, complex operating conditions in the later application. A reliable statement about the behavior of the system through a comprehensive validation in laboratory tests under standardized conditions is not achievable in this way due to a multitude of diversified load cases.

In previous work, a method was developed to allow testing of machine elements in the laboratory under detuned operating conditions. For this purpose, disturbance variables are applied to the system using paraffin wax phase change actuators in order to simulate real operation states and to analyze the behavior of the machine element under these conditions. The investigated disturbance variables are fluctuations and asymmetries of the operating load through superimposed temperature gradients. Complex interactions between the machine element and the adjacent components or the overall system can thus be taken into account.

The functionality of the methodology has been developed and briefly demonstrated so far. This paper presents the next level within the development process of the methodology. The necessary components are explained in detail and an AI black box evaluation tool is discussed. This work is based on a test bench that applies dynamically changing states of detuning under superimposed disturbances. Additionally, energy efficiency and performance of the test setup is advanced. As presented, the method opens up the possibility of validating new machine elements in the laboratory under realistic conditions.

Keywords: Product development · Uncertainty · AI · Machine elements

1 Introduction

Investment goods are by definition productive assets within a company, used for the production of goods or services within the production process. Typically, they have a much longer period of usage than the goods they produce [1]. A characteristic example for an innovative investment good is the servo mechanical press with the integration of a fully electrically driven shaft. It changes the usability significantly due to the increased operating speed [2]. Due to their significant impact on functionality and quality, investment goods are key-elements of production lines. A subsequent impact on technical, ecological and economic key figures is notable.

Innovative investment goods are unique items. Therefore, the practical knowledge of the product usage is confined. Additionally, investment goods and their accompanying processes are highly complex. This complexity along with the small quantities causes very high manufacturing costs resulting in a significant development effort. Since the manufacturer covers the total development costs, the case of failure often involves an existential risk. For this reason, and due to the high level of complexity, there is a need for functional reliability over the entire service life and within differing use cases.

As there are numerous stakeholders, the above-mentioned points are further complicated. These stakeholders (e.g. manufacturer, buyer, operator) must be involved in the development process of investment goods [3]. Different objectives, interests and varying social, economic conditions lead to a complex development environment.

However, due to its complexity the typical development of innovative investment goods is separated into the development and selection of numerous individual machine elements (ME). Those ME are often characterized by their uniqueness and development for this single purpose. Due to the influence of the specific installation and the actual operating conditions, the performance of the ME or modules is, on the one hand, highly dependent on the other parts of the investment good. On the other hand, the forces and energies acting on the structure of an investment good depend on the behavior of the embedded ME and modules. These interactions result in a high degree of complexity.

For a proper validation, experimental tests under environmental conditions and disturbances, as in later operation conditions, are necessary. Today, costly and numerous emulations of operating solutions are performed for machine tools or its subsystems. Still, the experience of different operating conditions and their overlay are only available for the next generation of the ME (compare Fig. 1). The idle development process directly combines the laboratory results with the usage experience to create an entirely satisfactory product (green process, Fig. 1).

However, due to their novelty and the aforementioned challenges, the development of innovative investment goods is a long and iterative process with high uncertainty. Initial designs are usually based on models and inputs derived from individual subsystem data. Additionally, inputs from testing under idealized conditions not closely reflecting the real application are used. Thus, unpredictable time-consuming and costly modifications are necessary when hidden interdependencies between the innovative ME and interacting components of the investment good impede the required performance.

Still, there are some methods to tackle the challenges of a complex design process. Typical tools are e.g. the Design Structure Matrix (DSM), the Quantification of Margins and Uncertainty (QMU) or the SCRUM method.

Fig. 1. Trade-off within the development process

QMU uses virtual models to quantitatively describe system behavior. It uses nominal values (M) and uncertainties (U) of components (compare Fig. 2). In general, QMU is a promising approach but it is not able to deal with the described challenges in the development of investment goods in an acceptable time frame [4].

Fig. 2. Typical procedure of a QMU based development process, according to [4]

The DSM is a model-based method to uncover and handle complex interdependencies. It allows structuring the development process for qualitatively captured dependencies [5]. This is available for some standardized ME such as screws [6]. However, for innovative ME in the early development of investment goods this requirement is typically not fulfilled. A quantitative description of their behavior has to consider geometrical influences, material properties and the actual operating conditions. Due to deviations between ideal and real conditions, this methodology is close to inapplicable.

A modern approach to keeping up with uncertainty and unknown interdependencies are agile and adaptive methods such as the SCRUM methodology. It is a software development approach to incorporate user experience into the development process. In this process, intermediate results are used for evaluation, stakeholder's feedback and definition of the next steps to eliminate uncertainty within the validation process [7]. Methodological challenges continue to hinder the use of SCRUM for innovative investment goods. As the method is used to change the requirements during the design process, conflicts with some of the stakeholders are foreseeable. Subdividing a physical object is challenging. In addition, materiality makes it difficult to create and evaluate a prototype after each sprint, and to make changes to a designed product when new requirements

arise. Obviously, it is not possible to offer customers a complex investment good, as for example the 3D Servo Press [2], with unfinished machine tools to tryout.

Summarizing, existing tools and methodologies for reliable development processes are not fully applicable, due to the complexity, novelty and characteristics of investment goods. Therefore, an approach for the validation and verification process is needed that handles the high level of unknown interdependencies and uncertainty. Thus, it is possible to ensure a sound base for the functional reliability of the investment goods and for the limitation of the development risks of the involved stakeholders.

The research described in this contribution therefore consistently continues the methodology developed in previous work [8]. The functionality of the methodology has so far been demonstrated at defined, static operating points. This contribution presents a test bench, which applies dynamically changing states of detuning under superimposed disturbances. Additionally, the energy efficiency and performance of the test setup is further developed. The successful application is presented and an evaluation method consisting of a black box AI model is discussed.

2 Approach

2.1 Model Representation – Bringing the Application to the Laboratory

Investment goods consist of a multitude of ME. Typically, several of these ME are individually designed for a unique investment good. Validation and verification within the design process is done separately. A laboratory environment with defined and standardized conditions is common. Especially for innovative ME, the effect of altered changing conditions on their behavior is unknown, since changing interface conditions or stochastic variations within the embedding structure are highly complex to simulate. In assembled investment goods, these changing interface conditions of individual MEs can reach a critical level that jeopardizes the investment good's overall functionality. Predicting these complex interface conditions is central to ensuring the products functionality. Therefore, superimposing thermal and mechanical loads have to be impinged in the laboratory. Additionally, it is of essential meaning to consider the complete field of possibly occurring operating points caused by the machine interfaces and the clamping conditions. Therefore, the test bench must be equipped with actuators that offer the option of simulating gradual changes in installation conditions and replicating dimensional changes due to tolerances or thermal loads. Furthermore, these actuators need to be compact enough to avoid larger design changes for their integration. Therefore, the paraffin wax phase change actuator (PCA) is the means of choice.

2.2 Paraffin Wax Phase Change Actuators for Detuning

Paraffin wax is a product of the petroleum industry, consisting of linear hydrocarbon strings of 20 to 40 carbon molecules. It is a phase change material with a significant increase of volume when changing from solid to liquid phase. Due to the small compression modulus it presents a suitable material for PCA. The activation of the paraffin wax is done by applying heat [9].

The used paraffin wax, SIGMA-ALDRICH paraffin wax mp. 58 – 62 °C, has a free volume extension of approx. 15% by heating from room temperature (25 °C) to the target temperature $\theta_t = 75$ °C (compare Fig. 3), a compression module of 1035 MPa [10] and a thermal conductivity of 0.371 W/mK.

Fig. 3. Dilatation ϵ_v (change in volume relative to the initial volume) of SIGMA-ALDRICH paraffin wax mp. 58–62 °C, according to [10]

The necessary characteristics of the actuators are the provision of sufficient actuating forces under thermal loads as well as a compact and robust housing. Neither rapid responses nor big displacements are needed. Therefore, a deep drawn sheet metal housing (dual phase steel 1.0936) consisting of two cups is used. The inner cup is filled with paraffin wax and a metallurgical bond via laser welding joins the actuator. A cutting seal by a brass sheet and the inner cups chamfer seals the PCA (compare Fig. 4) [11].

Fig. 4. Design of the PCA in a cross-sectional view, according to [11]

A radially applied thermal current activates the PCA. Due to the low thermal conductivity of wax, a delayed reaction is typical. This leads to a continuous increase of the axial compression force until the whole filled paraffin wax has reached the target temperature θ_t , which also determines the achievable maximum force. Forces of up to 60 kN have been proven at a working temperature of $\theta_t = 80$ °C [4]. The front faces transmit the force and are also responsible for the displacement. A displacement increases the inner volume

and is thus accompanied by a loss of force. A linear force-displacement-characteristic therefore follows. To avoid irreversible housing deformations, the axial displacement is limited to $w \leq 0,1$ mm. Additionally, a slight hysteresis behavior is visible (compare Fig. 5). The described material behavior shows a very good repetition accuracy.

Fig. 5. Force characterization (left) and force-displacement-characteristic (right) of a typical PCA for a target temperature of $\theta_t = 63^\circ\text{C}$; the displacement w is the controlled increase of the PCAs axial height due to the paraffin wax volume expansion in the characterization setup.

The use case within this work does not need a high dynamic; a slow but continuously increasing level of actuating force is rather needed to evaluate the ME behavior through the parameter field of clamping conditions. Nevertheless, higher actuator dynamics are achievable by thermal structures within the actuators housing, which shorten the thermal paths within the PCA or by additives within the paraffin wax.

2.3 Evaluation of Detuned Behavior

The paraffin wax PCAs are positioned between the ME and embedding laboratory environment. By activating the PCAs, a detuning as of a variation within the installation conditions can be simulated. Adjusting the PCA activation level allows for a wide variety of disturbances to emulate even more situations. Thus, complex disturbances in the component tests can be simulated by displacement fields that are close to the application. These small disturbances can have a significant impact on the functionality of key components as joints or bearings and subsequently on the over-all system behavior.

The resulting findings can be classified into two key areas. The first area focuses on the ME. Sensitivity with respect to specific disturbances can be evaluated and thus critical operation conditions are identified. This knowledge enables improvements at an early stage of the development process when modifications are still associated with comparatively low effort and expense. The second area affects the embedding structure. Necessary adjustments to the installation conditions can be deduced and even measures to improve the basic structure can be derived.

2.4 Backlash Free High-Load Bearing

The high machine flexibility of the 3D Servo Press is accompanied by challenging requirements for the MEs, especially for the bearings. The higher loads experienced in comparison with conventional forming presses can no longer be carried by pure roller bearings. For this reason, new types of combined roller and plain bearings have been developed which combine the specific advantages of conventional, pure roller or plain bearings for the application in servo presses.

Roller bearings have a lower starting torque than plain bearings, but provide poorer damping properties. At high operating loads, the economic advantages of plain bearings predominate the disadvantages due to installation space requirements. However, these are subject to backlash. In addition, in low speed ranges, mixed friction occurs in plain bearings. The developed special bearing counteracts these disadvantages. This is done by extending a plain bearing by two roller bearings arranged on either side of it. These can be either cylindrical roller bearings or ball bearings. Angular contact ball bearings have the advantage of allowing the radial preload to be changed by applying an axial force. For this reason, they are used for the investigations presented here.

Combining the two bearing types, the high load capacity and very good damping properties of the plain bearings can be combined with the absence of backlash and the good starting properties of the roller bearings [12]. In the range of low speeds and loads, the roller bearings carry most of the load and keep the bearing shaft centered in the bearing shell, thus avoiding mixed friction [13]. An increase in the operating load causes a displacement of the bearing shaft in the plain bearing shell and thus a deflection of the roller bearings. This in turn increases the load ratio of the plain bearing. An increase in speed also causes a higher plain bearing force, which leads to a reduction in the eccentricity of the shaft and relieves the roller bearings. Thus, high loads can be transmitted while avoiding backlash during start-up. Combined roller and plain bearings therefore offer great potential for meeting the challenging requirements of bearing arrangements for servo presses [14].

Both measurements and simulations confirm the load- and speed-dependent functional transition between the two bearing types [13, 15]. With increasing load, the shaft displacement initially increases more strongly until the plain bearing takes over the load-bearing components of the roller bearing and the increase in displacement decreases with increasing press force [12].

2.5 Test Bench

In preliminary work, a test bench was developed enabling the condition monitoring of a sensory equipped bearing during operation. This test bench enables continuous testing and evaluation with regard to defined technological and economic criteria as well as comparison with conventional bearings.

The developed sensor-equipped bearing and the test bench have been presented in [15]. The operating force is provided by a hydraulic actuator and absorbed by two support bearings which hold the shaft (compare Fig. 6 (1)) in the axis of the electric motor that generates the rotational movement. The test bearing (2, 3) is mounted in a housing (11), which transmits the force to the bearing. To detect the shaft displacement

path in the plain bearing, the test bearing is equipped with two eddy current sensors (10) placed 90° apart from each other, which measure the position of the shaft relative to the housing. Three temperature sensors measure the temperature on the outside of the roller bearing outer rings (8) as well as the outside temperature of the plain bearing shell (9). In order not to influence the lubricant film in the plain bearing, the lubricant temperature is not measured directly in the plain bearing, but only in the oil tank. In addition, the operating force is recorded by means of a piezo force transducer. The oil supply pressure is measured via a manometer attached to the inlet.

Fig. 6. Test bench of the combined roller and plain bearing

The distribution of the force flow F_{pb}/F_{rb} is determined by the stiffness of the roller bearings and the radial displacement $\vec{e}$ of the shaft assuming a constant stiffness of the rolling elements. Knowing the individual bearing forces, the operating behavior and the service life of the bearings can be estimated [14]. The compliance of the bearing is an important parameter to characterize the mechanical behavior of the bearing and, especially with regard to the use in a press, it is important for a model-based control of the ram movement. The total compliance δ of the combined bearing is determined by the displacement of the shaft in the direction of the operating force, and the operating force with e_x/F_{op} . In order to validate the bearing behavior at varying operating conditions, full-rotation and pivoting tests can be carried out [16]. Additionally, the damping properties of the bearing combination have been evaluated using punch tests [8]. To investigate the influence of detuned conditions, a test setup has been generated using PCAs to apply disturbance variables [8]. This procedure is adopted in the present work.

For ecological reasons, the actuator temperature control is based on water-flow actuator sleeves. The water is heated with a water boiler and pumped by an electrically driven pump in the test stand. Each actuator is coated by its own sleeves and is thermally isolated to the outer clamping to avoid energy losses as well as undesired heating of the bearing. There are four groups of actuators with eight actuators in total. Three actuators are positioned around each bearing cover and two separated PCAs are located on the operating force side of the bearings housing. Each group of actuators can be controlled separately and is supplied with hot or cold water.

2.6 Evaluation via AI

In order to quantify the influence of different input variables on the behavior of an engineering system, Machine Learning (ML) models can be used for predicting characteristic quantities. In general, the procedure of building a ML model to evaluate process states consists of several steps, which base on the heuristic process model Knowledge Discovery in Databases (KDD) that considers the acquisition, preprocessing and transformation of given data sets as well as the training and validation of the ML model [17]. One of the most efficient supervised ML model approaches is the multiple regression [18]. Multiple regression models allow to quantify the influence of several independent variables on one output parameter. Here, the output is represented by a weighted sum of the input parameters, allowing the influence of the input parameters to be quantified. In the simplest case, a multiple regression is linear and describes the correlation between input and output as follows:

$$y = \beta_0 + \sum_{i=1}^p \beta_i x_i + \epsilon.$$

The predicted output y is a weighted sum of its p input parameters x_i (called features). β_i represent the learned feature weights or coefficients. The first weight in the sum β_0 is called the intercept and is not multiplied with a feature. ϵ is an error term according to a Gaussian distribution. To find the optimal weight for each feature, a common approach is the least squares method to find the best fit for a data set

$$\hat{\beta} = \arg \min_{\beta_0, \dots, \beta_p} \sum_{i=1}^n \left(y^{(i)} - \left(\beta_0 + \sum_{j=1}^p \beta_j x_j^{(i)} \right) \right)^2.$$

In order to finally apply the multiple regression approach to predict the compliance of the bearing, in this work the procedure for implementing the model as shown in Fig. 7 is used.

Fig. 7. Procedure for predicting the bearings compliance using a multiple regression model

From the bearing system, process data are acquired using four actuator temperatures, the rotational speed and system data using of the compliance of the system. Based on the time series features are derived and split into a training and a test data set. To quantify the performance of the model, the root mean square error (RMSE) value between the actual and predicted compliance of the bearing is determined.

3 Application

In previous work [8], an approach for the validation of novel ME in investment goods was presented, which allows the emulation of realistic operating conditions in laboratory tests. Therefore, potential uncertainty influences were identified that can arise at interfaces between the ME and surrounding system, whereupon these were specifically manipulated in experiments. Paraffin wax PCAs were used, compare Sect. 2.3. The approaches are demonstrated uses the example of a novel combined roller and plain bearing used in the drive train of a newly developed flexible press (c.f. [2]).

Thereupon, on the one hand, the test setup is optimized within the scope of the present work. The PCAs are activated by heating sleeves through which a working medium (here water) flows, which that can be heated or cooled via a peripheral circuit. This modified control of the actuators allows both heating and active cooling. This allows different load situations to be generated one after the other in a targeted manner. Figure 8 shows the system for controlling the temperature of the actuators in a flow diagram. On the other hand, the design of an experimental design is presented, which simultaneously examines a maximum number of disturbance variables with a relatively small number of test series. An evaluation via AI is also presented, to evaluate individual disturbance variable influences from these predefined experimental results.

Fig. 8. PCA control: Schematic representation of the heating (shown)/cooling system; for simplicity only one bearing cover PCAs and one PCA on the operating force side are illustrated.

In [8], for comparability the same initial conditions are generated by a warm-up run before each test, until approximately stationary temperatures are reached at the

bearing points. Since heat transfer is not completely prevented by the used thermal isolation between PCA and bearing, the actual conditions may differ for each test run. Additionally, surrounding work floor conditions influence the experimental conditions significantly. In addition, the time required to carry out tests increases to an unmanageable extent when a higher number of possible disturbance and manipulated variables have to be investigated. Therefore, this procedure is now abandoned and instead the different initial conditions are taken into account by a continuously recording of all temperatures not only during the tests, but also in the intermediate periods.

The question is addressed whether the findings on the properties of the bearing can be reconstructed when operating conditions are approached from different initial conditions. The experimental procedure is described in the following section.

3.1 Test Procedure

In order to demonstrate the feasibility of the approach, the load distribution on the different bearing types and the total compliance of the combined roller and plain bearing are selected as output variables for the following considerations. Initially, only tests in full-rotation mode will be carried out. During a series of tests, several speed levels are approached. All data is measured continuously both during a test series and in between in order to resolve time-dependent effects. In order to reduce the test effort, test series are carried out without a defined time interval and without a previously performed warm-up phase. In order to identify and isolate the influence of individual input variables, an AI-based evaluation method is then applied.

Control variables for the system under investigation include speed, operating force, the preload of the rolling bearings and the oil feed pressure. In the pivoting operation mode, the pivoting angle and frequency determine the operating point. Possible interference effects result from the bearing temperatures, a reduction in the preload force (shown in the test by expansion of the PCAs attached to the bearing cover) or an asymmetrical application of force (possible in presses due to tilting of the ram or as a result of transverse forces). The latter is achieved in the test by applying different forces to the actuators mounted on the operating force side. From the possible manipulated variables, only a few selected ones are considered in the investigations presented here. The operating mode investigated is full-rotation mode. The total operating force F_{op} is 10 kN, the oil pressure at the infeed is 10 bar. The shaft speed is varied in 5 steps between 10 and 400 rpm. The roller bearings are preloaded by the bearing covers in a defined manner in the initial state (cold actuators).

3.2 Exemplary Results

The compliance of the tested bearing is considered as a decisive property for the dimensioning of the surrounding system. Compliance values are not only important for the characterization of the mechanical behavior of the drivetrain of presses but they are also necessary for a model based control of the ram movement. Figure 9 shows the compliance of the combined bearing determined during a representative series of measurements under different disturbance influences for different speeds. Tests under symmetrical operating load are shown in black. Tests in which the PCAs attached to the force side apply

different forces due to different temperatures, resulting in an asymmetrical load, are shown in blue dashed lines. Experiments with a one-sided loss of roller bearing preload due to increased PCA temperatures at one of the bearing covers (see Fig. 6) are marked with triangles. The results from tests with a decreased preload on both sides are plotted with circles. Normal preload conditions are labeled with diamonds.

In general, the compliance decreases with increasing speed due to the higher effectiveness of the plain bearing. The influence of the detuning decreases with increasing speeds as the values of different measurements converge at high speeds. The influence of the roller bearing preload is higher at low speeds due to the lower plain bearing load. Under symmetrical load, a one- or two-sided loss of preload leads to an increase in compliance. In the case of asymmetrical operating load, this is not observed. In the present case, the compliance values are even slightly lower, which can be explained by a tilting of the shaft and the associated solid body contact in the plain bearing shell.

Fig. 9. Compliance of the combined bearing for different operating conditions of a representative test series and corresponding averaged PCA temperatures

These observations are consistent with the results from [8], although the tests conducted there were carried out individually with prior warm-up and thus under stationary, reproducible conditions, whereas the investigations presented here involved dynamically variable operating conditions with uneven starting conditions. This reduces the effort required to validate the bearing behavior under realistic operating conditions. It is thus possible to investigate a much larger number of possible uncertainty influences. Since a large number of measurements are conducted in a short time and a correspondingly large amount of data is generated, the AI-based approach presented below is used to evaluate the complex relationships.

In order to quantify the influence of the expansion of the wax actuators as a result of their temperature on the performance of the investigated bearing, a regression model for predicting the compliance of the bearing is implemented according to Fig. 7. In the first step, the acquisition of temperature signals in each actuator as well as the rotational speed are conducted for different operating points. The temperatures of the four actuator groups are used as input parameters, with the three actuators on each of the two bearing covers being combined being averaged. These four temperatures are also averaged over a defined period of time prior to the actual acquisition of the data sets. Since the PCAs

achieve an approximately stationary force after 20 min at constant temperature, the averaging interval is set to 20 min. Taking into account five rotational speeds and 27 test series, there are 135 operating points with different speeds and actuator temperatures. The acquired time series are averaged for each rotational speed stage, resulting in a total of 175 predictor variables and 35 labeled responds given by the compliance of the system.

Fig. 10. Representation of the measured and predicted compliances of the test data using linear regression model (left) and a quadratic regression model (right)

To predict this compliance, both a linear and a quadratic regression model are derived considering the rotational speeds and the actuator temperatures. Finally, the transformed data set is randomly split into a training and a test data set to validate the model. Thereby, 25 operating points are used for training and ten operating points for testing the model. Figure 10(b) shows the results for the randomly selected operating points predicted by the regression model. While the linear regression model shows a deviation quantified by the RMSE of $1.7236 \cdot 10^{-9}$ m/N, the quadratic regression model performs slightly better with a value of $1.2284 \cdot 10^{-9}$ m/N. This is confirmed by the results shown in Fig. 10(a) for compliance of the bearing for different operating points. From the experimental results, an approximately quadratic response for the compliance of the bearing system can be seen, which accordingly justifies the quadratic performance of the regression model. The results show that both regression models are able to predict the compliance of the system as a function of actuator temperatures and rotational speeds. The performance of the models quantified by the RMSE, the maximum error as well as the coefficient of determination (R^2) is shown in Table 1.

Table 1. Statistical evaluation of the prediction results

	Linear model	Quadratic model
Root Mean Square Error (RMSE)	$1.7236 \cdot 10^{-9}$ m/N	$1.2284 \cdot 10^{-9}$ m/N
absolute maximal error	$2.7581 \cdot 10^{-9}$ m/N	$2.4865 \cdot 10^{-9}$ m/N
coefficient of determination (R^2)	78.57%	89.11%

4 Conclusion

Within this work, a consequent advancement of the methodology presented in [8] is promoted. So far, only explicit targeted states could be approached and an initial preheating to steady state conditions has been necessary. A cool down completed each run to secure reproducibility. Since only a few influencing variables and their combination can be investigated in manageable investigation periods, this procedure is not suitable for an efficient validation process. Considering the large number of influencing variables (e.g. speed, oil pressure etc.) and disturbances (e.g. bearing temperatures, asymmetrical load, etc.) a complete test cycle is not feasible. Additionally, no time-dependent disturbance overlays and dynamically changing conditions can be investigated.

Thus, it is a considerably more efficient test procedure to run through randomly selected operating points in sequence. This approach automatically incorporates dynamic processes and their resulting influence on system behavior into the test data. The test bench has been modified to implement this more efficient test method. In addition to an improved data recording, the concept for applying disturbances was revised. With the aid of water-flown sleeves, the paraffin wax PCA can be selectively heated or cooled. Four independent actuator groups (three PCAs on each bearing cover and two separate PCAs on the bearing housing) have been implemented on the test rig.

On the one hand, the dynamic application of disturbances as well as the investigation of different superimposed states allow a considerable reduction of the necessary test cycles. On the other hand, there is also a complex superposition of results, which makes the evaluation of the isolated effects of applied disturbances considerably more difficult. For the determination of results and the identification of necessary improvement measures, a methodology was discussed, which trains an algorithm by means of an AI black-box model. In this way, influences of individual values could be determined from the superimposed test results. This has been demonstrated by the compliance of the combined bearing.

The goal of this work was to show the applicability of the presented approach. The results show that the method works for the application example shown. The next step is to optimize the presented test setup by the implementation of additional measuring systems to record the PCA forces and displacements in order to improve the understanding of the observed relationships. The accuracy of the evaluation algorithm can be increased by more training data. Subsequently, the procedure has to be transferred to more complex investment goods and their components.

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