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Impact of Iron Dust on Electromechanical Systems: A Case Study

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Abstract—Several actuators (e.g. permanent magnet (PM) machines, magnet valves), sensors (e.g. reed sensors, Hall sensors, inductive proximity switches) and emerging inductive energy harvesting systems rely on a clean environment and/or well-defined magnetic conditions. However, in industrial environments iron dust or iron powder may be present, as e.g. resulting from machining, i.e. drilling or milling of mechanical parts or from mechanical wear, and could accumulate in the vicinity of magnetic components. Accordingly, a model for describing the magnetostatic properties of iron dust is required for analyzing a potentially negative impact on the operating behavior. The model derived in this paper is based on the B-H curve of an underlying base material (C45E steel in the presented case) and two further coefficients, representing the influence of powder density and the imperfect magnetic junction at the interfaces between iron particles. The model is then utilized for investigating the influence of iron dust on the operation of a recently introduced kinetic energy harvesting (KEH) system, as a case study. Three-dimensional finite element method (3-D FEM) simulations show that in this case the flux is actually enhanced by iron dust accumulated in front of the harvester. The paper concludes with an experimental verification of the iron dust B-H model and an experimental analysis of the KEH performance degradation due to iron dust.

I. INTRODUCTION

In industrial environments, iron dust or iron powder may be present, as a by-product of machining (e.g. drilling or milling) of mechanical parts or resulting from mechanical wear. If accumulated in critical locations, iron dust may impair the safe operation of magnetic actuators (e.g. permanent magnet (PM) machines, induction machines, magnet valves) or sensors (e.g. reed sensors, Hall sensors, inductive proximity switches) that rely on a clean environment and/or well-defined magnetic conditions. Moreover, emerging inductive energy harvesting systems, which were recently discussed in various publications [1–9], could be exposed to iron dust in their environments. Since the operating principle of these energy harvesters is based on building up a strong magnetic field, clearly, their performance could be influenced by iron dust collected by this magnetic field.

Such a system, which is analyzed in this work as a case study, is the kinetic energy harvester (KEH) recently proposed in [1, 2]. It is shown in Fig. 1 mounted in a test setup, which allows the analysis of various operating conditions and KEH geometries.

The system harvests energy from a moving conductive secondary (MCS) without mechanical contact, as its operation is purely based on eddy-current coupling [1]. This allows to enclose the KEH with a stationary cover, forming a robust, encapsulated system. A mechanical output power of $P_{\text{mech}} \approx 10$ W can be achieved for an air gap of $g_{\text{KEH}} = 10$ mm and a KEH diameter of $2r_1 = 75$ mm, when the speed of a MCS made of steel is $v_2 = 22$ m/s.

However, the presence of iron dust accumulated from the environment could potentially short circuit magnetic field lines from the PMs of the harvester to the MCS and accordingly change its performance. A stationary Polymethyl methacrylate (PMMA) cover is mounted on the setup in Fig. 1 and the
impact of an accumulated iron dust layer in front of the cover is investigated in this paper.

In Sec. II, a magnetostatic model of iron dust/iron powder is derived and verified with magnetic measurements on an iron dust sample. Sec. III estimates the maximum iron dust layer thickness, which would accumulate on the KEH cover considering the force equilibrium on a bulk of dust. Sec. IV analyzes the actual KEH air gap flux change under the presence of iron dust with three-dimensional finite element method (3-D FEM) simulations. Finally, measurements of the built up iron dust layer thickness and measurements on the KEH performance degradation due to iron dust in Sec. V verify the provided models. Sec. VI concludes this work.

II. MAGNETOSTATIC MODELING OF IRON DUST

Firstly, a representative magnetic model for iron dust, whose B-H curve is depicted in Fig. 3, shall be derived in order to be employed for evaluating the influence of iron dust on the KEH’s operation. The authors would like to state that the model derived in the following might also be applied to the KEH’s operation. The authors would like to state that the model derived in the following might also be applied to the KEH’s operation. The authors would like to state that the model derived in the following might also be applied to the KEH’s operation. The authors would like to state that the model derived in the following might also be applied to the KEH’s operation.

In order to describe the magnetic properties of iron dust, which is expected to show significantly different magnetic behavior than solid iron, a simplified B-H characteristic based on the equivalent model depicted in Fig. 2(b) can be employed

\[
H_{Dust} = H_{Fe}(B_{Fe}) \left(1 - k_{Ox}\right) + \frac{B_{Fe}}{\mu_{Ox}} k_{Ox} \tag{1a}
\]

\[
B_{Dust} = k_{Fe} \cdot B_{Fe} + \left(1 - k_{Fe}\right) \cdot \mu_0 H_{Dust} \tag{1b}
\]

\[
k_{Ox} := \frac{d_{Ox}}{l_{Dust}} \tag{1c}
\]

\[
\frac{V_{Fe}}{V_{Dust}} = \frac{A_{Fe}}{A_{Dust}} \cdot \frac{l_{Dust} - d_{Ox}}{l_{Dust}} = \frac{\mu_{Dust} - \mu_{Ox}}{\mu_{Fe}} \tag{1d}
\]

\[
k_{Fe} := \frac{A_{Fe}}{A_{Dust}} \approx \frac{\rho_{Dust}}{\rho_{Fe}} \tag{1e}
\]

The input parameters of this equation based model are an underlying iron particle B-H curve (technically, its inverse \(H_{Fe}(B_{Fe})\)) and parameters for the iron dust: density \(\rho_{Dust}\), grain size \(l_{Dust}\), effective oxide layer thickness \(d_{Ox}\) and oxide layer permeability \(\mu_{Ox}\) (cf. Fig. 2b). The effective oxide layer thickness \(d_{Ox}\) models the imperfect magnetic junction at the interfaces between iron particles due to oxide and geometry...
mismatch between the grains, and is therefore larger than a physically measurable oxide thickness on an iron particle's surface.

In order to compute the actual iron dust B-H curve with the implicit formulation in (1), \( B_{Fe} \) of the assumed raw material is swept and \( H_{Dust} \), \( B_{Dust} \) are obtained.

For this study, carbon steel C45E is selected as the raw material of iron dust as it could result from mechanical wear in an industrial environment. Its B-H curve has been measured electrically with a ring specimen and the hysteresis curves for different amplitudes of magnetic field strength \( H \) are depicted in Fig. 4. In Fig. 3, two B-H curves of iron dust with the therein specified parameters are shown.

The parameters \( k_{Ox} \) and \( k_{Fe} \) for the first sample of iron dust, denoted as iron dust 1 in the following were selected such that they agree with the density measurement \( \rho_{Dust} = 1.9 \text{ kg/dm}^3 \) and hysteresis measurements of an iron dust sample, depicted in Fig. 5. For measuring the B-H curve of iron dust, a setup as illustrated in Fig. 6 was built. The 3-D printed, hollow core body was filled with an iron dust sample through the filling opening without external compression. Afterwards, the filling opening was closed with a Polyethylene terephthalate (PET) electrical insulation tape with 60 \( \mu \text{m} \) thickness; a sensing coil and the excitation coil are wound around the closed and filled core body. The iron dust sample at hand was obtained by letting commercially available steel powder [10] with specified grain size in the range of 150 \( \mu \text{m} \leq l_{Dust} \leq 212 \mu \text{m} \) corrode in a moisture environment for 48 hours, as it would occur in the targeted environment of the energy harvesting system at hand.

On the other hand, the parameters for another sample of iron dust, iron dust 2, were selected to illustrate the B-H curve of compressed iron dust or iron powder as it could occur in other applications.

It can be found that the density of iron dust affects its saturation flux density and the assumed oxide thickness affects the permeability before saturation. The parameters of iron dust 1 according to Fig. 3 are used for the following considerations.

### III. Iron Dust Layer Thickness

Generally, it is of interest how iron dust influences the operation of magnetic sensors, actuators and in this case energy
harvesters. In a first step, the iron dust thickness \( h \) that accumulates in front of the KEH is studied in this section. This information is used later for further 3-D FEM simulations, which will detail the implications of iron dust for the KEH.

Fig. 7 illustrates the test setup with an accumulated iron dust layer of thickness \( h \) in front of the KEH PMs.

In an initial experiment, it was observed that dust indeed stays on the KEH cover (cf. Fig. 7) and rotates approximately with same speed as the KEH \((\omega_1)\), when the system is in operation.

Iron dust gets attached and stays (or rotates with the KEH) as a layer on the KEH cover’s surface due to an attracting Maxwell force normal to the PMs and the KEH cover (normal force \(F_N\)), which is built up because of the PMs’ field and the permeability of iron dust, which is larger than \(\mu_0\). On the other hand, gravitational force \((F_G)\) and centrifugal force \((F_C)\), occurring when the KEH is rotating

\[
F_G = m_i \cdot g, \quad (2a)
\]
\[
F_C = m_i \cdot \omega_1^2 \bar{r}, \quad (2b)
\]

with \(\bar{r}\) being the average distance to the axis of rotation, are acting on the iron dust and are limiting its accumulation.

It has to be noted that it is not the Maxwell force (normal force) that keeps the iron dust in position, but a friction force \(F_{fr}\) built up by the normal force and a friction coefficient

\[
F_{fr} \leq F_N \mu_{fr}, \quad (3)
\]

where the friction coefficient \(\mu_{fr}\) depends on the material pairing on the interface where it is acting. Therefore, the force equilibria on two interfaces as given in Fig. 7 are analyzed:

- Dust-cover interface: It is considered that a fraction of iron dust is sliding off the cover due to gravitational and centrifugal force. The apparent friction coefficient is \(\mu_{fr,Dust,Cover}\) and all further quantities are denoted with subscript S. 
- Dust-dust interface: A dust particle on top of the iron dust layer is observed\(^1\) and it is analyzed if this dust particle is sliding off on the dust layer due to gravitational and centrifugal force. The apparent friction coefficient is \(\mu_{fr,Dust,Dust}\) and all further quantities are denoted with subscript P.

Combining the information stated above and norming the expressions by dust fraction mass \((m_S)\) and dust particle mass \((m_P)\),

\[
\frac{a_{fr,S}(h)}{m_S(h)} \cdot \mu_{fr,Dust,Cover} \geq g + \omega_1^2 \bar{r} \quad (4a)
\]
\[
\frac{a_{fr,P}(h)}{m_P(h)} \cdot \mu_{fr,Dust,Dust} \geq a_{fr}(\omega_1) \quad (4b)
\]

\(^1\)This approach could be seen as an analogy to the concept of observing a sample charge in electric fields theory.
must hold, such that an iron dust layer of thickness \( h \) stays attached.

Considering a thin built-up iron dust layer, such that \( \{\alpha_{D,S}(h), \alpha_{D,P}(h)\} < 2(\omega_1) \) of (4), further iron dust from the environment could be attracted and attached. This could only be restricted by the geometric width of the KEH air gap (cf. \( g_{KEH} \) in Fig. 7). On the other hand, assuming for the sake of contradiction that an iron dust particle gets attached to an iron dust layer, such that \( \alpha_{D,S}(h) > 2(\omega_1) \) or \( \alpha_{D,P}(h) > 2(\omega_1) \), the iron dust cannot be held by friction and certain particles of iron dust will fall off until the equilibrium is recovered.

A. Estimation of Friction Coefficients

According to (4), a reasonably accurate estimation of friction coefficients \( \mu_{fr, Dust,Cover} \) and \( \mu_{fr, Dust,Dust} \) is essential for an accurate calculation of dust height thickness.

The grain-to-grain friction coefficient \( \mu_{fr, Dust,Dust} \) can be estimated by optically measuring the angle of repose from piled up iron dust (dust cone) as shown in Fig. 8. The angle is formed such that friction can just hold a particle on the pile’s surface against the grade resistance and therefore the friction coefficient results as

\[
\mu_{fr, Dust,Dust} = \tan 35^\circ = 0.7 .
\]  

(5)

An equivalent measurement was conducted for estimating the friction coefficient on the dust-cover interface. For the static case

\[
\mu_{fr, Dust,Cover,S} = \tan 20^\circ = 0.38
\]  

(6)

was measured. However, for the interesting case, where the KEH is rotating with \( \omega_1 > 0 \) and the iron dust slides on the dust-cover interface, the static friction coefficient does not apply. As the measurement of the friction coefficient on the dust-cover interface under variation of speed difference

and under various operating conditions (moisture or oily environment) is out of the scope of this paper, henceforth,

\[
\mu_{fr, Dust,Cover} = 0.15 
\]  

(7)

is assumed as a sliding friction coefficient on the dust-cover interface.

**TABLE 1: Simulation Parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM inner radius</td>
<td>( r_{1,i} )</td>
<td>17 mm</td>
</tr>
<tr>
<td>PM outer radius</td>
<td>( r_{2} )</td>
<td>37.5 mm</td>
</tr>
<tr>
<td>Avg. dust radius</td>
<td>( \bar{r} )</td>
<td>27.25 mm</td>
</tr>
<tr>
<td>PM height</td>
<td>( h_{PM} )</td>
<td>10 mm</td>
</tr>
<tr>
<td>Gap: PM to MCS</td>
<td>( g_{KEH} )</td>
<td>10 mm</td>
</tr>
<tr>
<td>Gap: PM to cover surf.</td>
<td>( g_{0} )</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>Number of PMs</td>
<td>( n_{PM} )</td>
<td>4</td>
</tr>
<tr>
<td>PM remanent flux density</td>
<td>( B_r )</td>
<td>1.4 T</td>
</tr>
<tr>
<td>Iron dust density</td>
<td>( \rho_{Dust} )</td>
<td>1.9 kg/dm³</td>
</tr>
<tr>
<td>Iron dust base material</td>
<td></td>
<td>C45E</td>
</tr>
<tr>
<td>Oxide coefficient</td>
<td>( k_{Ox} )</td>
<td>0.18</td>
</tr>
<tr>
<td>Oxide permeability</td>
<td>( \mu_{Ox} )</td>
<td>( \mu_0 )</td>
</tr>
<tr>
<td>Cover/dust friction coef.</td>
<td>( \mu_{fr, Dust,Cover} )</td>
<td>0.15</td>
</tr>
<tr>
<td>Cover/dust friction coef.</td>
<td>( \mu_{fr, Dust,Dust} )</td>
<td>( \tan 35^\circ = 0.7 )</td>
</tr>
<tr>
<td>KEH rot. speed</td>
<td>( \omega_1 )</td>
<td>{0, 50, 100, 200, 400} rad/s</td>
</tr>
</tbody>
</table>
B. 2-D FEM Simulations & Results

In order to calculate the attracting force $F_N$ on iron dust, as depicted in Fig. 9, a 2-D FEM simulation, where the PMs of the KEH disk are represented as linear bars, is utilized. The stationary 2-D FEM analysis considers the nonlinear magnetic property of iron dust according to the curve specified in Fig. 3 and further parameters according to Table I.

As depicted in Fig. 7, the interfaces: dust-dust and dust-cover are analyzed. For the analysis of the dust-cover interface, the iron dust is modeled, as depicted in Fig. 9, as blocks of variable dust thickness $h$ (horizontal) and a width (vertical), which is equivalent to $0.1\text{o}$ of KEH angle (cf. fraction of iron dust layer in Fig. 9). The separation in blocks of $10^{\circ}$ allows to obtain insight in how the attracting force varies with different positions in front of the KEH magnets. For analyzing the dust-dust interface and hence, computing the force on a dust particle on top of the iron dust layer, small dust particles (modeled as rectangles) are placed on top of the iron dust layer of the 2-D FEM simulation (cf. fraction of iron dust particle in Fig. 9).

The attracting forces $F_{N,S,i}$ and $F_{N,P,i}$, acting on the iron dust fractions and the particles respectively, are calculated numerically by the FEM simulation software by the integration of the Maxwell stress tensor on the fraction’s/particle’s surface. For obtaining accurate results with this method, a small gap of $0.2\text{ mm}$ is introduced between the fractions/particles in the 2-D FEM simulation. The attracting forces are extracted from the FEM simulation and the retentive accelerations $a_{fr,S,i}(h)$ and $a_{fr,P,i}(h)$ of iron dust layer in the air gap.

As both of the equilibrium conditions in (4) must hold, from...
the results, depicted in Fig. 10, can be concluded that

• the force equilibrium on a dust particle at the dust-dust interface is determining the dust layer thickness in standstill, while
• the force equilibrium on a dust fraction at the dust-cover interface is determining the dust layer thickness at rotating speeds $\omega > 100$ rad/s.

From Fig. 10 it can be seen that the expected maximum dust layer thickness on the KEH in standstill is $h_{\text{max,standstill}} \approx 40$ mm, whereas the expected maximum dust layer thickness at the interesting rotational speed of $\omega = 200$ rad/s is $h_{\text{max,rot}} \approx 3$ mm.

In summary, this section shows that the geometric air gap constraint $g_{\text{KEH}} = 10$ mm limits the dust layer thickness in standstill to $h \leq g_{\text{KEH}} - g_0 = 6.5$ mm in the area, where KEH and MCS overlap. On the other hand, the analysis of friction force between dust layer and the cover during KEH rotation predicts that negligible dust layer ($< 3$ mm) remains on the KEH’s cover, once the system is running. Measurement results that verify these findings are presented in Sec. V.

IV. IMPACT ON KEH FLUX

In this section, it is analyzed how the flux between KEH and MCS is influenced by iron dust in the standstill case, assuming that the air gap is fully filled. The actual geometry (as shown in Fig. 7) is simplified in the utilized 3-D FEM simulation setup (cf. Fig. 11), which allows to reduce numerical simulation errors and computational time. Simulation parameters according to Table I are employed for the simulation and the axial flux density on the circle indicated in Fig. 11 is calculated.

The stationary 3-D FEM simulation reveals that at standstill, the flux density in the air gap is increased by the presence of iron dust, for a wide variety of iron dust parameters ($\rho_{\text{Dust}}$ and $k_{\text{Ox}}$). This is due to the fact that the iron dust has a permeability significantly lower than iron, but higher than air, which leads to a reduced, but not vanishing, air gap reluctance. Fig. 12 indicates that the iron dust applied for later experimental results (iron dust 1) increases the peak flux density by $\approx 25\%$.

V. EXPERIMENTAL RESULTS

Finally, measurements with the setup of Fig. 1 are conducted. Firstly, the predictions of Sec. III concerning the built up dust layer thickness in standstill and at rotation of the KEH shall be verified. Iron dust is manually applied to the KEH in standstill until the thickness of the iron dust layer cannot be increased and the force equilibrium on said interfaces is established. Fig. 13(a) and Fig. 13(b) provide photographs of the KEH setup with iron dust applied during standstill. As predicted in Sec. III-B, the air gap between KEH cover and MCS is completely filled with iron dust. Moreover, the calculated maximum built up dust height in standstill $h_{\text{max,standstill}} \approx 40$ mm agrees well with the experimental result of Fig. 13(b) of 37 mm.

Moreover, as predicted, the majority of iron dust falls off the harvester once the MCS and the KEH are rotating ($\omega = 200$ rad/s). Fig. 13(c) shows the remaining iron dust.
layer after rotating the KEH with \( \omega_1 = 200 \text{rad/s} \), which is in fair agreement with the prediction of Sec. III-B of \( h_{\text{max,rot}} \approx 3 \text{ mm} \).

Finally, energy harvesting measurements were conducted to conclude the investigation of iron dust impact for the KEH. The measurement result in Fig. 14 show an only insignificant (\( \approx -5\% \)) degradation of harvested power due to iron dust.

VI. CONCLUSION

In this paper, the B-H characteristic and/or the magnetostatic behavior of iron dust is modeled. The input parameters are the B-H curve of an underlying base material (C45E steel in the presented case) and three further coefficients: \( k_{\text{Fe}} \), \( k_{\text{OX}} \) and \( \mu_{\text{OX}} \). Hysteresis measurements of the base material (C45E) and an iron dust sample are confirming the model. In the case at hand, the iron dust model is utilized to estimate the influence on the operation of magnetic devices at the example of a kinetic energy harvester (KEH). The predicted iron dust layer thickness was confirmed in the experiment and finally, an only insignificant (\( \approx -5\% \)) degradation of harvested power due to iron dust was measured.

The modeling approach is of general value and it can be used for estimating the thickness of an accumulated iron dust layer thickness and its implication on flux for various magnetic components such as inductive sensors (e.g. inductive proximity switches, PMs of reed sensors) and actuators (e.g. on the housing of permanent magnet (PM) machines or magnet valves).

In the course of further research a detailed experimental characterization of a variety of iron dust samples (higher density \( \rho_{\text{Dust}} \), variable grain size) at a higher magnetic field strength (\( H > 200 \text{kA/m} \)) could be performed using a setup in analogy to [11]. This would allow to verify the postulated model entirely or allow to refine the magnetostatic model of iron dust.

VII. ACKNOWLEDGMENT

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