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Quadrature current disturbance compensation for improved exoskeleton torque control

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Active exoskeletons for the elderly have very high demands on their actuators' performances to not injure or irritate their wearer. One crucial aspect is the angle-dependent torque of synchronous motors. Especially for a torque-controlled motor, ripples in the torque can lead to an actuator's behavior that feels uncomfortable for the wearer. In this paper, we present a new approach for online torque ripple compensation with the use of a feedforward disturbance compensator. The disturbance compensation is based on a harmonic current injection and tested in a scenario with a constant load and shows a significant reduction in torque ripple.

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I. Introduction

In the field of active medical exoskeletons, the drivetrain of the exoskeleton is one of the most crucial components. To assist the gait of the wearer, the motors must deliver a ripple free torque to avoid possible instabilities and discomfort while using the exoskeleton. This requirement gains even more importance if we look at exoskeletons for elderly people. The skin and bones of elderly people are way more sensitive to disturbance forces compared to those of young people. For example, a medical report from 2019 detailed multiple cases where patients experienced bone fractures due to an unexpected behavior of an exoskeleton [1]. To realize an active exoskeleton for elderly people that does not suffer from the previously stated problems, a new type of actuator with serial elasticity and a motor controller is developed.

I.I. Related work

The effect of torque ripples in *Brushless Direct Current* (BLDC) motor drives is widely recognized as a limiting factor for wearable actuation. Negative induced effects can be vibrations and degraded torque tracking. Such ripples can be of different origin, either from the inherent working principle of a BLDC motor itself, deviations in the mechanical assembly or an unbalanced load. Exoskeleton studies report that ripple impairs user comfort, gait stability and compliant interaction [2]. A strategy to reduce the torque ripple in exoskeleton and collaborative robot drives includes the use of *Field Oriented Control* (FOC) in multiphase or axial-flux machines [3]. Besides that, motor-design measures such as slotless windings for low cogging torque are being used [4]. More general methods rely on *additive compensation current injection,* or disturbance observers that estimate a periodic torque disturbance [5]. However, these approaches seldom address online, torque-scaled ripple suppression in exoskeleton actuators, especially for the intended use with the elderly. Here, we use feedforward disturbance compensation to eliminate the torque ripple creating current.

II. Material and methods

The developed actuator is inspired by the work of Bergmann et al. [6] and consists of a BLDC motor coupled to a ball screw in combination with an adjustable elastic element to absorb shocks and store / release energy during the gait cycle. To achieve a torque delivery of the BLDC motor, with minimal ripple, a harmonic disturbance compensation is included in the current control loop. The control architecture is shown in the block diagram in **Fig. 1**. The concept is inspired by the work of Wang [5], but instead of focusing on velocity control and simulation, it aims at current control for a BLDC motor for an exoskeleton.

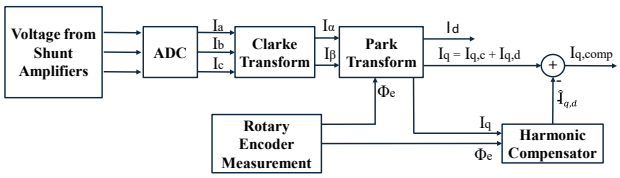


Figure 1: Integration of the disturbance compensation into the current control loop for compensating non-idealities affecting the q-axis current.

The compensation process begins with acquiring and digitizing the three-phase currents (I_a, I_b, I_c) using *Shunt Amplifiers* and an *Analog to Digital Converter* (ADC). These currents are then transformed using a *Clarke Transformation*. The *Clarke Transformation* yields I_α and I_β in the stationary $\alpha\beta$ frame. Subsequently, the *Park Transform* uses these $\alpha\beta$ currents and the electrical angle θ_e to convert them into the rotating dq frame currents, I_d (flux current) and the torque-producing quadrature current

I_q. The current I_q is the sum of the desired control current $I_{q,c}$ and the actual disturbance $I_{q,d}$.

$$I_q = I_{q,c} + I_{q,d} \quad (1)$$

The disturbance component $\hat{I}_{q,d}$ is estimated using the measurement from a position encoder of the rotor angle Φ_m (converted to the electrical angle θ_e) and the measured current I_q. The compensation stage mitigates non-idealities, subtracting the estimated disturbance $\hat{I}_{q,d}$ from I_q. This operation results in the compensated current $I_{q,comp}$. If $\hat{I}_{q,d} \approx I_{q,d}$ yields, it can be seen as a refined approximation of $I_{q,c}$.

$$I_{q,comp} = I_q - \hat{I}_{q,d} \quad (2)$$

To estimate the disturbance current $\hat{I}_{q,d}$, a multiplicative disturbance with harmonic characteristic in respect to the electrical frequency ($2\theta_e$) is used. A fixed gain of 0.7 and a fixed phase shift of 90° are applied to the cosine function to manually align the correction with the peak error of the measurement.

$$I_{q,comp} = I_q - \hat{I}_{q,d} = I_q - 0.7I_q \cdot cos(2\theta_e + 90°) \quad (3)$$

This correction smoothes the I_q feedback. With $|\hat{I}_{q,d}| \leq |0.7I_q|$ we effectively increase $I_{q,c}$ relative to I_q. This dynamic adjustment aims to improve inner current loop accuracy and therefore the output torque.

III. Results and discussion

To perform an evaluation of the disturbance rejection capabilities of the current control loop, a specific test is designed to assess the system's ability to mitigate torque ripple through disturbance compensation techniques. The test involves operating the motor under a constant load while measuring the torque-producing current I_q, across a full mechanical rotation of the motor shaft. This test was conducted using the mechanical setup shown in **Fig. 2**. A PID controller was used for position control to move the motor through a full rotation with a constant load

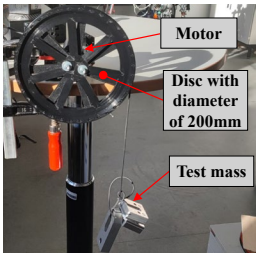


Figure 2: Mechanical test setup with motor of type BDUAV-5065-140kV.

Fig. 3 shows the results of the disturbance compensation. The uncompensated current (pink curve) shows angle-dependent oscillations and yields a ripple amplitude of roughly 1260 mA. In contrast, the compensated current (orange curve) exhibits much smaller and tighter fluctuations. Its ripple amplitude is about 420 mA. Both currents oscillate around the same global average of 3750 mA, confirming that the compensation selectively reduces the periodic disturbance without affecting the mean torque output. In an ideal system, we would expect a constant current while having a constant load and therefore torque. The current injection reduces the ripple amplitude by approximately 66.7 %, bringing the system closer to a constant torque output over a full rotation.

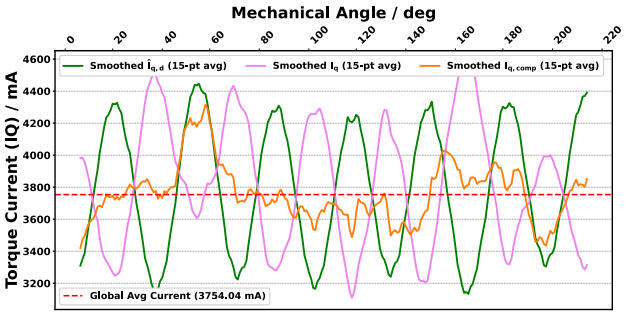


Figure 3: Result of the disturbance compensation on the I_q current over a full mechanical rotation of the motor shaft (clipped to 220° for visualization).

IV. Conclusions

It could be shown that the angle-dependent fluctuations in the current could be reduced by integration of a harmonic feedforward disturbance compensation. This mechanism results in a 66.7 % reduction in current ripple amplitude, confirming the system's ability to mitigate position-dependent disturbances and consequently enhancing torque smoothness. With this, the foundation for an exoskeleton actuator for elderly people is set. Further work involves test runs with tracking of a torque profile, while using the architecture from **Fig. 1**. Moreover, the usage of an adaptive disturbance compensation, to further reduce the torque ripple while enhancing robustness, can be considered.

Author's Statement

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