Saturation Model for Plastic-Iron Composites with Low Iron Concentration

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This paper deals with the experimental magnetic characterization of composites made of a plastic base material and iron-powder. The iron concentration is kept very low to obtain a low permeable but mechanically soft material for the construction of a bendable linear motor. From the experimental characterization a saturation model is derived that can be used for a Finite Element Analysis to study, if the force-to-weight-ratio of the bendable linear motor can be increased using the plastic-iron composite.

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I Motivation

Bendable linear motors have advantages over conventional stiff linear motors in Soft-Robotic applications [1] or as drives for soft exoskeletons, also called exosuits [2, 3]. For these application fields a bendable linear motor is developed. The first prototype of the motor was designed as an ironless permanent magnet tubular linear synchronous motor (PMTLSM) [4]. The primary of the motor consists of ring coils connected to a three-phase winding that are casted into a tubular shell using a soft rubber. The secondary is constructed from NdFeB ring magnets mounted on a flexible rope. For the benefit of bendability ferromagnetic components were preliminarily excluded from the motor design. To increase the force-to-weight-ratio, a coating of the motor with a material that is mechanically soft on the one hand, but on the other hand magnetically conductive, is investigated. The new material should replace the part of the primary cast outside of the stator coils, so that the magnetic flux of the motor is concentrated there. Thus, the stray flux is reduced and the motor force increased.

In order to evaluate, if such a composite of a soft elastomer and iron powder is able to increase the motors force-to-weight ratio, an experimental characterization is conducted. Based on that, a saturation model is proposed and parametrized regarding the experimentally obtained data.

II Experimental Material Characterization

There are several possibilities to measure the BH-curve of magnetic materials, whereas the Epstein-method [5] or the Single-Sheet-tester (SST) [6] are the most widely used ones. Both are defined by international standards and well suited for the characterization of material samples in the shape of iron sheets. For the characterization of plastic-iron-composites however, it is very difficult to manufacture sheet-shaped specimen, so that another measurement method is applied. The method is defined by standard IEC 60404-6 [7], which is explicitly defined for sintered, pressed or casted materials. As defined in the standard, ring specimen of the plastic-iron composite are casted and two coils are wound on it – one for excitation and one for measuring the magnetic response.

The excitation coil is fed by a sinusoidal current $i(t)$ which is generated by a signal generator whose output is amplified by a linear amplifier. Due to the current an alternating magnetic field inside of the ring specimen is generated, thus the voltage $u(t)$ is induced in the measurement coil. From the measured current and voltage waveforms $i(t)$ and $u(t)$ the magnetic field intensity $H(t)$ and the magnetic flux density $B(t)$ are calculated based on the number of turns N_1 (measurement coil) and N_2 (excitation coil), the mean path length of the magnetic field l_m and the cross-section area of the ring specimen A with (1) and (2). The integration constant B_0 becomes zero in stationary state.

$$H(t) = \frac{N_2}{l_m} \cdot i(t) \tag{1}$$

$$B(t) = -\frac{1}{N_1 A} \int_0^t u(\tau)\, d\tau + B_0 \tag{2}$$

The measurement is done for frequencies between 50 Hz and 1000 Hz showing no significant frequency dependency of the magnetic properties. The followingly presented results were obtained for the measurement at 1000 Hz. The temperature is monitored during the experiment using a thermoelement and kept below 40 °C to eliminate thermal influences.

For the experiment four specimens are prepared with a hard epoxide resin as a base plastic material and iron powder with a purity of 99 % and an average particle size of 90 µm. The volumetric iron power concentration amounts to 4,75 % for specimen 1, 5.91 % for specimen 2, 6.86 % for specimen 3 and 7.94 % for specimen 4. The iron concentration is limited to these low values because the cast material becomes too viscous in the liquid state aggravating the cast process. Also, with increasing iron concentration it has to be assumed that the material becomes more brittle, so the bendability of the linear motor would be limited. The soft rubber, that is used in the linear motors cast, cannot be used for the experimental characterization since it is not able to withstand the mechanical stress during the coil winding process. After casting, the specimens are hardened and the coils are wound on them. In Fig. 1 the low-pass-filtered (100 kHz cut-off frequency) measured BH curve of specimen 1 is presented exemplarily.

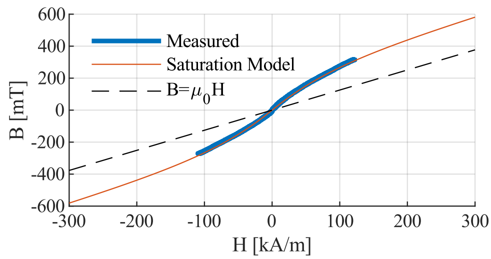

Figure 1: Measured BH curve of specimen 1

II Nonlinear Saturation Model

The measured curves show an increased slope for field intensities close to zero. With increasing field intensity, the slope of the curve decreases due to saturation and becomes parallel to the air field curve, which is a linear curve with the slope of μ_0. Hysteresis is present but does not have a significant impact on the curves.

To describe this behavior mathematically, the measured data are used to fit a nonlinear saturation model that can be used in a Finite Element Analysis of the bendable linear motor. In the literature approaches to represent BH-curves by analytic functions can be found [8–10]. However, they are mainly used to describe high permeable material with saturation flux densities typically above 1 T and accordingly high permeabilities. Because of that, these functions are not intended to be used to describe low permeable material as investigated in this study. To overcome this problem, a custom function defined by (1) to (3) is elaborated.

$$B(H) = B_1(H) + B_2(H) \tag{3}$$

$$B_1(H) = \mu_0 H \left[1 + k_b \left(\frac{\pi}{2} - \operatorname{atan}(\alpha H) \cdot \operatorname{sgn}(H)\right)\right] \tag{4}$$

$$B_2(H) = \frac{2b_0}{\pi} \operatorname{atan}(\alpha H) \tag{5}$$

In this function, $B_1(H)$ is dominant for low values of H, where the slope of the curve is above the slope of the air curve μ_0. For increasing H the slope decreases, which is represented by the atan function with k_b controlling the maximum slope. The multiplication with the signum function guarantees that all BH data points are in the first or third quadrant. The function $B_2(H)$ is dominating for high values of H, where the slope decreases and the BH curves continue parallel to the air field curve. The difference between the air curve and the analyzed BH-curve for infinite H is controlled by the parameter b_0. The transition between the influence of the functions B_1 and B_2 is determined by the atan terms with the transition factor α. To demonstrate the fitting quality, the fitted function for the measurement of specimen 1 is presented in Fig. 1 together with the original measurement data.

The fitted curves for all four specimens are presented in Fig. 2 and the corresponding regression parameters are listed in Table I including the regressions root mean square error (RMSE) values.

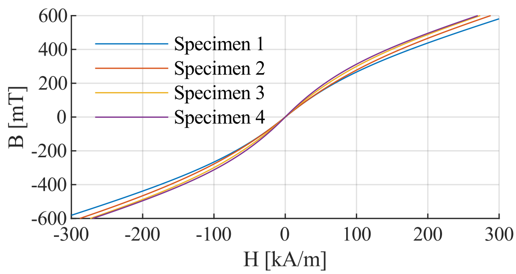

Figure 2: Fitted BH curves of the four specimens

The curves show that with increasing iron concentration the maximum slope of the curve increases slightly, thus the relative magnetic permeability μ_r of the material rises. However, the iron concentration in the range between 4,75 % to 7,94 % does not have a significant impact indicating a saturation of the small iron particles for low magnetic fields. The maximum μ_r can be obtained from the gradient of the BH curve [7] and amounts to about 3.5 for specimen 4.

III Conclusion

An experimental characterization based on international standard IEC 60404-6 of a plastic-iron composite with low iron concentration is performed. The analysis shows that relative permeabilities up to 3.5 are reached for a volumetric iron concentration of 7.94 %. The iron concentration of the analyzed specimens varying between 4.75 % and 7.94 % turns out to have a minor impact on the permeability indicating material saturation for low field intensities. The BH-curves are successfully used to parametrize a nonlinear saturation model for low permeable materials. In the next step, the found material models are used to re-optimize the bendable linear motor regarding the force-to-weight ratio using the obtained saturation models in a Finite Element Analysis.

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