

Differential Torque Measurement Concept for Condition Monitoring of a Cycloidal Gearbox in a Flight Control Actuator

M. Schmidt¹

¹DLR, Institute of Flight Systems, Lilienthalplatz 7, 38108 Braunschweig, Germany

Abstract

Electromechanical actuators for primary flight control require reliable monitoring of transmission-related loads because the gearbox is a critical subsystem with wear-prone components and potential single-point failures. This paper presents a differential torque measurement concept for a Sumitomo cycloidal gearbox used in a flight control actuator. The approach is based on the simultaneous measurement of torque and rotational speed at the gearbox input and output in order to derive load-dependent loss characteristics and operating signatures of the drivetrain. For this purpose, a compact contactless torque measurement shaft was integrated between the motor and gearbox, while complementary sensor systems were used to acquire torque and position data at both measurement locations. The paper focuses on the measurement architecture, sensor integration, and experimental implementation on an EMA test bench. In addition, the acquired measurement data were combined with model-based fault models and simulation data to perform an initial condition-monitoring-oriented evaluation. Time- and frequency-domain analyses, including FFT and order tracking, were used to assess the sensitivity of the measured quantities to fault-related effects such as increased friction and backlash variation. The results indicate that the proposed measurement concept provides physically meaningful features for distinguishing relevant gearbox fault patterns and forms a promising basis for further condition-monitoring investigations of cycloidal gearboxes.

Keywords: condition monitoring, cycloidal gearbox, differential torque measurement, electromechanical actuator, anomaly detection

1. Introduction

Electromechanical actuators are a key enabling technology for More Electric Aircraft concepts because they can replace conventional hydraulic actuation systems and thereby support weight reduction, improved efficiency, and simplified system integration [1]. In primary flight control applications, however, electromechanical actuators (EMAs) must also satisfy stringent requirements regarding reliability, fault detection, and maintainability, which has increased interest in prognostic and health management methods for safety-critical aerospace systems [2, 11, 13].

Within an EMA, the transmission is a particularly critical subsystem containing several wear-prone mechanical components and strongly influences the mechanical power flow of the actuator [2, 3]. For cycloidal gearboxes, this is especially relevant because their compact, low-backlash design and complex internal kinematics lead to characteristic dynamic load behavior that is difficult to observe using only conventional monitoring approaches alone [4, 5]. Reliable

access to torque- and speed-related quantities at the gearbox input and output is therefore an important prerequisite for understanding drivetrain losses, identifying abnormal operating behavior, and deriving physically interpretable health indicators [8, 9].

Against this background, the present work focuses primarily on the measurement system itself. It presents a differential torque measurement concept for a cycloidal gearbox in a flight control actuator, including sensor selection, mechanical integration, signal acquisition, and implementation on an EMA test bench. Chapter 2 introduces the differential measurement concept, and Chapter 3 describes its implementation on the EMA test bench. Chapter 4 presents the fault modelling and data basis, and Chapter 5 provides an exemplary feature analysis. In this way, the work demonstrates that the proposed measurement concept not only enables detailed observation of drivetrain behavior, but also provides a suitable experimental basis for fault-sensitive monitoring investigations of cycloidal gearboxes [2,3]. Chapters 6 and 7 discuss the

results and conclude with an outlook on future work.

2. Measurement concept

The proposed measurement concept aims to describe the mechanical behavior of the cycloidal gearbox by comparing the drivetrain state at the gearbox input and output. The proposed concept describes gearbox behavior by comparing drivetrain states at the gearbox input and output. For this purpose, torque M , angular position θ , angular velocity ω , and mechanical power are considered at both sides of the gearbox. The measured quantities are transformed to a common reference side in order to derive differential quantities that reflect transmission-internal effects more directly than absolute signals alone [2, 5, 9].

The general measurement principle is illustrated in Fig. 3.1 of the experimental setup. The gearbox is treated as a transmission element with an input-side mechanical state (M_1, θ_1, ω_1) and an output-side mechanical state (M_2, θ_2, ω_2). In order to compare both states consistently, the output quantities are referred to the input side by means of the transmission ratio $i = 29$ for the investigated Sumitomo cycloidal gearbox. The first step is the transformation of the measured output quantities to the input-side reference frame. With this, the referenced output quantities are defined as

$$M_{2,ref} = \frac{M_2}{i}, \quad \theta_{2,ref} = i\theta_2, \quad \omega_{2,ref} = i\omega_2 \quad (1)$$

Based on this reference transformation, differential quantities can now be formulated in a compact and physically interpretable way. A first derived quantity is the torque difference

$$\Delta M = M_1 - M_{2,ref} = M_1 - \frac{M_2}{i} \quad (2)$$

which describes deviations in load transfer across the gearbox. This quantity is less influenced by the absolute actuator load level than a single torque signal and emphasizes changes that originate within the transmission itself.

A second quantity is the relative angular deviation

$$\Delta\theta = \theta_1 - \theta_{2,ref} = \theta_1 - i\theta_2 \quad (3)$$

which represents the differential motion between input and output. This term can include elastic deformation, backlash-related effects, and general transmission irregularities. In this way, the position measurement does not only provide kinematic information, but also contributes to a more direct description of the internal mechanical coupling.

The corresponding speed deviation follows as

$$\Delta\omega = \omega_1 - \omega_{2,ref} = \omega_1 - i\omega_2 \quad (4)$$

and extends the differential comparison into the dynamic domain. It is particularly useful for describing transient effects and oscillatory deviations in the motion transfer.

Based on the same reference-side formulation, a differential power quantity can be introduced as

$$P_{Diff} = M_1\omega_1 - M_{2,ref}\omega_{2,ref} \quad (5)$$

which yields

$$P_{Diff} = M_1\omega_1 - \frac{M_2}{i}(i\omega_2) \quad (6)$$

and thus

$$P_{Diff} = M_1\omega_1 - M_2\omega_2 \quad (7)$$

Although the transmission ratio cancels out algebraically in the final expression, the reference transformation remains an important conceptual part of the differential method because it places all compared quantities in one common mechanical frame. The resulting power difference represents the energetic deviation across the gearbox. In stationary operation it is dominated mainly by internal losses, whereas in dynamic operation it may additionally contain elastic and inertial drivetrain effects [7, 8, 9].

Finally, the differential load and motion quantities can also be combined into an equivalent stiffness-related measure,

$$k_{eq} = \frac{\Delta M}{\Delta\theta} \quad (8)$$

provided that $\Delta\theta \neq 0$. This term is not used here as a full physical gearbox model, but as an additional compact descriptor of the mechanical coupling behavior.

Overall, the differential measurement concept is based on the comparison of mechanically related quantities at both sides of the gearbox. Its main advantage is that it shifts the focus from absolute operating levels to transmission-internal effects between the two measurement points. The resulting quantities therefore provide a physically interpretable basis for subsequent feature generation in time and frequency domain, while the concrete sensor implementation is addressed in the following chapter [4].

3. Experimental setup

This chapter describes the practical realization of the differential measurement architecture for the evaluation of the Sumitomo cycloidal gearbox drivetrain. It focuses on the sensor integration at gearbox input and output such that the mechanical quantities M_1 , θ_1 , M_2 , and θ_2 are simultaneously available for evaluation.

The investigated system consists of an electric motor, the cycloidal gearbox, and an output stage connected to an external load machine via a rigid lever-based kinematic chain. In this setup, the load machine is used to apply reproducible output loads and operating conditions, while the main contribution lies in the sensor integration inside and directly around the actuator drivetrain.

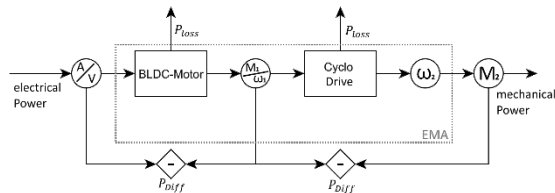


Fig. 3.1: Schematic overview of the measurement concept and sensor positions

The measurement architecture is based on the concept introduced in the previous chapter. On the input side, the transmitted torque M_1 is measured by a compact contactless torque measurement shaft integrated between motor and gearbox, while the input angle θ_1 is provided by a resolver. On the output side, the load torque M_2 is measured by an external torque flange installed between actuator output and load machine, and the output angle θ_2 is acquired by an encoder. Angular velocities ω_1 and ω_2 are not measured directly but derived from the respective position signals. Together, these four measured quantities provide the complete experimental basis for computing the differential variables ΔM , $\Delta \theta$, $\Delta \omega$ and P_{Diff} as defined in Chapter 2.

The core element of the setup is the input-side torque measurement shaft from MANNER, a compact custom design combining a strain-gauge sensing element with an integrated contactless telemetry system. The shaft has a torque range of 0.1 kNm and a measurement bandwidth of up to 1 kHz . The output-side torque flange covers load levels up to 1 kNm and thus characterizes the full mechanical load at the actuator output. Both sensors are connected to dedicated signal conditioning units for amplification and preprocessing before the signals are passed to the central acquisition system.

The mechanical integration of the torque measurement shaft required modifications to the original actuator. In the original design, the extended motor shaft is connected to the gearbox input via a spline connection. The same spline geometry was transferred to the custom measurement shaft, which was inserted between motor shaft and gearbox input. The required additional axial space was created by

an intermediate flange between motor and gearbox housing. This flange also carries the stationary pickup for contactless signal transmission and provides cable routing to the outside of the actuator. To minimize the axial extension, the measurement shaft was realized as a compact custom design with integrated antenna and minimal shaft length.

All signals were acquired by a dSPACE system, which also handles test bench control and regulation. Torque signals were recorded at 1 kHz , providing a common temporal basis for the differential evaluation. Using a single acquisition platform ensures consistent time alignment between input- and output-side measurements, which is essential for physically meaningful differential quantities.

The experiments were conducted under dynamic conditions derived from representative primary rotor blade control trajectories of a helicopter flight-control application. The reference trajectories are approximately sinusoidal with two higher-harmonic components, covering excitation frequencies between roughly 1 Hz and 6 Hz and output amplitudes up to 10° . These conditions excite relevant drivetrain dynamics while remaining sufficiently structured for systematic signal analysis and comparison in the time and frequency domain [2, 3].

4. Fault modelling and data basis

To provide a basis for the condition-monitoring-oriented evaluation, the failure modes relevant to the investigated Sumitomo cycloidal gearbox were identified and modelled analytically. Rather than deriving features directly from experimental fault states, the present approach uses a physics-based actuator model to generate fault-affected signal data and compares these data with nominal measurements from the EMA test bench.

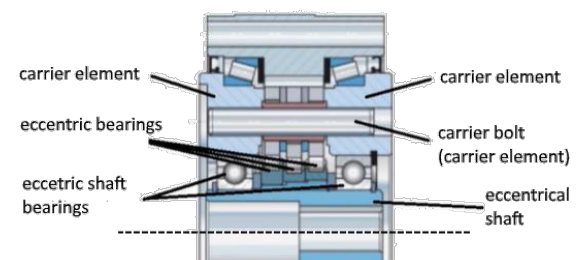


Fig. 4.1: Relevant components of the investigated cycloidal gearbox.

Figure 4.1 shows the main gearbox components relevant to the subsequent fault analysis, including the eccentric shaft, the associated bearings, the carrier elements, and the carrier bolt. This component-level view

provides the structural basis for identifying the considered fault mechanisms.

The failure modes considered in this work are based on a systematic analysis of critical damage mechanisms in EMA transmissions [3, 13]. The cycloidal gearbox contains several wear-prone components whose degradation can produce characteristic changes in the mechanical quantities accessible through the differential measurement concept.

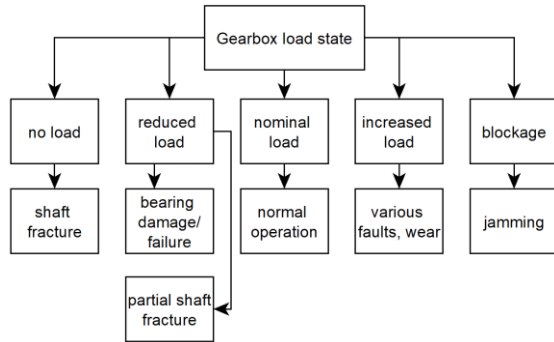


Fig. 4.2: Classification of gearbox load states and exemplary associated failure cases.

As illustrated in Fig. 4.2, the spectrum of possible load-path deviations ranges from a fully open load path to complete blocking of the drivetrain through bearing jamming. Between these extremes, progressive damage mechanisms produce more gradual changes in transmission behavior that are of particular interest for condition monitoring.

Tab. 4.1: Overview of considered failure modes, including component, fault class, and description

Component	Failure	Description
Rolling bearing / tribological contact	Increased friction	Additional resistive torque caused by wear, degradation, or increased contact friction
Transmission kinematic coupling	Increased backlash	Enlargement of the angular dead zone in the drivetrain
Carrier bolt	Carrier bolt wear or deformation	Local wear or deformation at carrier bolt in contact with the cycloidal discs

The three fault classes addressed in this work are summarized in Tab. 4.1. Particular focus is placed on carrier bolt wear or deformation, since the carrier bolt is a primary wear location in this gearbox type [1]. This failure mode is expected to manifest as increased internal friction and increased backlash, both of which produce observable changes in the differential

quantities ΔM , $\Delta\theta$, and P_{Diff} defined in Chapter 2. Increased friction more broadly captures degradation of rolling bearings and lubrication-related effects, while backlash changes mainly affect the position-domain differential quantity $\Delta\theta$ and the equivalent stiffness descriptor k_{eq} introduced in Eq. (8).

The fault modelling is based on an existing physics-based actuator model extended with parametric fault representations. The model describes the mechanical state of the drivetrain and captures the relevant input–output quantities M_1 , θ_1 , M_2 , and θ_2 as functions of the applied load trajectory and internal model parameters. Increased friction is introduced into the model as an additional resistive torque term acting on the input side of the gearbox. The friction torque is described by a combined Coulomb and viscous model

$$M_f(\omega_1) = \text{sign}(\omega_1) (k_v |\omega_1| + M_c) \quad (9)$$

where k_v denotes the viscous friction coefficient and M_c the Coulomb friction offset. Under nominal conditions, both parameters are set to zero. For the fault case FM 211, the Coulomb offset is increased to a small positive value representing the additional resistive torque caused by carrier bolt wear. This additional torque directly increases M_1 at the input while leaving M_2 largely unchanged for the same output load, thereby increasing the torque difference ΔM and the differential power P_{Diff} . Backlash is introduced as a dead zone element in the kinematic coupling between input and output, as illustrated in Fig. 4.3. Under the fault condition, this dead zone is widened parametrically, which produces a loss of mechanical coupling in the $\Delta\theta$ signal during direction reversals and is directly visible in the equivalent stiffness measure k_{eq} .

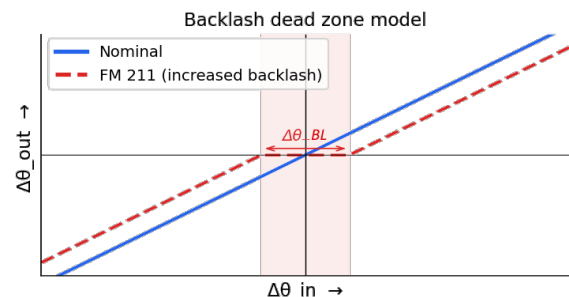


Fig. 4.3: Qualitative backlash dead zone characteristic of the gearbox model

The simulation data generated with the fault model cover the same dynamic operating conditions used during experimental measurements on the EMA test bench, as described in Chapter 3. The trajectories are approximately sinusoidal with higher-harmonic content at excitation frequencies between

roughly 1 Hz and 6 Hz, consistent across simulation and experiment. This allows direct comparison of differential signal characteristics between the nominal simulation, the fault-injected simulation, and the measured test bench data.

The available experimental data comprise a set of representative measurements under nominal operating conditions at different trajectory amplitudes and load levels. These data are intended to serve as a reference baseline for future validation of the model behavior against measured drivetrain signatures. The exemplary evaluation in Chapter 5 is entirely based on simulated signals, comparing nominal simulation output against fault-injected simulation data for the selected fault case, with the purpose of illustrating the proposed condition monitoring approach [2,3].

5. Exemplary feature analysis

Based on the differential quantities introduced in Chapter 2 and the fault modelling described in Chapter 4, an exemplary feature analysis was performed to illustrate how fault-related effects can be extracted from the simulated signals [2,3,6]. The purpose of this chapter is to demonstrate a compact and practical evaluation workflow that links the differential measurement concept to simple fault-sensitive signal characteristics.

As a representative example, the fault case carrier bolt wear or deformation is considered in the following. This fault is particularly suitable because it combines two effects that are relevant for the proposed method, namely increased internal friction and increased backlash. Both effects are expected to influence the dynamic load transfer of the gearbox and should therefore become visible in the differential quantities [1,5].

For the present study, the analysis is performed on short, synchronized observation windows of the simulated trajectories. This keeps the procedure transparent and allows a direct comparison between nominal and fault-affected operation [2,3].

A compact first representation is obtained in the time domain by evaluating the differential power derived in Eq. 7. Since this quantity directly describes the energetic deviation across the gearbox, it combines the information contained in torque and speed into a single physically interpretable signal [4]. A visual comparison of the nominal and fault-affected cases already indicates whether the fault leads to a changed loss level or to increased dynamic irregularities.

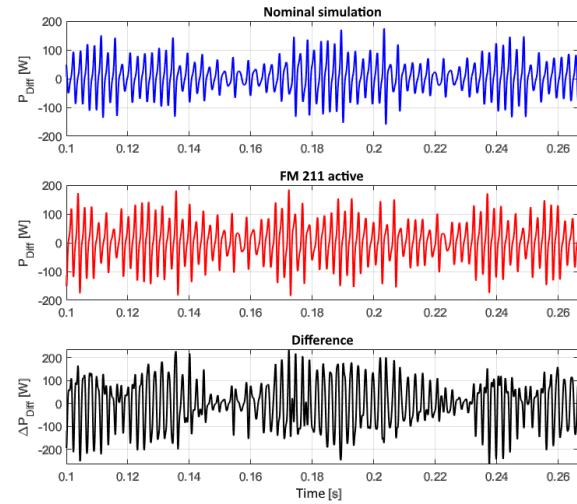


Fig. 5.1: Time-domain comparison of the differential power P_{Diff} for nominal operation and the simulated fault case carrier bolt wear or deformation.

For a simple quantitative description, basic statistical features can be extracted from each observation window. Suitable examples are the mean value, the root-mean-square value, and the peak-to-peak value of P_{Diff} [2,3]. In the considered fault case, an increase in the mean value can indicate additional dissipative losses, while an increase in the peak-to-peak value can point to stronger dynamic variations caused by the altered transmission behavior.

To complement the time-domain view, the same windows can be transformed into the frequency domain by applying a fast Fourier transform to P_{Diff} [2,3,5].

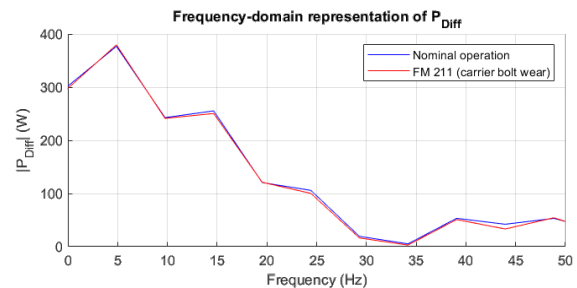


Fig. 5.2: Frequency-domain representation of the differential power P_{Diff}

As shown in Fig. 5.2, the FFT-based representation reveals that the overall spectral shape of nominal operation and the fault-affected case remain largely similar, with no clearly dominant new frequency components appearing under the fault condition. This indicates that the fault-related effect of carrier bolt wear or deformation does not produce a strong isolated spectral signature in the fixed-frequency domain under the investigated operating conditions.

A more sensitive representation is obtained by means of order tracking [2,3,10]. In contrast to the FFT, order tracking relates the spectral content to the instantaneous rotational speed and thereby compensates for speed variations in the trajectory. As shown in Fig. 5.3, this representation reveals a clearly elevated spectral content across multiple orders in the fault-affected case compared to nominal operation, which is not visible in the fixed-frequency FFT. This demonstrates that the fault-related changes in P_{Diff} are more effectively captured in the rotational-reference domain, and that order tracking provides a more discriminative basis for condition-monitoring-oriented feature extraction under dynamic operating conditions [3, 5, 10].

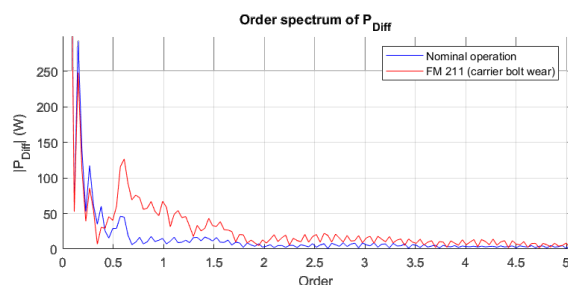


Fig. 5.3: Order spectrum of the differential power P_{Diff}

The three representations shown here, namely time signal, FFT, and order spectrum, provide an initial basis for illustrating the proposed workflow. They show how the differential measurement concept can be transferred into simple and physically motivated features that are suitable for distinguishing fault-related behavior [2,3,6]. A neural-network-based classification could be used in a subsequent step to extend the present feature analysis and potentially improve the separation of fault-related operating states based on the differential signal representations [2,3,6].

6. Discussion of the Results

The results presented in the previous chapters show that the proposed measurement concept provides meaningful access to gearbox-related behavior that cannot be obtained from a single measurement location alone. By combining torque and position information at gearbox input and output, the drivetrain can be evaluated in terms of differential load transfer, relative motion, and energetic deviation across the transmission. This makes internal gearbox effects more directly observable and provides a physically interpretable basis for feature extraction and condition-monitoring-oriented assessment [2, 3, 5].

The exemplary analysis of the simulated fault case carrier bolt wear or deformation indicates that the derived quantities are sensitive to fault-related changes in the gearbox. In particular, the differential power signal provides a compact representation of dissipative losses and dynamic irregularities. Under the investigated conditions, order tracking proved more sensitive than fixed-frequency FFT analysis.

Besides differential power, the other derived quantities also contribute to the interpretation of drivetrain behavior. Differential torque emphasizes deviations in load transfer across the gearbox and is therefore closely linked to changes in internal friction and transmission losses. Differential angle captures relative motion effects between input and output and is therefore particularly relevant for backlash-related behavior, elastic deformation, and local irregularities in the mechanical coupling. In summary, these quantities help to distinguish loss-related effects from backlash-related motion deviations and thereby support the interpretation of gearbox behavior.

A central result of the work is the successful experimental realization of the measurement architecture on the EMA test bench. The integration of the compact contactless torque measurement shaft into the restricted installation space of the actuator, together with synchronized acquisition of input- and output-side quantities, enables the computation of differential variables directly from measured drivetrain states. Compared with approaches that rely on isolated local measurements or purely external load information, this improves the observability of transmission-related effects and extends the experimental basis for gearbox monitoring [4].

The results also underline the benefit of comparing both mechanical interfaces of the gearbox rather than considering absolute quantities at only one side. In the differential representation, the dominance of the overall operating level is reduced and the focus is shifted more strongly toward processes within the gearbox itself. This is particularly useful for cycloidal transmissions, where compact design, low backlash, and complex internal kinematics can make the interpretation of conventional monitoring signals more difficult [2, 3, 5]. Under these conditions, the proposed approach provides a clearer relation between measured quantities and internal effects such as friction increase, altered load transfer, and backlash-related deviations.

The combination of experimental nominal data and model-based fault representation further supports the benefits of the concept. The experimental measurements provide a realistic

reference for drivetrain behavior on the test bench, while the simulation-based fault cases allow expected effects of relevant damage mechanisms to be studied in a controlled manner. In this form, the available data provide a basis for an initial fault-sensitive evaluation of the selected differential quantities and signal representations, while the exemplary feature analysis presented here is based on simulated data [3, 11, 12].

At the same time, some limitations remain in the current state of the study. The fault-related effects discussed here are based on model-based signal variation and the exemplary evaluation of one representative fault case. The present results therefore provide an initial indication of the potential of the proposed differential quantities and signal representations. These considerations provide the basis for the concluding assessment of the proposed measurement concept in the following chapter.

7. Conclusion and outlook

This paper presents a differential torque measurement concept tailored to the condition-monitoring-oriented investigation of a cycloidal gearbox in a flight control actuator. The contribution of the work is not the introduction of differential quantities as a general principle, but their application to this specific drivetrain subsystem, together with the corresponding measurement architecture, sensor integration, and experimental realization on an EMA test bench. In this way, the study provides a practically implemented measurement setup that makes gearbox-related behavior accessible through the comparison of mechanical states at the input and output of the transmission.

The results indicate that the selected differential quantities provide a suitable basis for deriving physically interpretable features from drivetrain measurements. In particular, the differential power quantity P_{Diff} proved to be a compact and informative representation because it combines torque and speed information and reflects energetic deviations across the gearbox. Together with the time- and order-domain representations considered in this work, the presented approach enables an initial fault-sensitive assessment of characteristic effects such as increased friction and backlash-related changes [2, 3, 5]. While a fixed-frequency FFT representation showed limited discriminability for the investigated fault case, order tracking proved effective in revealing fault-related spectral changes under dynamic operating conditions.

A central outcome of the work is the implemented combination of input- and output-side measurement, differential signal representation, and first condition-monitoring-oriented evaluation for the investigated EMA gearbox application. The presented example shows how measurement implementation, physically motivated signal representation, and condition-monitoring-oriented evaluation can be linked at component level. Beyond the investigated gearbox application, the same approach may also be transferred to other drivetrain components, such as the motor or additional transmission stages, provided that suitable measurement access is available.

Future work should focus on a broader validation of the proposed approach using additional measurement data and extended operating conditions. This includes the comparison of model-based and experimentally observed fault signatures, the consideration of further relevant fault cases, and the assessment of robustness under varying loads, trajectories, and boundary conditions. In addition, the differential quantities introduced here can be extended toward further feature generation and more advanced monitoring approaches, including model-based and data-driven methods. Quantities such as differential torque, differential angle, and equivalent stiffness-related measures may provide additional information for this purpose. The limited sensitivity of fixed-frequency spectral analysis further motivates the use of rotation-synchronous signal processing methods for fault-sensitive feature extraction [10]. In this sense, the presented measurement concept provides a suitable experimental basis for future condition-monitoring studies in electromechanical actuator drivetrains [3, 12, 13].

Acknowledgements

This work was carried out within the joint research project smartHUMS within the framework of the German Aviation Research Programme LuFo VI-1 under grant number 20D1918E. The presented paper was prepared in the context of this project

Literature

- [1] G. Qiao, G. Liu, Z. Shi, Y. Wang, S. Ma, and T. C. Lim, "A review of electromechanical actuators for More/All Electric aircraft systems", Proceedings of the Institution of Mechanical Engineers, Part C: *Journal of Mechanical Engineering Science*, vol. 232, no. 22, pp. 4128–4151, 2018, doi: 10.1177/0954406217749869.

- [2] S. Fu and N. P. Avdelidis, "Prognostic and Health Management of Critical Aircraft Systems and Components: An Overview", *Sensors*, vol. 23, no. 19, art. 8124, 2023, doi: 10.3390/s23198124.
- [3] Z. Yin, N. Hu, J. Chen, et al., "A review of fault diagnosis, prognosis and health management for aircraft electromechanical actuators", *IET Electrical Power Applications*, vol. 16, no. 11, pp. 1249–1272, 2022, doi: 10.1049/elp2.12225.
- [4] A. Schütze, N. Helwig, and T. Schneider, "Sensors 4.0 – smart sensors and measurement technology enable Industry 4.0," *Journal of Sensors and Sensor Systems*, vol. 7, pp. 359–371, 2018, doi: 10.5194/jsss-7-359-2018.
- [5] I. Komorska, "Fault Diagnosing of Cycloidal Gear Reducer Using Statistical Features of Wavelet Leader Multifractal Spectra", *Sensors*, vol. 23, no. 3, art. 1645, 2023, doi: 10.3390/s23031645.
- [6] G. Balaban, A. Saxena, P. Bansal, et al., "Prognostic Health-Management System Development for Electromechanical Actuators", *Journal of Aerospace Information Systems*, vol. 12, no. 3, pp. 249–263, 2015, doi: 10.2514/1.1010171.
- [7] K. Michaelis, B.-R. Höhn, and M. Hinterstoißer, "Influence factors on gearbox power loss", *Industrial Lubrication and Tribology*, vol. 63, no. 1, pp. 46–55, 2011, doi: 10.1108/003687911111101830
- [8] C. M. C. G. Fernandes, P. M. T. Marques, R. C. Martins, and J. H. O. Seabra, "Gearbox power loss. Part I: Losses in rolling bearings", *Tribology International*, 2015, doi: 10.1016/j.triboint.2014.10.017
- [9] C. M. C. G. Fernandes, P. M. T. Marques, R. C. Martins, and J. H. O. Seabra, "Gearbox power loss. Part II: Friction losses in gears", *Tribology International*, 2015, doi: 10.1016/j.triboint.2014.10.019
- [10] R. B. Randall, "Analysis of computed order tracking," *Mechanical Systems and Signal Processing*, vol. 11, 1997, doi: 10.1006/mssp.1996.0056
- [11] R. Dixon and A. W. Pike, "Application of condition monitoring to an electromechanical actuator: a parameter estimation-based approach," *Computing & Control Engineering Journal*, 2002, doi: 10.1049/cce:20020203
- [12] M. Mazzoleni, M. Scandella, Y. Maccarana, F. Previdi, G. Pispola, and N. Porzi, "Condition assessment of electro-mechanical actuators for aerospace using relative density-ratio estimation", *IFAC-PapersOnLine*, vol. 51, no. 15, pp. 957–962, 2018, doi: 10.1016/j.ifacol.2018.09.391
- [13] M. Ismail, E. Balaban, and J. Windelberg, "Spall Fault Quantification Method for Flight Control Electromechanical Actuator", *Actuators*, vol. 11, 2022, doi: 10.3390/act11020029, doi: 10.1108/003687911111101830