



# Systematic identification of disturbance factors on electric characteristics of mechanical gearboxes

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## Abstract

Failures of machine elements can cause critical machine breakdowns, e.g. bearing damage accounts for almost 20% of all machine failures. Hence, monitoring machine elements is of particular importance for condition monitoring of gearboxes. Therefore, new approaches based on electrical impedance analysis are proposed in literature, e.g. for the measurement of rolling bearing load or damage condition with so-called sensory utilizable machine elements (SuME). For this approach, an electrical signal is transmitted through the structure to be observed and the resulting impedance is measured. With this technique it is possible to detect loads and damages not only for bearings, but also for the entire gearbox. Another application of this method can be the transmission of electrical signals through machine elements and the gearbox themselves. However, uncertainty arises with regard to the distinct signal transmission in these processes, mainly due to parasitic capacitances. In this contribution, the disturbing factors on the measured impedance of a gearbox at different working points are investigated. For this purpose, disturbance factors are systematically identified and used as basis for a full factorial experimental design for screening the operational characteristics of a gearbox. The data obtained from the tests is analyzed to identify correlations between the disturbance factors and parasitic capacitances. The experiments show a speed- and torque-dependent behavior of the parasitic capacitances in a gearbox. These results can be used for further research of SuME and structure-integrated energy supply and signal paths as well as the evaluation of related measurement data by reducing the associated uncertainty.

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## Systematische Identifikation von Störfaktoren auf die elektrischen Charakteristiken von Getrieben

### Zusammenfassung

Ausfälle einzelner Maschinenelemente können kritische Anlagenstillstände nach sich ziehen. So sind ca. 20 % aller Maschinenausfälle auf Lagerschäden zurückzuführen. Somit ist die Überwachung von Maschinenelementen für die Zustandsüberwachung von Getrieben entscheidend. Daher wurden neue Ansätze basierend auf der elektrischen Impedanzmessung in der Literatur aufgezeigt, z. B. zur Messung der Wälzlagerlast und des Schadenszustandes mit so genannten sensorisch nutzbaren Maschinenelementen (SuME). Zu diesem Zweck wird ein elektrisches Signal durch Strukturelemente geleitet und die resultierende Impedanz gemessen. Mit dieser Technik können nicht nur Schäden oder Lasten an den einzelnen Lagern detektiert werden, sondern auch im gesamten Getriebe. Ein weiteres Anwendungsfeld ist die Signalübertragung elektrischer Signale durch Maschinenelemente und Getriebe. Nichtsdestotrotz treten in beiden Fällen Unsicherheiten auf, welche Einfluss auf die Signale haben, vornehmlich parasitäre Kapazitäten. In dieser Arbeit werden die auf die Impedanz eines Getriebes wirkenden Störfaktoren zu verschiedenen Betriebszeitpunkten untersucht. Dazu werden die Störfaktoren systematisch identifiziert und als Basis für einen vollfaktoriellen Versuchsplan genutzt, um die Charakteristiken des Getriebes zu bestimmen. Die Versuchsdaten werden analysiert, um Zusammenhänge zwischen den Störfaktoren und den parasitären Kapazitäten zu entdecken. Die Untersuchungen zeigten ein drehzahl- und drehmomentenabhängiges Verhalten der parasitären Kapazitäten. Die Ergebnisse können für weitere Forschungsfragen hinsichtlich der SuME, der strukturintegrierten Energieversorgung und Signalleitung sowie zur Bewertung von Messdaten durch die Reduktion von wirkenden Unsicherheiten verwendet werden.

## 1 Introduction

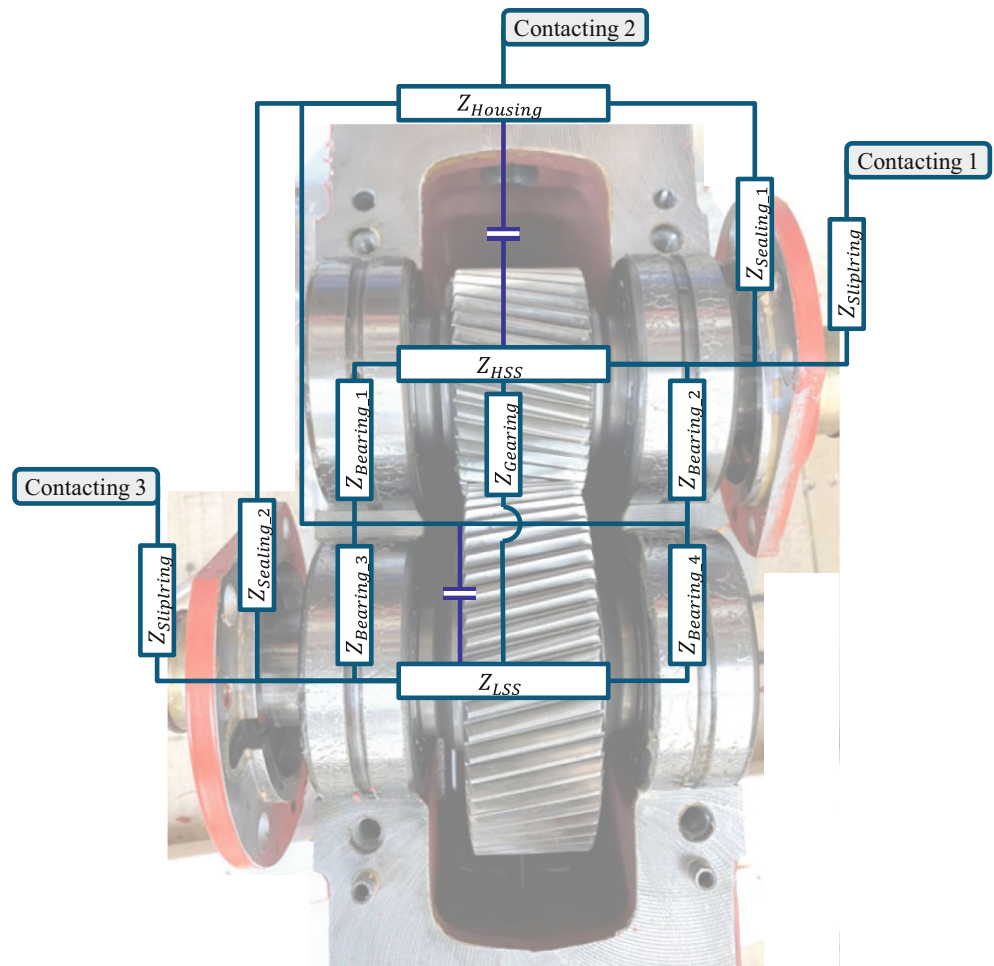
The ongoing digitalization represents a significant challenge for mechanical engineering. In visions of the future, such as Industry 4.0, self-diagnosis, self-correction and self-calibration of technical systems as well as cooperation and communication with the user and other technical systems are key objectives. They can help to optimize the operational time of machines and technical systems, such as industrial gearboxes. Condition monitoring of specific machine elements as one of these key factors can help to reduce unplanned downtimes and increase system reliability. These intelligent systems are intended to complement the conventional mechanical functions of technical systems, but at the same time show a steadily increasing need for reliable and meaningful process and condition information [1, 2].

In addition to the systematic identification and management of uncertainty of currently available process and condition information, the trend is towards sensory solutions for the acquisition of this information with the least possible associated uncertainty. For this purpose, current research suggests the integration of sensory functions in technical systems as close to the process to be monitored as possible, including sensor integration in machine elements or even the sensory utilization of conventional machine elements with as few technical modifications as possible [3]. For example, the monitoring of bearing conditions such as speed, load and damage is of particular importance for condition monitoring in industrial gearboxes. New approaches based on the measurement of electrical impedance are proposed by Schirra et al. for the measurement of rolling bearing load and Martin et al. for the monitoring of damage condition

of rolling bearings [4, 5]. Both use conventional, unmodified rolling bearings and utilize the capacitive properties of the lubrication film between the rolling elements and the raceways to determine bearing load or bearing damage. According to Vorwerk-Handing et al., rolling bearings used in this way for sensing are referred to as sensory utilizable machine elements (SuME) [3].

Figure 1 illustrates a cross-section of an industrial gearbox and the corresponding reduced electrical equivalent circuit. The impedances of the machine elements (shafts, bearings, gearing, sealings and housing) can be seen as blue boxes. These represent a reduced model of the real electrical models (see Sect. 1.1). Furthermore, electrical capacitances between shafts and the housing are drawn in purple, representing so-called parasitic capacitances. These are capacitances in the electrical system that occur unintentionally and can influence the electrical properties to be measured for sensory purposes as mentioned before. In case of the sensory utilization of a rolling bearing in a gearbox it is not always possible to integrate SuME into conventional measurement systems, e.g. via cables. Especially with rotating machine elements, such as rolling bearings, cable connections are reaching their application limits. Instead, parts of the surrounding machine structure can be used as a structure-integrated energy supply and signal path. As proposed by Schirra et al., a defined AC voltage carrier signal can be transferred to the shaft via a slipring [4]. From there, the signal is conducted via the shaft to the rolling bearing under investigation, e.g. bearing 2 and from there through the bearing to the outer ring contact. The electrical impedance of this path is measured and converted either into an equivalent bearing load or an equivalent damage condition. As can

**Fig. 1** Cross-section of an industrial gearbox and the corresponding reduced electrical equivalent circuit



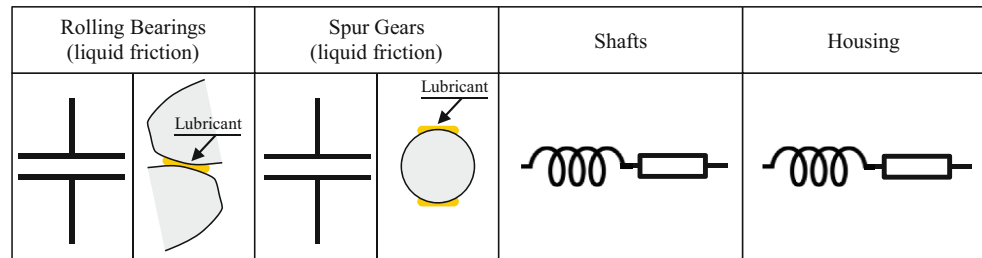
be seen in the described structure-integrated energy supply and signal path, the path contains elements of the gearbox structure, such as the shaft, as well as other elements, such as the slipring or sealings. In addition, electrical effects can occur between components of the gearbox structure, such as capacitive effects between the shaft and the gearbox housing due to the air or oil gaps in between or parasitic currents via other parallel bearings. Due to these effects, the integration and application of SuME with a structure-integrated energy supply and signal path is associated with a high degree of uncertainty. The electrical properties of the technical system, in this case a defined measurement path through a gearbox, must be available in order to reduce the uncertainty in the context of sensor integration and to ensure data quality and reliability.

In the context of this contribution, parasitic capacitances in those structure-integrated energy supply and signal paths in gearboxes are qualitatively analyzed. For this purpose, the gearbox as technical system is systematically evaluated with regard to factors that influence the parasitic capacitances. In the subsequent, these factors are designated as disturbance factors. Subsequently, the influence of the

identified disturbance factors is investigated experimentally within a screening design and their significance is evaluated. The aim of this contribution is to qualitatively identify significant disturbance factors on the parasitic capacitances in structure-integrated energy supply and signal paths, which influence the impedance measurement in the context of SuME, e.g. a rolling bearing.

In Sect. 1.1, relevant fundamentals regarding electrical properties of machine elements and gearboxes as well as measurement approaches for the electrical impedance are provided. Subsequently, in Sect. 1.2, fundamentals of a systematic identification of disturbance factors and the thereby caused uncertainty are presented. Section 2 describes the approach for the identification of disturbance factors, the technical system under consideration, the measurement system used, as well as the design of experiments and evaluation, before Sect. 3 presents the results of the screening designs carried out. The work concludes with a brief discussion of the results in Sect. 4 and an outlook on further research in Sect. 5.

**Fig. 2** Common machine elements and their equivalent electrical components



## 1.1 Electrical properties of machine elements and gearboxes

Design elements in general and machine elements in particular have characteristic electrical properties [6]. Structural components, such as shafts or gearbox housings, tend to have a resistive behavior at low frequencies and an increasingly inductive behavior at high frequencies [7]. Machine elements with separating lubricating films of oil or grease, such as rolling and plain bearings or gears, behave in a first approximation like a capacitor [8–12]. In this way, machine elements can be modeled as an electrical component and represented in an electrical equivalent circuit model. A selection of machine elements and their equivalent electrical components is shown in Fig. 2. These models are simplifications of the real, rather complex electrical behavior of these machine elements, but for the experimental investigations of parasitic currents in gearboxes in this contribution these models are sufficient.

The electrical properties of machine elements depend on various influencing factors, e.g., on the properties of the lubricant, its film thickness and temperature, loads or speeds [8]. These phenomena can be used in a sensory way by measuring the electrical impedance, i.e. the complex resistance, of machine elements in operating condition and deriving the quantities of interest via model-like relations [4].

In the following, a simplified overview of the state of the art and research of the most common machine elements and components of a gearbox are presented from an electrical perspective. Subsequently, the focus is on the electrical properties of a gearbox as an assembly of these elements, as it is experimentally investigated in this work.

### 1.1.1 Structural components (e.g. shaft and gearbox housing)

Structural elements made of metallic materials, such as shafts or gearbox housings, tend to a frequency-dependent behavior under alternating current [7]. In the low frequency range, the resistive effect dominates the total impedance, while the inductive effect dominates in higher frequency ranges. This phenomenon can be explained by the skin ef-

fect, for instance [13]. Figure 2 summarizes the equivalent models of structural components.

A sensory use of these electrical properties without additional components, such as strain gauges, is not known. This can mainly be related to the usually very small changes in the absolute value of impedance and the need for amplification of the measurement signal.

### 1.1.2 Bearings (e.g. rolling elements bearings)

In rolling bearings, the rolling elements and the raceways of the inner and outer ring form an elastohydrodynamic (EHD) contact zone [14]. The electric behavior of an EHD contact depends on numerous factors, such as bearing load, shaft speed, temperature of the bearing and the lubricant [8]. The contact forms an area after the Hertzian theory, depending on the contact geometry [15]. It can be distinguished between single point and line contacts in rolling bearings, depending on the rolling element form [15]. In case of liquid friction, this contact zone between each raceway and rolling element can be modelled as a plate capacitor [8]. For dry friction, the contact zone behaves like an ohmic resistance due to the direct metallic contact between the rolling elements and the raceways [10]. The exact impedance model of the rolling bearing is more complex, so, for example, the edge zone influence has to be considered [5, 7]. For the sake of the experimental investigations addressing parasitic currents in gearboxes in this paper, the simplified models are sufficient to describe the electrical behavior.

Earlier research demonstrated the opportunities of using rolling bearings as sensors. Measuring the bearing impedance can monitor bearing loads, which helps to get information about the operating conditions in the technical system under consideration [4]. It is based on calculating the bearing loads from the EHD contact capacity by using the Hertzian theory to estimate the capacitor area. Since the impedance of a rolling bearing depends on the surfaces of rolling elements and raceways, surface failures influence the bearing impedance. Martin et al. showed the possibilities of surface damage detection of pittings in rolling bearings by using the above-mentioned impedance signal [5].

### 1.1.3 Gears

Analog to rolling bearings, lubricated contacts between gears in a gearbox also follow the Hertzian theory [12, 16]. The tooth contacts form EHD contacts, in this way their electrical behavior can be described as plate capacitors. This results in an electrical impedance under AC voltage that can be measured in the same way as the impedance of rolling bearings. It was found that rolling bearings behave in a constant way at a specific operating point, in contrast, the electrical behavior of gears varies due to different contact conditions along the gear mesh [7]. Because of the related electrical behavior of gears compared to rolling bearings, it is obvious that their impedance also depends on the load, contact speed and temperature.

Furtmann investigated a lubrication film gauging method for gears using direct current and the capacitor-charging characteristics [12]. A further sensory utilization of electrical properties of gears is not known to the authors so far. However, due to the similarities to the sensory utilization of rolling bearings, it can be assumed that there is a potential research gap.

### 1.1.4 Gearbox assembly

In addition to the previously considered and electrically described machine elements, electrical descriptions and modeling of complete gearboxes or drivetrain assemblies are already described in literature [7, 11]. The following descriptions refer to the gearbox shown in Fig. 1. In a gearbox, the individual machine elements are connected in series or in parallel from an electrical point of view, resulting in a significantly more complex electrical equivalent model. An electric drive train model for high frequency application was developed by Furtmann et al., which focuses on calculating damaging EDM currents for EHL contact components [11]. The machine elements were modelled as capacitances in serial and parallel connection. In this context, it was shown that parasitic currents occur depending on the operation conditions. Parasitic currents can be transmitted through galvanic couplings. These can be observed if two or more electric circuits share the same impedance, e.g. the shaft circuits and gearbox housing are connected over the sealing and bearing impedance in Fig. 1. The electric signals of one of these circuits influence the signals of the other circuit as a disturbing factor [17]. If parasitic currents are transmitted over two components with a potential difference, capacitive couplings are a result, which are shown as capacitance in Fig. 1 [17]. This and further previously unobserved effects can occur as a result of interactions between two or more machine elements. Figure 1 shows the electrical equivalent circuit model of the gearbox used in this work.

In research on electrical properties of machine elements, the machine elements under consideration are primarily investigated in detached test environments with as few occurring disturbing factors as possible. While this is reasonable in an experimental setting, it is not feasible in practical applications. As mentioned before, electrical interactions occur between the machine elements in a gearbox and previously unnoticed effects can have a significant effect. This includes, e.g., parasitic capacitances between machine elements or ambiguous current paths.

At this point, the state of research still shows some unexplored gaps regarding the integration of various individual machine elements into one gearbox assembly. Since no systematic identification of disturbance factors on the electrical behavior of a gearbox has been carried out so far, there is still a lack of knowledge about which factors can significantly effect the electrical behavior of a gearbox.

## 1.2 Systematic identification of disturbance factors and uncertainty

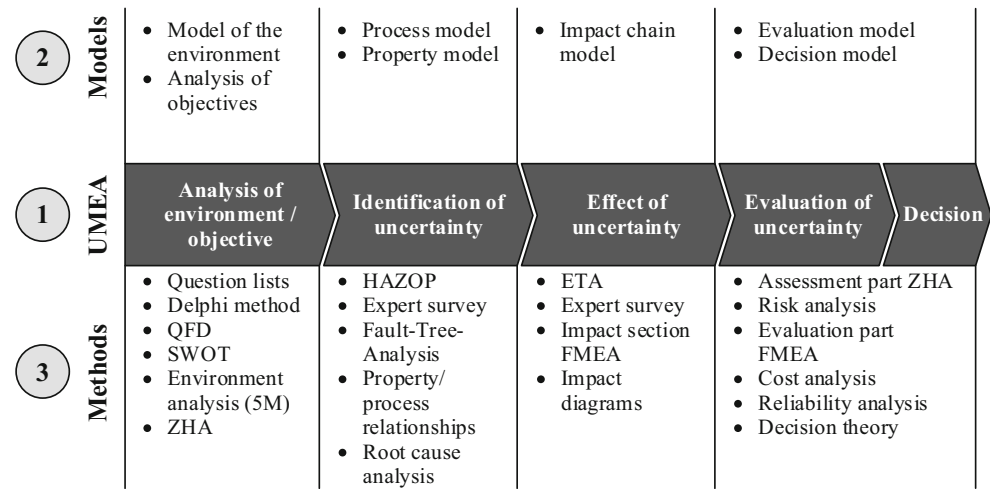
Disturbance factors—in literature also referred to as disturbance variables or noise factors—are any uncontrollable factor, unintended input of a technical system, respectively, that results in a deviation of the system's behavior from its intended function [18–20]. This is why their consideration in the product development process is crucial in order to ensure the latter success of a system to be developed, as stated by Pahl et al. [19]. Disturbance factors can e.g. be a heat transfer into or from the system, humidity or vibrations. Based on the origin of the disturbance factor, a basic distinction can be made between external disturbance factors—originating from outside the system boundary—and internal disturbance factors—originating within the system boundary, e.g. in the form of secondary variables of a subsystem [18, 21].

However, disturbance factors do not directly influence the function of a system [22, 23]. Instead, disturbance factors cause function variables and design parameters utilized for the fulfillment of the system's function to vary, leading to so-called model and data uncertainty and resulting in a variation of the system's output [23–25]. Uncertainty is defined in this context, according to ISO Guide 73, as “the state, even partial, of deficiency of information, related to, understanding or knowledge of, an event, its consequence, or likelihood.” [26]. In general, uncertainty results in a deviation of objectives from their expectations and thus leads to a risk. In turn, a risk is critical if it results in a failure and ultimately a hazard [26].

In order to identify, analyze and evaluate uncertainty regarding its criticality for the functionality of technical systems, a methodical framework, the Uncertainty-Mode-and-Effects Analysis (UMEA) was developed [27]. Although



**Fig. 3** Uncertainty Mode and Effects Analysis (UMEA)—Structure, models and methods [29 translated from 30]



the UMEA was initially developed for the analysis of uncertainty in load-carrying mechanical systems, Welzbacher et al. have shown that it can also be applied to SuME [28]. The fundamental structure of the UMEA as well as the methods and models assigned to each step are shown in Fig. 3. The individual steps are briefly described in the following.

In the first step of the UMEA-framework, an analysis of the systems environment and the objectives of the system is conducted in which the system is delimited against its environment by means of a system boundary. Furthermore, interfaces to surrounding systems are defined and their influences on the considered system are analyzed. The identification of disturbance factors—internal as well as external—is subject of this step in the UMEA-framework. Typically, the quality of the results of the identification process is depending on the knowledge and experience of the developer. However, in order to decouple the quality of the results from the experience and knowledge of the developer as well as ensuring a systematic manner and thus the completeness of the identification process, checklists can be applied. An example for such a tool is the disturbance factor control list by Welzbacher et al., which is based on the fundamentals of multipole-based modeling theory [22]. In the next step, occurring uncertainty and its causes are identified, e.g. by means of the multipole-based effect catalog by Vorwerk-Handing [31]. Therefore, system models are required in order to be able to identify included uncertainty, i.e. in terms of model and data uncertainty caused by disturbance factors, and describe its influence with sufficient accuracy. In the subsequent steps, the effects of the previously identified uncertainty on the systems output is determined and subsequently evaluated regarding its criticality, e.g. by means of a modified FMEA as proposed by Vorwerk-Handing et al. or Welzbacher et al. [25, 28]. Based on the results of the evaluation, a reasoned decision can finally be made whether an uncertainty and thus the causing

disturbance factor(s) must be managed in order to ensure the systems functionality or not [27, 30].

## 2 Materials and methods

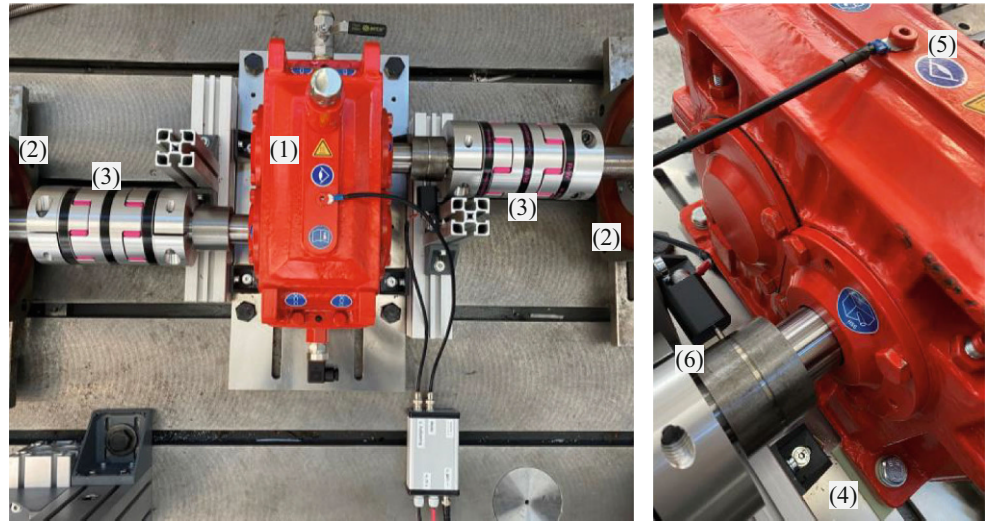
In the following, the materials and methods used in this work are briefly described. The materials include the experimental setup consisting of an industrial gearbox and the measurement system used. The methods include the approach used for the systematic identification of disturbance factors, the design of experiments and the evaluation of measurement data.

### 2.1 Industrial gearbox

The experimental investigations are carried out on a single-stage industrial gearbox (1) of type M1PSF10 from SEW-EURODRIVE as shown in Fig. 4. The gearbox is speed- and torque-loaded by two identical 30kW asynchronous servomotors (2). Speed and torque monitoring and control is performed by system integrated sensors. The electrical insulation of the gearbox from the electrical machines and the environment is achieved by using two electrically insulated elastic claw couplings (3) and an insulation towards the machine bed (4). The gearbox is electrically connected to the measurement system by shielded cables at the housing (5) and with a slip ring (6) on one of the two shafts. In this way, two measurement paths—from the high-speed shaft (HSS) as well as from the low-speed shaft (LSS) to the housing—can be realized.

In order to be able to specifically investigate parasitic capacitances without measuring the bearing capacitances, the bearings are replaced by type 6308 hybrid bearings with ceramic rolling elements and a plastic cage. In this way, parasitic current flow through the bearings can be avoided.

**Fig. 4** Test rig for the electrical characterization of an industrial gearbox



The above-mentioned gearbox can electrically be modeled as an electrical equivalent circuit as described in Sect. 1.1 and shown in Fig. 1. The electrical components are shown simplified as impedances. Additional capacitances are drawn in purple between nearby machine elements that are separated only by an air gap or lubrication film. These are referred to as parasitic capacitances in this work, since they can potentially influence the measurement of a desired impedance, such as the bearing capacitances when using a rolling bearing as a SuME. In addition to these parasitic capacitances, which have not yet been investigated in this way in literature, other interfering electrical effects can occur which are not considered in Fig. 1.

## 2.2 Disturbance factor identification

In order to analyze parasitic capacitances and thus uncertainty in the structure-integrated energy supply and signal path of an industrial gearbox, the UMEA-framework by Engelhardt et al. is used [27]. For the identification of disturbance factors influencing parasitic capacitances, the system is first delimited against its environment by defining a system boundary. Based on the defined system boundary, a clear distinction can be made regarding the origin of occurring disturbance factors and thus their classification into external and internal disturbance factors. Following the definition of the system boundary, the industrial gearbox is decomposed into its different subsystems, shown in Fig. 1. This enables the identification and analysis of potential interactions of the different components and subsystems in terms of internal disturbance factors.

In the first step of the disturbance factor identification, the environment of the considered system is analyzed in a team of six researchers regarding therefrom originating external disturbance factors. Therefore, the disturbance factor control list by Welzbacher et al. is used as a guideline in

order to ensure the systematic nature of the analysis [22]. In this context, each disturbance factor listed in the control list is discussed and evaluated in the team regarding their probability of occurrence. In the subsequent identification step, the previously defined subsystems and components are analyzed regarding therefrom originating internal disturbance factors. This includes, e.g., the consideration of secondary variables emitted during function fulfillment of the different subsystems, such as heat radiation, vibrations or emitted foreign matter, such as particles due to wear of a friction pairing. For this purpose, the disturbance factor control list by Welzbacher et al. is also used [22]. Similar to the analysis of external disturbance factors, the identified internal disturbance factors are discussed and evaluated in the team. An excerpt of the results of the identification process is shown in Fig. 5. It must be noted that for better readability of the excerpt, disturbance factors that originate from outside but also from the inside of the industrial gearbox are summarized in one entry.

In the subsequent step of the UMEA-framework, the model and data uncertainty caused by the identified disturbance factors would now be determined systematically, e.g., by means of the multipole-based effect catalog by Vorwerk-Handing [31]. However, since there is not yet an electrical model of the gearbox that quantitatively describes the parasitic capacitances, a factor screening is conducted in order to investigate and thus determine the influence of the identified disturbance factors. The measurement system used for this factor screening is described in the following subsections.

## 2.3 Measurement system

The measurement system used in this work for the determination of the parasitic capacitances of a defined structure-integrated energy supply and signal path in the gearbox is

		Disturbance factor	Pictogram	Occurrence
Mechanics	Translatory and rotatory momentum	Normal force		☒
		Shear force		☒
		Bending moment		☒
		Change in angular acceleration		☒
...	...	...	...	...
Thermodynamics	Heat transfer	Heat conduction		☒
		Heat convection		☒
		Heat radiation		☒
...	...	...	...	...

Fig. 5 Excerpt of the filled in disturbance factor control list [22]

based on the principle of a measuring bridge which, in contrast to the Wheatstone Bridge [32], is operated with AC voltage. The measurement system and its equivalent circuit is displayed in Fig. 6. Three known reference impedance  $Z_1$ ,  $Z_2$  and  $Z_3$  are used to calculate the unknown impedance  $Z_{DUT}$  from the measured generator voltage  $U_G$  and the bridge voltage  $U_M$ . The algorithms for calculating the missing impedance  $Z_{DUT}$  using the known reference impedance are explained in Sect. 2.5.

Based on literature, primarily capacitive effects are expected in the gearbox, which are caused by rolling bearings and the gearing due to their EHD contacts. Resistive and inductive effects may have a small influence as well. To determine these unknown parasitic capacitances, capacitors are used as comparison elements in the reference impedance  $Z_1$ ,  $Z_2$  and  $Z_3$  in the measuring bridge [32]. A sinusoidal AC voltage with a frequency of 20 kHz and an amplitude of 5 V is applied as the carrier signal. The parameters were calculated based on the hypotheses of Mütze to minimize the risk

of harmful bearing currents [33]. The capacitances and resistances of the three reference impedances  $Z_1$ ,  $Z_2$  and  $Z_3$  are measured beforehand for the frequency of the carrier signal and considered in the associated evaluation algorithm in Sect. 2.5. The fourth and unknown capacitance of the measurement circuit  $Z_{DUT}$  is the structure-integrated energy supply and signal path through the gearbox under investigation, subsequently referred to as device under test (DUT). Figure 6 shows the equivalent circuit of the measurement system on the right and the real measurement system with its components on the left.

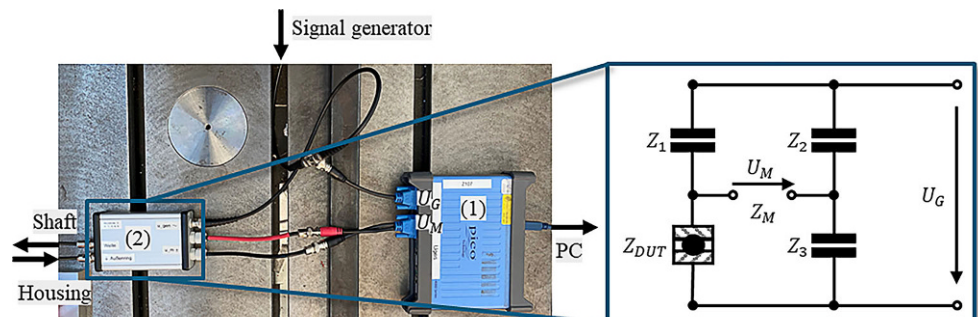
The previously presented measurement bridge (2) is supplemented by additional components. The voltages occurring in the measurement bridge are recorded using a PicoScope 4444 PC oscilloscope (1) and transmitted to a PC via USB. The necessary carrier signal in defined form, frequency and amplitude is provided by a signal generator of type Rigol DG1022. All electrical lines are realized as coaxial cables to reduce interference.

## 2.4 Design of experiments

In order to analyze the preidentified disturbance factors regarding their actual effects and to evaluate their significance, a screening design from design of experiments is conducted. With this screening design, it is possible to evaluate the significance of occurring disturbance factors as efficiently as possible. For this purpose, the disturbance factors to be examined are varied on three factor levels and the corresponding effects are evaluated. Further information on design of experiments and screening designs can be found, e.g., in [34].

Two measurement paths are investigated in this contribution: HSS to housing and LSS to housing. This is to avoid that measured effects occurred randomly. From the disturbance factor identification results that the torque and the speed are to be examined as factors. For this purpose, the two factors are varied on three levels, which are listed in Table 1. In the full factorial screening design, each factor level combination was run twice from the machine standstill and three measurements were carried out in each cycle at an interval of 60 s. Following the tests, the six individual

Fig. 6 Measurement system of the test rig and its equivalent circuit





**Table 1** Factors and factor levels for the full factorial screening design

Factor	Level “-”	Level “0”	Level “+”
Speed [rpm]	500	1000	1500
Torque [Nm]	50	100	150

measurements for each working factor combination were averaged and used in the evaluation.

**2.5 Evaluation of measurement data**

After recording the measured values and evaluating them, it provides information of the measured impedance including real and imaginary parts, capacitance and phase angle. For this purpose, according to the measurement system described in Fig. 6, the generator voltage  $U_G$  and the measurement bridge voltage  $U_M$  are acquired by an oscilloscope and the desired impedance of the DUT  $Z_{DUT}$  is calculated considering the known reference impedances  $Z_1, Z_2$  and  $Z_3$ . The associated algorithms are implemented in MATLAB. The calculation of the impedance of  $Z_{DUT}$  is based on the following Eq. 1, where  $Z_M$  denotes the impedance of the measuring device:

$$Z_{DUT} = Z_1 \frac{Z_3 Z_M + [(Z_2 + Z_3) Z_M + Z_2 Z_3] \frac{U_M}{U_G}}{Z_2 Z_M - [(Z_2 + Z_3) (Z_M + Z_1) + 1] \frac{U_M}{U_G}} \quad (1)$$

The ANOVA method is used for the statistical analysis of the measured data. The larger the  $F$ -value becomes, the less likely is an occurrence of random effects. To make this more precise, the  $p$ -value is calculated, which represents the probability of the occurrence of a random high  $F$ -value. So,  $p$ -values that tend towards zero indicate that the factor or factor combination under investigation has a significant effect. Further information about the ANOVA method can be found in [34].

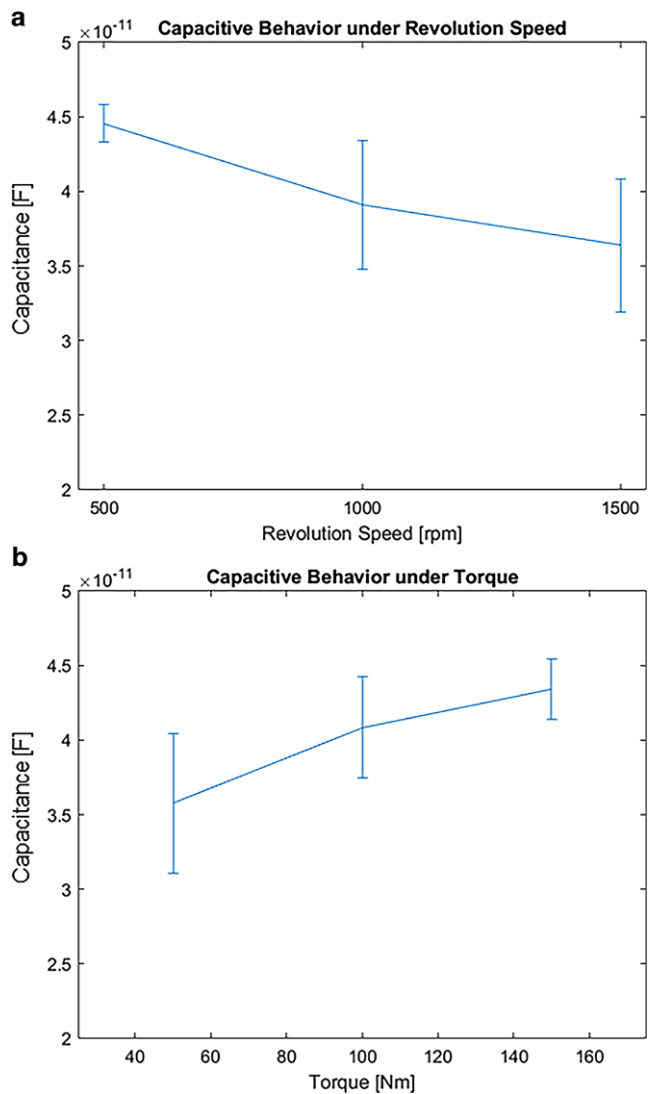
**3 Results**

In this section the results of the experimental investigations of the gearbox shown in Fig. 1 are presented and described. Two different experimental setups with different electrical contacting points were investigated. In the first setup, cf. Section 3.1, the parasitic capacitance between the HSS (contacting 1) and the housing (contacting 2) is measured. In the second setup, cf. Section 3.2, the parasitic capacitance between the LSS (contacting 3) and housing (contacting 2) is measured. Due to the measurement results, additional measurements regarding the specific influence of torque are conducted and described in Sect. 3.3. The measurement results are shown in the following and described in detail.

**3.1 Experimental setup 1: Measurement path from HSS to housing**

In the first experimental setup, the parasitic capacitance between the HSS and the housing is measured. As shown in Fig. 7, the parasitic capacitance decreases with increasing speed. In contrast, the capacitance increases with increasing torque. The standard deviation of the measured values increases with increasing speed and decreases with increasing torque.

The results of the ANOVA are shown in Table 2. It can be seen, that torque and speed are associated with high  $F$ -values. The values of the single effects are higher than of the two-way interaction between torque and speed. The small  $p$ -values indicate a dependence of the parasitic capacitance on torque and speed and also on their two-way interaction.



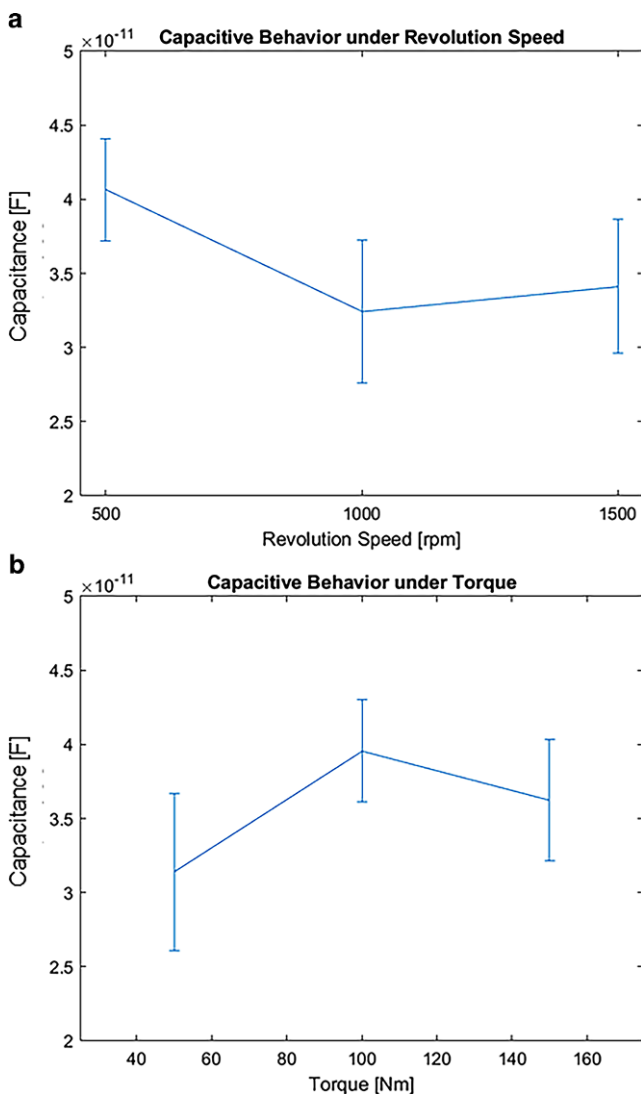
**Fig. 7** Effect of speed (a) and torque (b) on the parasitic capacitances using the measurement path HSS to housing

**Table 2** F- and p-values of the effects on the parasitic capacitances using the measurement path HSS to housing

Factor	F-value	p-value
Torque ( $T$ )	51.84	2.10e-12
Speed ( $n$ )	59.47	2.32e-13
$T$ and $n$	12.10	9.30e-07

### 3.2 Experimental setup 2: Measurement path from LSS to housing

In the second experimental setup, the parasitic capacitance between the LSS and the housing is measured. As shown in Fig. 8, the parasitic capacitance decreases with increasing speed and increases with increasing torque. The standard deviation of the measured values in this experimental setup is relatively constant at a higher level than in experimental

**Fig. 8** Effect of speed (a) and torque (b) on the parasitic capacitances using the measurement path LSS to housing**Table 3** F- and p-values of the effects on the parasitic capacitances using the measurement path LSS to housing

Factor	F-value	p-value
Torque ( $T$ )	25.80	~0.00
Speed ( $n$ )	28.81	~0.00
$T$ and $n$	2.97	0.03

**Table 4** Factors and factor levels for the third experimental setup

Factor	Level “-”	Level “0”	Level “+”
Speed [ $rpm$ ]	500	1000	1500
Torque [ $Nm$ ]	[50; 60; 70; 80; 90; 100; 110; 120; 130; 140; 150]		

setup 1 and independent of speed and torque. However, the curves indicate a slight bend in the middle at 1000rpm and 100Nm respectively, which is not present in the first experimental setup.

The results of the ANOVA are shown in Table 3. It can be seen, that torque and speed are associated with high  $F$ -values. The values of the single effects are higher than of the two-way interaction between torque and speed. The small  $p$ -values indicate a dependence of the parasitic capacitance on torque and speed and also on their two-way interaction as in experimental setup 1.

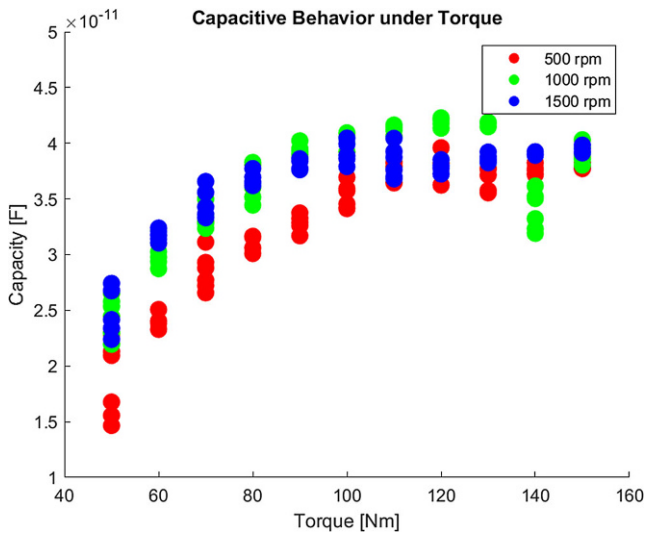
Due to the relatively high standard deviation of the measured values for the torque dependence, the experimental setups could lead to wrong conclusions. For this reason, it was decided to analyze the torque dependence in more detail in a third experimental setup.

### 3.3 Experimental setup 3: Detailed influence of torque

In the third experimental setup, the detailed torque dependence is investigated. For this purpose, operating points between 50Nm and 150Nm are approached at intervals of 10Nm on the three speed levels. The factor steps are shown in Table 4.

As shown in Fig. 9, the parasitic capacitance increases with increasing torque. The three speed levels, shown in color in Fig. 9, are accompanied by a constant parallel shift of the measured values of the parasitic capacitance. The standard deviations of the individual measuring points are partly smaller than the distance to a new speed level.

The amplitude spectrum investigation do not show any significant frequencies. Neither the rotary frequencies of the shafts, the gear mesh frequencies nor the characteristic bearing frequencies can be identified in this analysis. This means that the torque and revolution speed correlation are not in a relation to the frequencies of the rotary machinery.



**Fig. 9** Parasitic capacitances using the measurement path HSS to housing with constant 1000 rpm and different torque levels

## 4 Discussion

The tests clearly indicate that the parasitic capacitances in the gearbox are both speed- and torque-dependent. Since no geometric distances between structural elements such as shafts or housings change, these influences can most likely only be attributed to dynamic machine elements. In addition to bearings, these also include the gearing and seals.

The seals could be responsible for a speed-dependent behavior, but not for a torque-dependency, since they do not transmit any loads. There is the possibility that shaft deformations based on a higher torque can influence the gap between shaft and sealing, which can influence their electric behavior. Further investigations regarding the electrical properties of seals should be pursued in future research.

Since the hybrid bearings in the experimental setups were designed with non-conductive ceramic rolling elements, these should have no influence on the measured capacitances in the gear unit. However, since the components cannot be clearly measured individually—i.e. the capacitance of the gearbox without bearings and the capacitance of the hybrid bearings only—measurable effects could still occur here.

Furthermore, an electrical path across the gearing can also have a significant impact on the parasitic capacitance in a gearbox. For this, the electrical properties of the gearing should be further investigated in future research. Frequency analyses of the capacitance curves recorded in these experiments are also conceivable. In this way significant frequencies could be identified, e.g., which are derived from the shaft speeds or the gearing.

As known from the literature, capacitive elements always show a frequency-dependent behavior. Due to the available

measurement system, the described experiments were only carried out with a constant carrier frequency of 20 kHz. It therefore makes sense to investigate the frequency-dependence in more detail using frequency sweeps.

Furthermore, the chosen systematic approach for the identification of disturbance factors showed deficits. It was sometimes difficult for the participants in the workshop on the identification of disturbance factors to decide which disturbance factors can occur in the system under consideration and which cannot, if the technical expertise was lacking. It was not always clear which items on the checklist should be checked off and which should not. For example: does radioactive radiation occur at the test setup or not? The checklist seemed very detailed and particularly overloaded. During the subsequent selection of the disturbance factors to be investigated, it quickly became apparent that some factors cannot be simply investigated within the framework of screening designs. In these cases, more complex experimental setups would be necessary.

## 5 Conclusion

In this paper, the parasitic capacitances in an industrial gearbox were investigated. At first, potential disturbance factors have been identified in a workshop and their influence has been rated. During the workshop, deficits in the systematic approach could be seen.

Torque and speed as adjustable factors build the basis for a full-factorial screening design. The measurement was done at constant carrier signal frequency and voltage amplitude. The analysis of variances shows a correlation between the parasitic capacitances, torque and speed. A linkage of the parasitic capacitances to the characteristic frequencies could not be shown.

For further research, it is necessary to identify the reason of the behavior of the parasitic capacitances. This includes electric investigations sealings and electrical connectors, but also the influence of the gear mesh itself by a measuring from shaft to shaft. As shown in earlier research, the frequencies of the carrier signal have an effect on the electric behavior of different machine elements and structural components like bearings, shafts and housing, which has not been considered for assembled transmission parts yet.

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