INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.86

Evaluation of the methodical framework for the management of uncertainty in the context of the integration of sensory functions

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Abstract

As digitalization progresses, the development and integration of sensory functions in technical systems become increasingly important. Managing uncertainty, especially in the early phase of this process, is crucial to ensure the reliability of the data provided. Therefore, a methodical framework for the identification, analysis and consideration of uncertainty was presented in prior works. In this contribution, the effectivity of the framework is evaluated by applying it to a sensory function for rotational speed and offset measurement of a disk pack coupling using sensor integrating bolts.

Keywords: robust design, uncertainty, methodical design, sensory function, evaluation

1. Introduction and motivation

Obtaining reliable information about relevant state and process variables of technical systems gains more and more importance due to Industry 4.0 and current trends like condition monitoring and predictive maintenance (Matt and Rauch, 2020). To satisfy the demand for reliable information, in-situ measurements come to the fore. Compared to ex-situ measurements, in-situ measurements result in a reduced transmission path between the origin of the quantity to be measured and the point of measurement. This in turn leads to reduced uncertainty due to the minimization of conversions and transformations of the quantity to be measured (Hausmann *et al.*, 2021). Sensing machine elements (SME), which build upon the primary mechanical functions of conventional machine elements and enhance them with sensory functions, represent a promising approach to realize in-situ measurements in technical systems (Vorwerk-Handing *et al.*, 2020a). Since SME almost maintain the standardized interfaces of conventional machine elements and thus require only little additional building space, they offer a great potential regarding the retrofit of sensory functions into existing technical systems (Vorwerk-Handing *et al.*, 2020a). This makes SME an enabler for Industry 4.0 (Kirchner *et al.*, 2024). However, despite reducing uncertainty by minimizing the transmission path between the origin of the quantity to be measured and the point of measurement by using SME, uncertainty remains. This uncertainty arises due to disturbance factors, e.g., and must be considered to ensure the reliability of the data provided (e.g. Meyer zu Westerhausen *et al.*, 2023). For the identification, analysis and consideration of uncertainty in this context, a methodical framework was already developed by Welzbacher *et al.* (2022; 2023). However, this framework is yet to be evaluated in regard of its effectivity, which is the goal of this contribution. Therefore, the framework is applied to a sensory function for rotational speed and radial offset measurement of a disk pack coupling using sensor integrating bolts as SME. The goal is to analyze the sensory function regarding its robustness against occurring disturbance factors, identify resulting uncertainty that is critical for the reliability of the provided data and ensure the robustness of the sensory function by means of suitable measures.

This contribution is structured as follows: Section 2 displays the fundamentals and state of the art, in particular of the methodical framework and the sensory function for the rotational speed and radial offset measurement of a disk pack coupling. In Section 3, the framework is applied to the sensory function for rotational speed and radial offset measurement and evaluated in terms of the effectivity of the developed measures. The contribution ends in Section 4 with a brief conclusion and outlook.

2. Fundamentals and state of the art

The fundamentals and state of the art for the subsequent application and evaluation of the methodical framework by Welzbacher *et al.* (2022; 2023) are described in this section. First, a definition for the term "uncertainty" is given and the classification approach based on its manifestation is described, which forms the basis for the methodical framework. In this context, the fundamental understanding of a disturbance factor is introduced. Secondly, the methodical framework for the identification, analysis and consideration of uncertainty by Welzbacher *et al.* (2022; 2023) is outlined. Finally, the sensory function for the rotational speed and radial offset measurement of a disk pack coupling is described.

2.1. Uncertainty and disturbance factors

Uncertainty is a term that is used in multiple scientific disciplines with different understandings (e.g. Grebici *et al.*, 2008). To achieve a uniform understanding of this term for the remainder of this contribution, uncertainty is defined according to the ISO-Guide 73:2009 as "*[...] the state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood.*" (International Organization for Standardization, 2009).

Since uncertainty is characterized by various aspects, multiple classification approaches for uncertainty exist (e.g. Walker *et al.*, 2003; McManus and Hastings, 2005). A selection of approaches is shown in Figure 1 in form of a coordinate system. In the following, the focus is on the classification approach based on its manifestation in the system, its model, respectively, since it forms the basis of the framework by Welzbacher *et al.* (2022; 2023). In this approach, uncertainty is distinguished into context uncertainty, data uncertainty, model uncertainty and phenomenological uncertainty, cf. Figure 1.

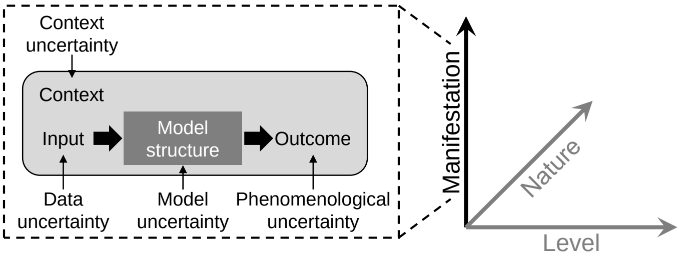


Figure 1. Classification approaches for uncertainty (Welzbacher *et al.*, 2022, based on Kreye *et al.*, 2011 and Walker *et al.*, 2003)

Context uncertainty describes the potential influence of the system's context - the circumstances and conditions surrounding the system - on the system itself, e.g., by disturbance factors originating in the use context of the system (De Weck *et al.*, 2007). Here, disturbance factors are defined as any unwanted and thus unintended input of the system, which negatively influences its behavior (Welzbacher *et al.*, 2021). Uncertainty connected to the system input is designated as *data uncertainty*. In this context, the term "input" not only refers to the actual input of the system but also the design parameters that are included in the system model. *Model uncertainty* is located within the system model and describes consciously as well as unconsciously made modeling inaccuracies, such as simplifications. If relevant information is unknown at the time of modeling, *phenomenological uncertainty* is present. This manifestation is connected to the system output and refers to the unpredictability of the future. Consequently, as there might be always an unexpected and thus neglected influence, phenomenological uncertainty cannot be described or modeled completely. (Kreye *et al.*, 2011; Walker *et al.*, 2003; Vorwerk-Handing *et al.*, 2020b)

2.2. Methodical framework for the identification, analysis and consideration of uncertainty

For the identification, analysis and consideration of uncertainty in the context of the integration of sensory functions by means of SME, Welzbacher *et al.* (2022; 2023) introduced a methodical framework. The steps of the framework as well as the associated results and tools are shown in Figure 2.

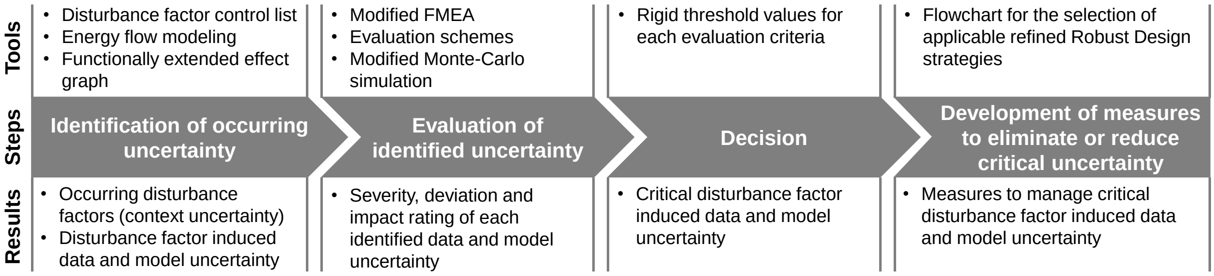


Figure 2. Structure of the methodical framework (cf. Welzbacher *et al.*, 2023)

In the first step of the framework, occurring uncertainty is identified. Since disturbance factors cause design parameters and functional variables included in the model of the sensory function to vary and thus result in data and model uncertainty, context uncertainty is first identified. Therefore, the disturbance factor control list by Welzbacher *et al.* (2021) is used. In this list, standardized disturbance factors are linked, according to multipole-based modeling theory, to two specific variables - the (sub-) domain specific flow and effort variable. For a systematic identification of disturbance factors that arise within the system in form of secondary variables, occurring dissipative physical effects must be identified. Therefore, the modeling approach by Malmiry *et al.* (2016) is used, in which the energy flows within and between the different system elements are modeled. Dissipative effects can then be identified by analyzing the effectivity of the respective energy conversions, transformations and conductions within and between the different elements. Subsequently, data and model uncertainty is identified using a functionally extended effect graph. For this purpose, the (sub-)domain specific flow and effort variables of the identified disturbance factors are considered as starting points and the functional variables as well as design parameters included in the model of the considered sensory function as end points. Using these specific start and end points, the functionally extended effect graph allows to identify relationships in form of (interconnected) physical effects between these points that result in data and model uncertainty. By doing that in an automated manner using the graph, the efficiency of the identification process is significantly improved compared to an identification based on an analog effect catalog, e.g., the one by Vorwerk-Handing *et al.* (2023), as originally proposed in Welzbacher *et al.* (2022). Since many physical effects have prerequisites for their occurrence, the results obtained from the graph must then be reviewed by the user to ensure the occurrence of the included physical effects in the system. Therefore, a filter option can be used to discard all results that include physical effects that do not occur in the considered system. (Welzbacher *et al.*, 2022; Welzbacher *et al.*, 2023)

In the next step, identified data and model uncertainty is evaluated in a modified Failure-Mode and Effects-Analysis (FMEA) to determine its criticality for the reliability of the data provided by the sensory function. Uncertainty is evaluated in this context using three different criteria:

- *Severity:* level of uncertainty connected to a functional variable or design parameter included in the model of the sensory function.
- *Deviation:* maximum relative deviation of the value of a functional variable or design parameter initially assumed in the model resulting from the considered uncertainty.
- *Impact:* sensitivity of the model in terms of a deviation of its output caused by an uncertainty affected functional variable or design parameter using a global sensitivity analysis.

For the determination of an uncertainty's impact, a modified Monte-Carlo simulation can be used. In this context, the previously determined deviation of the variable or parameter caused by the considered uncertainty is taken as input to calculate the resulting deviation of the model output. To ensure a reproducible valuation, rigid evaluation schemes are used for each criterion, which are, e.g., oriented at the prevailing level of available and reliable information regarding an uncertainty or the required measuring accuracy. The evaluation schemes range from 1 to 5, where 1 means a small and 5 a significant severity, deviation or impact. (Welzbacher *et al.*, 2022; Welzbacher *et al.*, 2023)

Based on the results of the evaluation, a reasoned decision can be made whether or not an uncertainty is critical for the reliability of the data provided by the sensory function. Therefore, rigid threshold values are used that are oriented at, e.g., the maximum permissible measuring error of the sensory function. (Welzbacher *et al.*, 2022; Welzbacher *et al.*, 2023)

In the final step of the methodical framework, measures are developed to eliminate or reduce critical uncertainty. In order to methodically support the user in this step, Welzbacher *et al.* (2023) adapted the Robust Design strategies by Mathias *et al.* (2010) for mechanical load bearing systems and refined them for sensory functions. To enable the selection of suitable refined Robust Design strategies, a flowchart was developed to empower the user to identify suitable strategies for the considered application case. In the flowchart, the prerequisites for the applicability as well as effectivity of the refined strategies are systematically checked by means of user questions. To answer the specific user questions, information from preceding steps of the methodical framework is used. (Welzbacher *et al.*, 2023)

2.3. Sensory function for rotational speed and radial offset measurement of a disk pack coupling

The LP6/6000 disk pack coupling from R+W Antriebselemente GmbH, in which the sensory function is integrated, is installed in a test bench in a ventilated mobile enclosure at the author's institute. The test bench is powered by two 350 kW drives, each of which is connected to the disk pack coupling via an elastic claw coupling and the X2FS100e/HU/B helical gearbox from SEW. For the rotational speed and radial offset measurement of the disk pack coupling, two sensor integrating bolts PB16 from ConSenses GmbH are used as SME, which are based on the piezoelectric effect. The main components of the test bench, the disk pack coupling with integrated sensory function as well as the measuring system are shown in Figure 3. It must be noted that the second sensor integrating bolt is positioned on the opposite side of the coupling's intermediate piece and is thus covered by it in the bottom-left part of Figure 3.

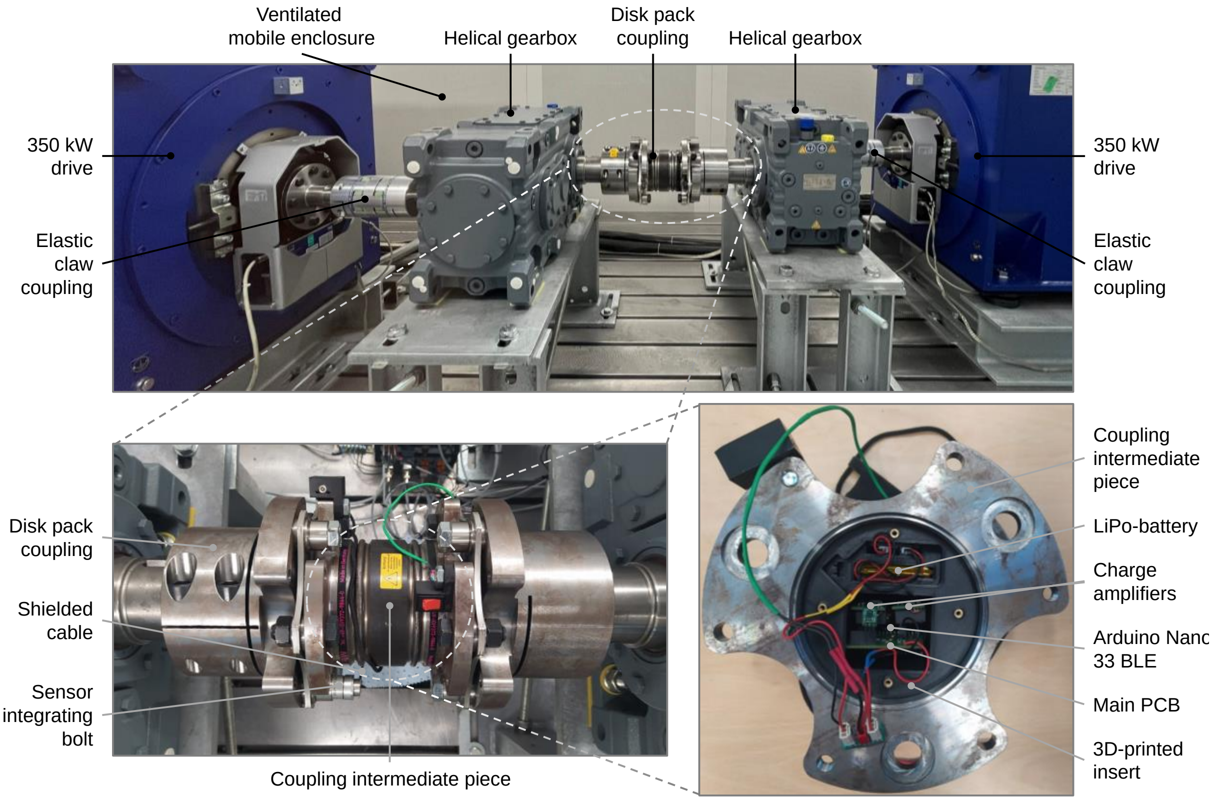


Figure 3. Structure and main components of the test bench (top), the disk pack coupling with integrated sensory function (bottom-left) and the used measuring system (bottom-right)

A rechargeable Lithium-Polymer battery (LiPo-battery) powers the measuring system, which can be disconnected from the remaining system by a manual switch. The two sensor integrating bolts measure the temporal change in bolt force over the rotation of the coupling and are each connected by a shielded cable to a charge amplifier. The charge amplifiers are in turn connected by operational amplifiers to an Arduino Nano 33. To enable a wireless data transfer from the measuring system within the rotating disk pack coupling to the stationary signal-processing unit located outside the mobile enclosure, the Arduino Nano is equipped with a Bluetooth Low Energy (BLE) module. The measured signal is transmitted by BLE from the Arduino to a stationary receiver within the mobile enclosure and subsequently via USB to the stationary signal-processing unit. There, the measured signal, the digital voltage values from the analog-to-digital converter (ADC) of the Arduino Nano 33, respectively, is normalized and transferred from the time domain to the frequency domain. In the frequency domain, the rotational frequency of the coupling becomes apparent. Based on the specific amplitude level at the rotational frequency of the coupling, conclusions about the present radial offset can be drawn.

3. Evaluation of the methodical framework

To evaluate the methodical framework by Welzbacher *et al.* (2022; 2023) regarding its effectivity, it is exemplarily applied to the sensory function for the rotational speed and radial offset measurement of the disk pack coupling in Section 3.1. This is to analyze the robustness of the sensory function, to identify uncertainty that is critical for the reliability of the provided data and to ensure the robustness of the sensory function by means of suitable measures to eliminate or reduce critical uncertainty. The results of the application of the framework in form of the implemented developed measures are then assessed in regard of their effectivity in Section 3.2.

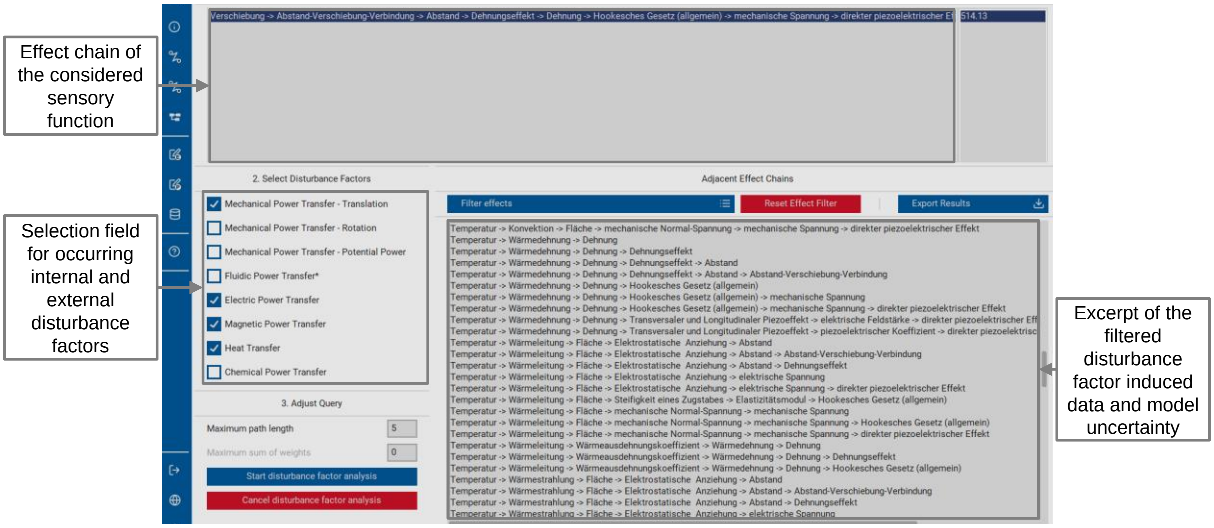
3.1. Application of the methodical framework to the sensory function for rotational speed and radial offset measurement of a disk pack coupling

In this section, the methodical framework is applied to the sensory function for rotational speed and radial offset measurement of the disk pack coupling described in Section 2.3.

Identification of uncertainty

Since the test bench and the disk pack coupling, in which the sensory function is integrated, are located within a ventilated mobile enclosure, it is reasonable to define the enclosure as the system boundary. Subsequently, occurring internal as well as external disturbance factors are identified. Therefore, the disturbance factor control list by Welzbacher *et al.* (2021) is used. To identify internal disturbance factors, the test bench and its subsystems are modeled according to Malmiry *et al.* (2016) and analyzed in regard of secondary variables that arise during function fulfillment. Considering, e.g., the two drives used to power the test bench, secondary variables occur in form of vibrations and heat dissipation. Since the test bench is mounted on a machine bed and located in a mobile enclosure within a test field, almost no external disturbance factors occur. However, since the mobile enclosure is only ventilated but not air-conditioned, heat convection appears. The results of the identification process are shown in Figure 4 as checked boxes in the selection field for occurring disturbance factors of the effect graph.

Based on the identified occurring disturbance factors, the resulting data and model uncertainty is identified. Therefore, the functionally extended effect graph by Welzbacher *et al.* (2023) is used. After selecting the underlying chain of physical effects of the sensory function to be analyzed and occurring disturbance factors in the graphical user interface (GUI) of the graph, a list of disturbance factor induced data and model uncertainty in form of (linked) physical effects is displayed. As described in Section 2.2, the results are then reviewed by the user for the occurrence of each included physical effect. To discard results that include physical effects that do not occur in the system, the integrated filter function is used. An excerpt of the identified disturbance factor induced data and model uncertainty is shown in the results field of the effect graph in Figure 4.



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Verschiebung -> Abstand-Verschiebung-Verbindung -> Abstand -> Dehnungseffekt -> Dehnung -> Hookesches Gesetz (allgemein) -> mechanische Spannung -> direkter piezoelektrischer Ef   514.13
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☑ Mechanical Power Transfer - Translation
☐ Mechanical Power Transfer - Rotation
☐ Mechanical Power Transfer - Potential Power
☐ Fluidic Power Transfer*
☑ Electric Power Transfer
☑ Magnetic Power Transfer
☑ Heat Transfer
☐ Chemical Power Transfer

Maximum path length 5
Maximum sum of weights 0

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Temperatur -> Konvektion -> Fläche -> mechanische Normal-Spannung -> mechanische Spannung -> direkter piezoelektrischer Effekt
Temperatur -> Wärmedehnung -> Dehnung
Temperatur -> Wärmedehnung -> Dehnung -> Dehnungseffekt
Temperatur -> Wärmedehnung -> Dehnung -> Dehnungseffekt -> Abstand
Temperatur -> Wärmedehnung -> Dehnung -> Dehnungseffekt -> Abstand -> Abstand-Verschiebung-Verbindung
Temperatur -> Wärmedehnung -> Dehnung -> Hookesches Gesetz (allgemein)
Temperatur -> Wärmedehnung -> Dehnung -> Hookesches Gesetz (allgemein) -> mechanische Spannung
Temperatur -> Wärmedehnung -> Dehnung -> Hookesches Gesetz (allgemein) -> mechanische Spannung -> direkter piezoelektrischer Effekt
Temperatur -> Wärmedehnung -> Dehnung -> Transversaler und Longitudinaler Piezoeffekt -> elektrische Feldstärke -> direkter piezoelektrischer Eff
Temperatur -> Wärmedehnung -> Dehnung -> Transversaler und Longitudinaler Piezoeffekt -> piezoelektrischer Koeffizient -> direkter piezoelektrisc
Temperatur -> Wärmeleitung -> Fläche -> Elektrostatische  Anziehung -> Abstand
Temperatur -> Wärmeleitung -> Fläche -> Elektrostatische  Anziehung -> Abstand -> Abstand-Verschiebung-Verbindung
Temperatur -> Wärmeleitung -> Fläche -> Elektrostatische  Anziehung -> Abstand -> Dehnungseffekt
Temperatur -> Wärmeleitung -> Fläche -> Elektrostatische  Anziehung -> elektrische Spannung
Temperatur -> Wärmeleitung -> Fläche -> Elektrostatische  Anziehung -> elektrische Spannung -> direkter piezoelektrischer Effekt
Temperatur -> Wärmeleitung -> Fläche -> Steifigkeit eines Zugstabes -> Elastizitätsmodul -> Hookesches Gesetz (allgemein)
Temperatur -> Wärmeleitung -> Fläche -> mechanische Normal-Spannung -> mechanische Spannung
Temperatur -> Wärmeleitung -> Fläche -> mechanische Normal-Spannung -> mechanische Spannung -> Hookesches Gesetz (allgemein)
Temperatur -> Wärmeleitung -> Fläche -> mechanische Normal-Spannung -> mechanische Spannung -> direkter piezoelektrischer Effekt
Temperatur -> Wärmeleitung -> Wärmeausdehnungskoeffizient -> Wärmedehnung -> Dehnung
Temperatur -> Wärmeleitung -> Wärmeausdehnungskoeffizient -> Wärmedehnung -> Dehnung -> Dehnungseffekt
Temperatur -> Wärmeleitung -> Wärmeausdehnungskoeffizient -> Wärmedehnung -> Dehnung -> Hookesches Gesetz (allgemein)
Temperatur -> Wärmestrahlung -> Fläche -> Elektrostatische  Anziehung -> Abstand
Temperatur -> Wärmestrahlung -> Fläche -> Elektrostatische  Anziehung -> Abstand -> Abstand-Verschiebung-Verbindung
Temperatur -> Wärmestrahlung -> Fläche -> Elektrostatische  Anziehung -> Abstand -> Dehnungseffekt
Temperatur -> Wärmestrahlung -> Fläche -> Elektrostatische  Anziehung -> elektrische Spannung
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Figure 4. Excerpt of the identified data and model uncertainty for the sensory function of the disk pack coupling, shown in the GUI of the functionally extended effect graph

Evaluation of uncertainty

The identified disturbance factor induced data and model uncertainty is subsequently evaluated using the modified FMEA described in Section 2.2. To determine the deviation and impact of the identified uncertainty, the model of the sensory function is first modeled in MATLAB and then extended by the disturbance factor induced data and model uncertainty. For this purpose, the laws of the physical effects that link the causing disturbance factors and the influenced functional variables as well as design parameters in the model of the sensory function are used. These are stored in a general form in the effect graph and have been refined as well as adapted for the considered application case. Using the extended model of the sensory function, a global sensitivity analysis in form of a modified Monte-Carlo simulation is carried out in MATLAB to determine the impact of the identified disturbance factor induced data and model uncertainty. Based on the results from the simulation in terms of resulting deviations of the model output due to the identified uncertainties, the impact of each uncertainty can be evaluated objectively using the corresponding evaluation scheme. An excerpt of the evaluation results of the identified data and model uncertainty is shown in Table 1.

Table 1. Excerpt of the results of the evaluation of identified data and model uncertainty

Disturbance factor induced data and model uncertainty	Severity	Deviation	Impact
Mechanical vibration excitation of the disk pack coupling	3	1	1
Mechanical stretching of the measuring cables of the sensor integrating bolts	1	1	1
Thermal expansion of the sensor integrating bolts	1	3	**5**
Thermally induced change of resistance of the charge amplifiers	3	1	3
…	…	…	…

Both thermally induced data and model uncertainties exemplarily shown in Table 1 are assessed with low or medium values regarding their severity and deviation. However, in contrast to the thermally induced change of resistance of the charge amplifiers, the thermal expansion of the sensor integrating bolts is assessed regarding its impact on the model output, the data provided by the sensory function, respectively, with the maximum value 5 based on the results of the modified Monte-Carlo simulation. This means that despite its low severity and medium deviation it has a significant impact on the model output, which exceeds the defined maximum permissible measuring error of the sensory function.

Decision

Based on the evaluation results of identified data and model uncertainty and rigid threshold values derived from the requirements for the sensory function, e.g., in terms of maximum permissible measuring error, a reasoned decision is made whether or not an uncertainty is critical for the reliability of the data provided by the sensory function. As indicated in Table 1 by bold characters, especially the thermal expansion of the sensor integrating bolts is critical, since it has a major impact on the model output and thus the reliability of the provided data. Consequently, measures to eliminate or reduce this critical uncertainty must be developed.

Development of measures to eliminate or reduce critical uncertainty

To develop suitable measures to eliminate or reduce critical uncertainty, the flowchart by Welzbacher *et al.* (2023) is utilized. The flowchart is run through for each critical uncertainty and measures to eliminate or reduce the causing disturbance factors, their influences or their impacts are developed. An excerpt of the results is shown in Table 2 for the critical, thermally induced uncertainty from Table 1.

Table 2. Excerpt of the developed measures to eliminate or reduce critical uncertainty

Critical disturbance factor induced data and model uncertainty	Eliminate/ reduce disturbance factor	Eliminate/ reduce disturbance factor influence	Eliminate/ reduce disturbance factor impact
Thermal expansion of the sensor integrating bolts	-	• Application of a reflective coating to the sensor integrating bolts • Thermal isolation of the sensor integrating bolts	• Active temperature control of the sensor integrating bolts • Measurement of bolt temperature and extension of the model of the sensory function
…	…	…	…

Considering the critical, thermally induced uncertainty in Table 1, the developed measures shown in Table 2 are explained and evaluated in the following:

- **Eliminate/reduce disturbance factor:** Since the causing disturbance factor occurs within the test bench and the measuring system in form of secondary variables during function fulfillment, no measures to eliminate or reduce the causing disturbance factors can be developed.
- **Eliminate/reduce disturbance factor influence:** Regarding the thermal expansion of the sensor integrating bolts, it is principally possible to eliminate or reduce the disturbance factor influence. This can be achieved, e.g., by applying a reflective coating to the sensor integrating bolts or by thermally isolating them (e.g. Breimann *et al.*, 2023). However, the effectivity of these measures is estimated to be low in the considered application case. This is because they only prevent heat convection and radiation but not conduction, e.g., from the gearboxes attached to the coupling. Hence, these measures are not considered further.
- **Eliminate/reduce disturbance factor impact:** Comparing the two measures to eliminate or reduce the disturbance factor impact in Table 2, the active temperature control of the thermally influenced components results in a significant design modification of the measuring system and the coupling. Therefore, the measurement of the respective temperatures of the two sensor integrating bolts is chosen to be implemented, as the effectivity of this measure is considered to be high, while requiring only a little effort for implementation.

3.2. Assessment of the results

In the following, the selected measure to eliminate or reduce critical uncertainty from Section 3.1 is implemented and evaluated in regard of its effectivity. Therefore, the measurement results obtained from the sensory function for rotational speed and radial offset measurement of the disk pack coupling without and with the implemented measure to eliminate or reduce critical uncertainty are compared.

Figure 5 exemplarily shows the measurement results of one of the sensor integrating bolts at a constant rotational speed of 75 rpm of the coupling and an applied torque of 2.200 Nm for various radial offsets in the time and frequency domain. The left-hand side of Figure 5 shows the measurement results without and the right-hand side with the implemented measure to manage critical uncertainty. The sampling rate for all measurements shown in Figure 5 is constant at 1 kHz and the measuring time is 5 seconds per measurement, resulting in 800 samples per revolution and 6.25 revolutions of the coupling.

The measurement amplitude clearly changes in the time domain for all measurements for one revolution similar to a sine wave, cf. Figure 5. Therefore, the rotational speed can be calculated using the measurement signal. Considering the measurement results without the developed measure on the left-hand side of Figure 5, it is obvious that in the time domain an almost constant drift is present in the data provided by the sensor integrating bolt. This results in a superimposition of the rotational frequency of the disk pack coupling at low speeds in the frequency domain. Hence, the rotational frequency of the disk pack coupling cannot be obtained from the spectrogram. In addition, no clear correlation between the amplitudes of the obtained signals for different radial offsets can be observed at lower frequencies. The drift observed in the measurements without implemented measures is mainly due to a minor change in temperature at the sensor integrating bolt during the measurements.

In contrast, considering the measurement results with the developed measure on the right-hand side of Figure 5, the thermally induced drift in the time domain is compensated for based on the information provided by the temperature sensor applied to the sensor integrating bolt. As a result, in the frequency domain, the rotational frequency of the disk pack coupling can be clearly identified by the largest amplitude, which occurs at 1.25 Hz. Moreover, a clear correlation can be observed between the amplitude level at the rotational frequency of the coupling and the applied radial offset. As the radial offset increases, the amplitude level at the rotational frequency of the coupling also increases.

In conclusion, it can be stated that the developed measure to eliminate or reduce critical uncertainty is effective, as the rotational speed of the clutch is now clearly visible in the frequency domain. Furthermore, due to the implemented measure, it is now possible to draw conclusions about the present radial offset by the amplitude level at the rotational frequency of the coupling.

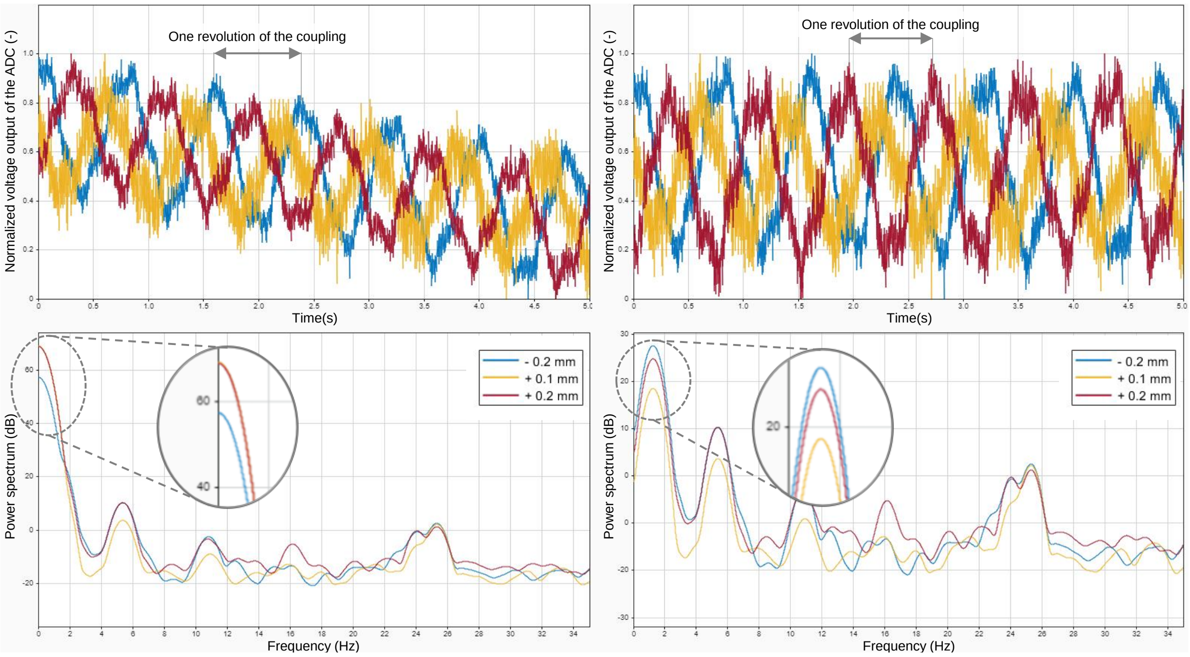

Figure 5. Measurement results for various radial offsets in the time (top) and frequency (bottom) domain at a rotational speed of the disk pack coupling of 75 rpm and an applied torque of 2.200 Nm without (left) and with (right) developed measure to manage critical uncertainty

4. Conclusion and outlook

In this contribution, the methodical framework by Welzbacher *et al.* (2022; 2023) for the identification, analysis and consideration of uncertainty in the context of the integration of sensory functions by means of SME was first evaluated in regard of the effectivity of the resulting measures to eliminate or reduce critical uncertainty. Therefore, it was exemplarily applied to a sensory function for rotational speed and radial offset measurement of a disk pack coupling using sensor integrating bolts. However, sensory functions by means of SME can always be abstracted to their underlying physical effects, which represent the major input of the methodological framework in addition to the disturbance factors occurring in the considered use context. This also applies to sensory functions that do not utilize SME. As the procedure within the framework is independent of the inputs, the application of the framework to other sensory functions therefore only differs with regard to these inputs. Hence, the results of the evaluation can be generalized and transferred to other sensory functions - with or without SME.

In the first step of the methodical framework, disturbance factors that occur in the use context of the considered sensory function were identified using the disturbance factor control list by Welzbacher *et al.* (2021). Based on the identified disturbance factors, the resulting data and model uncertainty was identified using the functionally extended effect graph by Welzbacher *et al.* (2023). In this context, a limitation of the functionally extended effect graph became apparent. The effect graph was initially developed by Kraus *et al.* (2022; 2023) for the identification of effect chains to realize a sought for sensory function and thus build a relationship between a quantity to be measured and a variable in the domain of electricity. Consequently, the sensory function for rotational speed and radial offset measurement of a disk pack coupling could not be directly obtained from the graph. In fact, the effect chains generated by the graph ended with the voltage obtained from the sensor integrating bolts, cf. Figure 4. To overcome this limitation, the considered sensory function, its underlying effect chain, respectively, was split into different parts, that could each be obtained from the effect graph and thus be analyzed in regard of disturbance factor induced data and model uncertainty.

In the next step, identified data and model uncertainty was evaluated using a modified FMEA. After determining the severity of each data and model uncertainty and calculating the resulting deviations, their impacts on the output of the sensory function were calculated. Therefore, the model of the sensory function for rotational speed and radial offset measurement was modeled in MATLAB and extended by the disturbance factor induced data and model uncertainty. To determine the impact of each uncertainty, a global sensitivity analysis in form of a modified Monte-Carlo simulation was conducted.

Based on the evaluation results, a reasoned decision was made whether or not an uncertainty is critical for the reliability of the data provided by the sensory function. In this process, it became apparent that the thermal expansion of the sensor integrating bolts had a major impact on the output of the sensory function and thus required measures to be developed for the management of this critical uncertainty.

For the development of measures to eliminate or reduce critical uncertainty, in particular of the critical thermally induced uncertainty, the flowchart by Welzbacher *et al.* (2023) was used. After developing different measures for each critical uncertainty, the measures were evaluated to obtain the most promising ones. In this context, special attention was paid to their effectivity and the required effort for implementation. Regarding the thermal expansion of the sensor integrating bolts, this resulted in the selection of a measure that is based on the integration of additional sensors for temperature measurement at the two bolts. By measuring the prevailing temperature at the sensor integrating bolts, the resulting uncertainty could be determined and its impact on the measurement results compensated for.

After implementing the selected measure to eliminate or reduce critical uncertainty, multiple measurements were conducted at different radial offsets to allow for a comparison of the measurement results without and with the implemented measure. Based on the measurement results, the effectivity of the developed measure was evaluated. As shown in Figure 5, the impact of the thermally induced uncertainty on the measurement results could be eliminated, proving the effectivity of the developed measure and thus the methodical framework used for its identification, analysis and consideration.

In the next step, an adaptation of the functionally extended effect graph is planned to overcome the limitation described above. For this purpose, a manual extension of the generated effect chains is conceivable to obtain the complete effect chain that describes the considered sensory function. This would make the identification process of disturbance factor induced data and model uncertainty more efficient. After the adaption of the functionally extended effect graph is carried out, a study in cross-over design is planned to evaluate the overall efficiency and usability of the methodical framework.

Finally, a more comprehensive analysis of the measurement results obtained from the sensory function for rotational speed and radial offset measurement of the disk pack coupling is planned, e.g., regarding its potential in terms of condition monitoring of the gearboxes attached to the coupling.

Acknowledgement

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - 426030644

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