No-Load Investigations of Sub-Fractional Horsepower Permanent Magnet Motors

Relevant for: Rheology, Electrical Engineering, Electric Machines and Drives, Universal Micro Testing Machine MCR

Accurately measuring the *cogging torque*, *hysteresis torque*, and *iron losses* of permanent magnet motors is a challenging task. This is especially true for sub-fractional horsepower variants used, e.g., in auxiliary drives for automotive fan and pump applications. Their *cogging torque* and *hysteresis torque* peak values are often in the sub-milli-Newton meter range, causing conventional measuring methods and devices to fail as especially friction impedes the measurement significantly. Moreover, the *iron losses* of such motors are hard to determine and usually merely estimated in the literature. Fortunately, a rheometer (universal micro testing machine MCR) can provide a remedy.

1 Introduction

Sub-fractional horsepower (SFHP) permanent magnet (PM) motors are often used as part of fan systems for cooling of electronics in many different industries. The example case motor used for the investigations with the universal micro testing machine MCR—a miniature claw-pole motor with an outer-rotor—is illustrated in Figure 1. (See [1] and [2] for more detailed information on the claw-pole motor.)

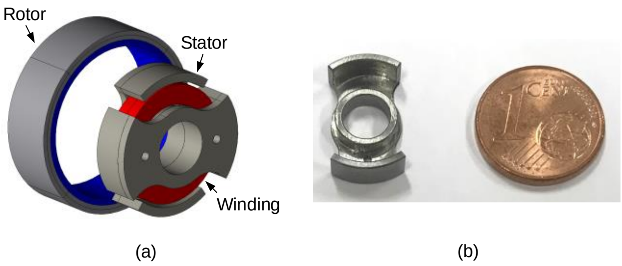

Figure 1: (a) 3-D view of a miniature claw-pole motor and (b) prototype stator part of the claw-pole motor; source: [3].

Due to the PM, the motor is characterized by *cogging torque* (i.e., the no-load interaction of the PM flux with the slotted stator structure), *hysteresis torque* (because the magnetic field of the PM is different from that of a subset of the magnetic dipoles in the stator iron), and *iron losses* (essentially *eddy current* and *hysteresis losses*). These characteristics are sensitive to parameter variations and manufacturing influences, making experimental investigations in addition to finite-element simulations essential. The following sections show the rheometer-based (using the universal micro testing machine MCR) determination of the *cogging torque*, the *hysteresis torque*, and the *iron losses* of SFHP PM motors.

2 Experimental Setup

Figure 2(a) illustrates a typical rotational test on a liquid sample sandwiched between a lower stationary part and an upper rotary part (e.g., parallel plate arrangement) to determine the necessary driving force to perform the preset rotation or oscillation. (In Figure 2(a), ω is the angular frequency.)

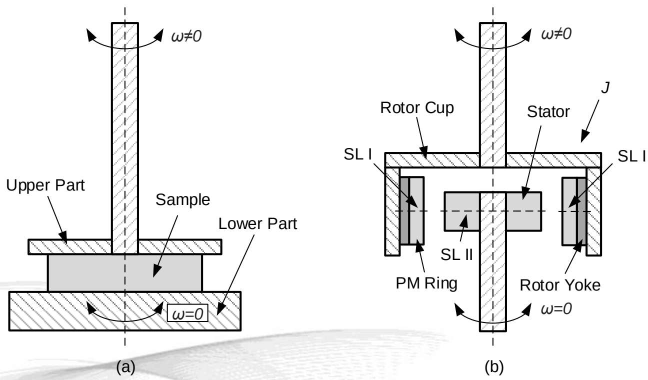

Figure 2: (a) rotational shear test on a sample and (b) adapted test setup for investigations of small electric motors; source: [3].

Figure 2(b) shows the adapted setup to measure the *cogging torque*, *hysteresis torque*, and *iron losses* of SFHP outer-rotor motors, e.g., the one shown in Figure 1(a). Therefore, a rotor cup (which holds the PM ring and the rotor yoke) is attached to the upper rotary part ($\omega \neq 0$) of the universal micro testing machine MCR, while the stator is attached to the lower stationary part ($\omega = 0$); both are positioned coaxially with no shaft connection as depicted in Figure 2(b). Hence, the described arrangement is noncontact, eliminating the influence of bearing friction of the motor under test.

The total inertia of the rotary part is denoted as J; SL I and SL II are the symmetry lines of the rotor and stator, respectively. The measuring method is not limited to outer-rotor motors; it can easily be applied to inner-rotor topologies as well.

In accordance with Figure 2(b), Figure 3 shows the experimental test setup to measure the *cogging torque*, *hysteresis torque*, and the *iron losses* of SFHP PM motors.

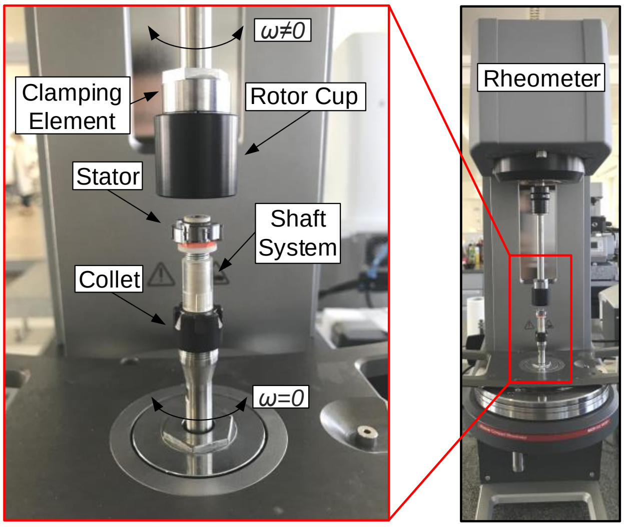

Figure 3: Experimental test setup (universal micro testing machine MCR); source: [3].

Therefore, the universal micro testing machine MCR (WESP) from Anton Paar is used to perform torque measurements in the clockwise (CW) and counterclockwise (CCW) directions at a preset rotational speed n. It features both axial and radial air bearings to eliminate the influence of friction. The controlled shear rate (CSR) operating mode is used for the measurements.

3 Experimental Results

Figure 4 shows the measured no-load torque waveforms T_{rheo} of the claw-pole motor at n = 1 rpm in the CW and CCW directions as a function of the rotor angle φ. A positive offset (T_{offset}) is identified for the CW direction and a negative one for the CCW direction. At such a low speed, *eddy current* effects in the stator iron can be neglected. Hence, each measured torque waveform is a superposition of the *cogging torque* and the *hysteresis torque*, which are separated in the following.

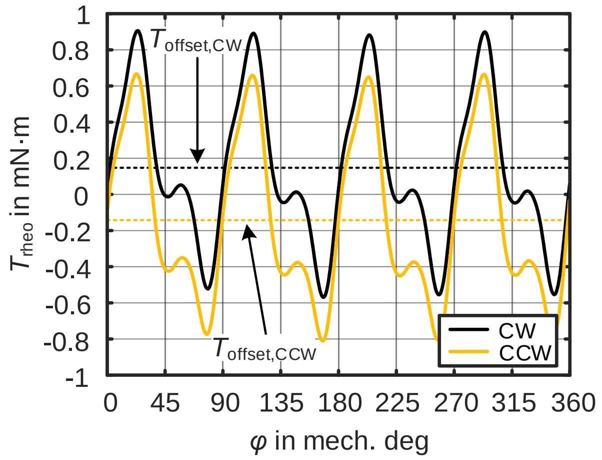

Figure 4: Measured no-load torque waveforms of the claw-pole motor in the CW and CCW directions; source: [3].

Figure 5 shows how the measured CW and CCW torque waveforms from Figure 4 can be used to extract the *cogging torque* T_{cog} and the *hysteresis torque* T_{hys} based on the following two equations:

$$T_{\mathrm{cog}} = \frac{T_{\mathrm{rheo,CW}} + T_{\mathrm{rheo,CCW}}}{2}$$

$$|T_{\mathrm{hys}}| = \frac{\pm T_{\mathrm{rheo,CW}} \mp T_{\mathrm{rheo,CCW}}}{2}$$

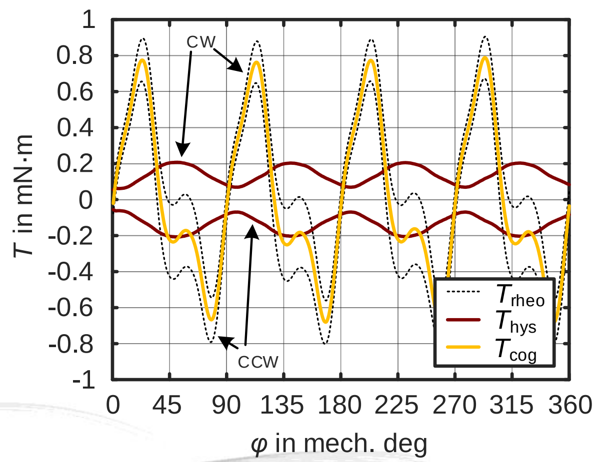

Figure 5: Extraction of the *cogging torque* and *hysteresis torque* from the measured CW and CCW no-load torque waveforms; source: [3].

Note that the *hysteresis torque* is a function of the rotor position due to the stator slots. Its average value $\bar{T}_{\mathrm{hys}}$ is equal to the measured offset in Figure 4. (The *cogging torque* is inherently offset-free.)

At elevated rotational speeds, *eddy current* effects occur in the stator iron changing the measured no-load torque notably, including an increasing offset torque component. Figure 6 illustrates $T_{\mathrm{offset,CW}}$ as a function of the rotational speed *n*.

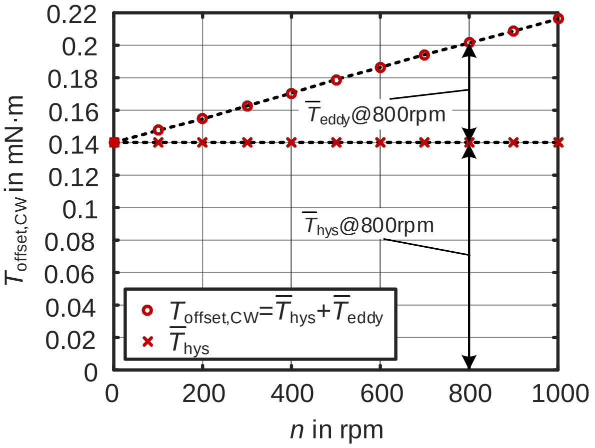

Figure 6: Measured offset torque versus rotational speed and torque separation; source: [3].

Starting from 0.14 mN·m, the offset increases linearly with increasing speed. Because the *hysteresis torque* is essentially speed-invariant, the linear increase in the offset torque is caused by the *eddy currents*. Hence, a separation of the average *eddy current* and *hysteresis torque* components $\overline{T}_{\mathrm{eddy}}$ and $\overline{T}_{\mathrm{hys}}$ can be made, which is exemplarily shown for a rotational speed of 800 rpm.

The measured offset torque from Figure 6 can be used to determine the corresponding no-load *iron losses* based on the following equation, see Figure 7.

$$P_{\mathrm{offset,CW}} = 2\pi n T_{\mathrm{offset,CW}}$$

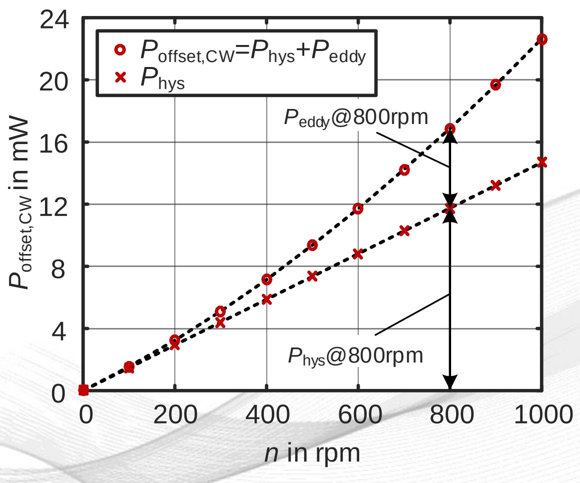

Figure 7: No-load *iron losses* of the claw-pole motor and their separation into *hysteresis* and *eddy current losses*; source: [3].

As expected the *iron losses* show a quadratic growth with increasing rotational speed. In accordance with Figure 6, a separation of the *iron losses* into *eddy current* and *hysteresis losses* can be performed, which is exemplarily shown for a rotational speed of 800 rpm.

4 Conlusions

Using the presented setup, settings, and evaluation methods, the universal micro testing machine MCR can successfully be used to measure the *cogging torque* and *hysteresis torque* waveforms in the sub-milli-Newton meter range and the *iron losses* of sub-fractional horsepower permanent magnet motors, both with excellent accuracy. More detailed information on the presented investigations are reported in [3] and [4].

5 References

[1] S. Leitner, H. Gruebler, and A. Muetze, "Innovative Low-Cost Sub-Fractional HP BLDC Claw-Pole Machine Design for Fan Applications," in *IEEE Transactions on Industry Applications*, vol. 55, no. 3, pp. 2558-2568, May-Jun. 2019, doi: 10.1109/ TIA.2019.2892023.

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[3] S. Leitner, G. Krenn, H. Gruebler, and A. Muetze, "Rheometer-Based Cogging and Hysteresis Torque and Iron Loss Determination of Sub-Fractional Horsepower Motors," in *IEEE Transactions on Industry Applications*, vol. 56, no. 4, pp. 3679-3690, Jul.-Aug. 2020 doi: 10.1109/TIA.2020.2990876.

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