Comparative Finite Element Analysis of a Voice Coil Actuator and a Hybrid Reluctance Actuator

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This paper evaluates the performance of a hybrid reluctance actuator for application in high-precision motion systems. For this purpose, its properties are compared with those of a voice coil actuator, which is the choice actuator for many high-precision applications. To properly investigate the non-linearities of these systems, finite element analysis (FEA) is employed. Spacial-domain analysis shows that the hybrid reluctance actuator can deliver both higher forces per volume (by a factor up to app. 10.5) and thrust constant (by a factor up to app. 9.6) than the voice coil actuator. However, these values depend strongly on the position of the mover, causing a high non-linear stiffness. Frequency-domain analysis yields the power losses of the actuators, as well as the dynamic thrust constant. It is shown that at all frequencies the hybrid reluctance actuator suffers from higher iron loss (by a factor up to app. 5.1) than the voice coil actuator. Additionally, its thrust constant shows a large magnitude slope (app. −14.4 dB/dec) and phase lag (app. −71° at f = 10 kHz) in the frequency domain, resulting in a narrowed control bandwidth. These results clearly indicate a trade-off between thrust constant, linearity and dynamic behavior, which should be considered for employment in high-precision applications.

Keywords: electromagnetic actuators, high-precision motion, finite element analysis

1. Introduction

In industrial applications and scientific instrumentation, motion with micro- or nanometer resolution is indispensable to achieve the required high performances. An example is represented by wafer scanners, which are employed to realize integrated circuits (ICs) with feature sizes down to 20 nm. Another example is vibration isolation devices for metrology applications, which are designed to compensate for external disturbances in the nanometer range.

In these cases, voice coil actuators are typically employed because of their large stroke (mm range), high resolution (nm range) and their ability to attenuate environmental vibrations. One of the main drawbacks of these actuators is their relatively low thrust constant, defined as the ratio between the actuation force and the input current. This factor can limit the performance in systems where a large moving mass needs to be accelerated (e.g. wafer scanners), as high currents are required to generate the necessary actuation force.

This limitation may be overcome by employing hybrid reluctance actuators. These actuators rely on two separate sources of magnetic flux (namely, a permanent magnet and a coil current) to generate a high force, which is proportional to the input current. The resulting thrust constant is typically higher than that of comparable voice coil actuators. Due to this property, hybrid reluctance actuators have been employed in industrial applications, such as magnetic bearings and fast steering mirrors. However, these actuators suffer from several drawbacks, such as negative stiffness, which can make a system unstable and must therefore be counteracted via a mechanical flexure or control action. An additional disadvantage stems from the iron loss in the ferromagnetic components of the actuator. Such loss has been shown to cause a decrease in the magnitude of the force and a phase lag in the frequency response of the actuator, thereby affecting the achievable control bandwidth and positioning precision of the overall system.

Analytical models have been proposed to analyze some of the properties of hybrid reluctance actuators, such as the actuation force and the phase lag caused by iron loss. However, the accuracy of such analytical approaches is limited by the employed simplifications. For example, the magnetic flux leakage is typically modeled by a constant, which is usually difficult to determine analytically. Additionally, the relative magnetic permeability of the used ferromagnetic material is often considered constant, although it is a non-linear function due to hysteresis and saturation, as seen in the B-H curve of the material itself.

The aforementioned modeling uncertainties can seriously affect the design of the system and result in sub-optimal actuator performance in comparison with voice coil actuators, which can be accurately described analytically. This
motivates the use of numerical approaches such as the finite element analysis (FEA) to assess the performance of hybrid reluctance actuators, because they enable to directly compute the non-linear effects from the system geometry and material parameters. Additionally, they allow to evaluate the interdependence between the different parameters of the system, which may not always be feasible experimentally. FEA was already employed to compare the performance of different voice coil and reluctance actuator types in respect to the power dissipation, the mass of the mover and the actuation force. However, other important parameters, such as the resulting thrust constant and the magnetic field, were not investigated. Additionally, the actuators were only examined in the spatial domain and their dynamic behavior was not assessed. This may represent a limit in the design of an actuator for high-precision applications, as it neglects the potential influence of the iron loss on the control bandwidth.

The contribution of this paper is to employ FEA to evaluate the performance of a hybrid reluctance actuator in high-precision motion systems. For this purpose, a comparative analysis with respect to a voice coil actuator is carried out to identify the main performance trade-offs, both in the spatial and in the frequency domain. First, the output force, thrust constant and the ratio between force and actuator volume are analyzed to estimate the achievable throughput. Additionally, to study the influence of the non-linearities (such as the negative stiffness and the magnetic flux leakage), these parameters are simulated for different values of the DC input current and of the position of the mover. To evaluate the energy efficiency and power dissipation of the actuators, the iron and copper loss is then computed for different frequencies of the AC input current. Finally, the dynamic thrust constant is also simulated to assess the influence of the iron loss on the output force and achievable control bandwidth, thereby enabling phase lag budgeting for the design of high-bandwidth hybrid reluctance actuators.

The paper is organized as follows. In Sec. 2, the design and working principle of the studied actuators are presented. In Sec. 3, the material and dimensional parameters of the actuators are introduced. Sec. 4 presents the simulation results for both the spacial (Sec. 4.1) and the frequency domain (Sec. 4.2). The conclusions are then provided in Sec. 5.

2. Principle of Operation

2.1 Voice Coil Actuator

Figure 1 shows a cross-section view of the studied voice coil actuator. It consists of a ferromagnetic stator (grey), a radially polarized permanent magnet (purple) and a coil (orange).

The magnetic flux generated by the permanent magnet flows through the air gap, the coil and the stator in a closed path (red loop in Fig. 1). In the air gap, it is perpendicular to the current flowing inside the coil. As a result, a Lorentz force \( \vec{F} \) is generated on the coil:

\[
\vec{F} = I \vec{l} \times \vec{B}, \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots }
magnetic flux in the air gap where the two fluxes have the same direction and a lower overall magnetic flux in the air gap where the two fluxes have opposite directions. As a result, a force \( F \) is generated on the mover in the direction of the increased magnetic flux \( \Phi_{g1} \).

\[
F = \frac{\Phi_{g1}^2 - \Phi_{g2}^2}{2 \mu_0 a} \quad \text{................................. (2)}
\]

where \( \Phi_{g1} \) and \( \Phi_{g2} \) are the overall magnetic fluxes in the left and right variable air gaps, respectively, \( \mu_0 \) is the magnetic permeability of vacuum and \( a \) is the cross-sectional area of the variable air gaps. Notice that the sign (and therefore the direction) of \( F \) can be reversed by changing the current direction in both coils. The force can also be expressed as a function of the current \( I \) and the position of the mover \( x \) \( \text{ (18)} \):

\[
F(I, x) = K_I I + K_x x \quad \text{................................. (3)}
\]

where \( K_I \) and \( K_x \) depend on dimensional and material parameters, such as the magnetic permeability of the material \( \mu_r \) and the flux leakage. If the values of these parameters are assumed constant, \( K_I \) and \( K_x \) are constants as well.

As the mover approaches one side of the stator, the corresponding variable air gap narrows, decreasing the total magnetic reluctance on that side. As a consequence, the permanent magnet flux increases in the corresponding half of the actuator and decreases in the opposite half. This causes a force, which is represented by the term \( K_x x \) in (3). Such force increases along the direction of motion, thereby creating negative stiffness, which can result in system instability \( \text{(14)} \). For this reason, a mechanical flexure is typically installed on the mover to compensate for the negative stiffness \( \text{(7)(13)} \). However, as for the voice coil actuator, the presence of such flexure does not significantly influence the studied properties of the actuator (magnetic flux and force). Therefore, no flexure is modeled in the present analysis and the mover is considered stationary in the simulation.

3. Modeling of the Actuators

For the purpose of comparison, the coils of the two actuators are designed with the same wire cross section and total number of turns \( \text{(7)} \). This means that each of the two series-connected coils of the hybrid reluctance actuator must contain half the number of turns as the single coil employed in the voice coil actuator. Consequently, a larger coil outer diameter \( D_{c, out} \) is selected for the voice coil actuator to accommodate the higher number of turns. Under this condition and neglecting the skin and proximity effect in the coils, the copper loss is the same for the two actuators.

Both actuators are designed to provide a stroke of \( \pm 1 \) mm. For this reason, the permanent magnet of the voice coil actuator is designed to be \( 2 \) mm longer than the coil. Additionally, the inner diameter of the magnet is set to \( D_{m, in} = 39 \) mm to provide \( 1 \) mm of radial clearance between the coil and the permanent magnet. The dimensional parameters of the voice coil actuators and of the permanent magnets are listed in Table 1 for the two actuators.

Electrical steel (50JNE470, JFE Systems, Inc., Japan) is adopted as material for the ferromagnetic parts of the two actuators, while a neodymium alloy (NdFe45) is employed for the permanent magnets and copper for the coils.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Voice coil actuator</th>
<th>Hybrid reluctance actuator</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>Coil inner diameter (D_{c,in})</td>
<td>23</td>
<td>23</td>
<td>\text{mm}</td>
</tr>
<tr>
<td>Coil outer diameter (D_{c, out})</td>
<td>37</td>
<td>30</td>
<td>\text{mm}</td>
</tr>
<tr>
<td>Coil length (L_c)</td>
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<td>22</td>
<td>\text{mm}</td>
</tr>
<tr>
<td>Number of turns per coil (N_t)</td>
<td>240</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>Number of coils (N_c)</td>
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<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Magnet length (L_m)</td>
<td>24</td>
<td>19</td>
<td>\text{mm}</td>
</tr>
<tr>
<td>Magnet inner diameter (D_{m, in})</td>
<td>39</td>
<td>-</td>
<td>\text{mm}</td>
</tr>
<tr>
<td>Magnet volume (V_m)</td>
<td>(8.8 \times 10^3)</td>
<td>(4.3 \times 10^3)</td>
<td>\text{mm}</td>
</tr>
<tr>
<td>Actuator volume (V)</td>
<td>(7.4 \times 10^4)</td>
<td>(9.3 \times 10^4)</td>
<td>\text{mm}</td>
</tr>
</tbody>
</table>

4. Finite Element Analysis

In this paper, ANSYS Electronics Desktop 2017.0 (ANSYS, Inc., Canonsburg, USA) is employed for the electromagnetic simulations.

4.1 Spacial-domain Analysis

In this section, the actuators are analyzed for the case of a DC input current. The actuation force and thrust constant are simulated for different current amplitudes and positions of the mover.

4.1.1 Actuation Force

A spacial analysis is performed to simulate the force acting on the movers of the two actuators. Figure 3 shows the force \( F \) for the case of the voice coil actuator as a function of the current \( I \) and of the normalized position of the mover. This is defined as \( x/x_{\text{max}} \), where \( x \) is the position of the mover measured from the middle position and \( x_{\text{max}} \) the motion range. Because of the attraction force generated by the coil on the ferromagnetic stator, the overall actuation force is higher for positive than for negative values of the current \( \text{(7)} \). Notice that the force curve shows an almost linear behavior respect to the current \( I \), with a maximum linearity error of app. 4.1\%. Additionally, the force does not change significantly with the position of the mover. This has two main implications. In the first place, it means that the voice coil actuator is able to deliver about the same force at all positions of the mover. In the second place, it means that the actuator introduces little or no additional stiffness due to the position independency of the force \( \text{(7)} \). This results in low transmission of environmental vibrations, which is a desired feature in several high-precision applications \( \text{(6)} \).

Figure 4 shows the force \( F \) acting on the mover of the hybrid reluctance actuator. In this case, the relation between force and current is strongly non-linear, especially for high currents. This is due to the saturation in the ferromagnetic
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Fig. 3. Simulated force $F$ acting on the mover of the voice coil actuator. The force shows good linearity with the current and low dependency on the normalized position of the mover $x/x_{\text{max}}$.

Fig. 4. Simulated force $F$ acting on the mover of the hybrid reluctance actuator. The force is non-linearly dependent on the current $I$ and the normalized position of the mover $x/x_{\text{max}}$.

material, which causes the relative permeability $\mu_r$ to level off for high values of the magnetic field strength $\vec{H}$. Notice that the absolute value of $F$ increases as the mover approaches the stator. This is due to the negative stiffness $K_x$, which can impair the performance of the actuator, for example with regard to the transmission of environmental vibrations. As a solution, a mechanical flexure can be installed on the mover to compensate for the negative stiffness with its own positive stiffness. However, the negative stiffness varies non-linearly with respect to the position of the mover between app. $-4 \times 10^4$ N/m and app. $-3.7 \times 10^5$ N/m. This can pose a challenge to design the flexure to compensate for a specific value of $K_x$.

The ratio between force and volume of the actuator is often used as a key indicator to assess the performance of electromagnetic motors and actuators. Figure 5 shows the simulated force to volume ratio for the two studied actuators. For a given input current, the force to volume ratio of the voice coil actuator is constant at all positions of the mover and varies between app. $-0.26$ MN/m$^3$ (for $I = 3$ A) and app. $0.20$ MN/m$^3$ (for $I = -3$ A). In the case of the hybrid reluctance actuator, the force to volume ratio changes greatly within the position of the mover, with a maximum absolute value of app. $2.1$ MN/m$^3$ for $x/x_{\text{max}} = 0.95$ and $I = 3$ A. As a result, over the entire motion and current range the hybrid reluctance actuator can generate up to app. 10.5 times higher forces per volume than the voice coil actuator.

4.1.2 Thrust Constant

The thrust constant $K_I$ is typically employed as an indicator to estimate the performance of electromagnetic motors and actuators. For the voice coil actuator, such constant can be calculated for a given input current $I_0$ and position of the mover $x_0$ as:

$$K_I(I_0, x_0) = \frac{F(I_0, x_0)}{I_0}.$$

For the hybrid reluctance actuator, $K_I$ is derived from (3) as:

$$K_I(I_0, x_0) = \frac{F(I_0, x_0) - F(0, x_0)}{I_0}.$$

Figure 6 shows the simulated thrust constant of the two actuators. For comparison purposes, the $K_I$ is calculated for an input current $I_0 = 500$ mA. For the voice coil actuator,
the value of the thrust constant is app. 6 N/A at all positions of the mover. For the hybrid reluctance actuator, the value of $K_I$ varies between app. 22 N/A (when $x/x_{\text{max}}=0$) and app. 57.5 N/A (when $x/x_{\text{max}}=0.95$). This means that, for the same current, the force generated by the hybrid reluctance actuator is between app. 3.7 and app. 9.6 times higher than that of the voice coil actuator, depending on the position of the mover.

In the case of the hybrid reluctance actuator, the force $F$, the thrust constant $K_I$ and the negative stiffness $K_s$ change non-linearly as the mover approaches the stator. This is in disagreement with the analytical model shown in (3), which establishes a linear relation between the force, the current and the position of the mover. Such discrepancies may be caused by changes of the magnetic flux leakage at different positions of the mover. To gain better understanding of this behavior, an electromagnetic simulation is performed to compute the magnetic flux leakage of the two actuators.

### 4.1.3 Magnetic Flux Leakage

The magnetic flux leakage is typically quantified via the efficiency factor $\lambda$, defined as:

$$\lambda = \frac{\Phi_g}{\Phi_m}$$  \hspace{1cm} (6)

where $\Phi_m$ is the magnetic flux generated by the permanent magnet and $\Phi_g$ is the magnetic flux which is available for actuation. This is defined as the magnetic flux intersecting the coil for the voice coil actuator, or as the sum of the magnetic fluxes in the left and right variable air gap (both measured at the stator) for the hybrid reluctance actuator. Notice from (6) that, for a given magnet, the value of $\lambda$ is solely determined by the value of $\Phi_g$. A high flux leakage results in a low value of $\Phi_g$ and, consequently, in a low value of $\lambda$.

Figure 7 shows the simulated efficiency factor $\lambda$ of the two actuators as a function of the normalized position of the mover. Small ripples in the curves are likely due to numerical errors. At all positions of the mover, $\lambda$ is between app. 1.04 and app. 1.36 times higher for the hybrid reluctance actuator than for the voice coil actuator. Additionally, while in the case of the voice coil actuator, the value of $\lambda$ fluctuates with small deviations around an average value $\lambda_{\text{mean}} \approx 0.68$, for the hybrid reluctance actuator it increases steeply as the mover approaches the stator. This is due to the decreased size of the variable air gap, which results in a lower flux leakage in the side of the actuator where the magnetic flux is highest. As a result, the usable magnetic flux for actuation increases greatly as the mover approaches the stator. This causes a steep increase of the force and thrust constant close to the end of the motion range, as observed in Sec. 4.1.2.

For analytical modeling, the flux leakage is usually represented as a constant $\lambda_{\text{eff}}$, which typically lies between $\lambda = 0.25$ and $\lambda = 0.75$. Although this approach could be adopted to describe the behavior of the voice coil actuator, it is completely insufficient for the hybrid reluctance actuator. In this case, the value of $\lambda$ is strongly dependent on the position of the mover and in some cases exceeds the typical maximum value $\lambda = 0.75$. This simulation clearly demonstrates the need of FEA to accurately analyze the characteristics of hybrid reluctance actuators.

### 4.2 Frequency-domain Analysis

In this section, the actuators are analyzed for the case of an AC input current. The power losses, as well as the thrust constant, are simulated for different frequencies of the input current.

#### 4.2.1 Power Losses

In most electromagnetic motors, actuators and transformers, power dissipation mainly occurs in the form of copper loss (in the actuator coils) and iron loss (in the ferromagnetic components)\(^{25}\). Such losses can cause several undesired effects, such as decreased energy efficiency, overheating and acoustic noise\(^{26}(27)\). Therefore, in this section FEM is employed to compute the copper and iron loss of the two considered actuators. Since such losses are known to increase with the frequency of the input current\(^{28}\), a frequency-domain simulation is performed from 1 Hz to 10 kHz.

Figure 8 shows the simulated copper and iron loss for an input current amplitude $I_0 =100$ mA. At low frequencies, the copper loss is constant and approximately the same for the voice coil (3 mW) and the hybrid reluctance actuator (2.7 mW). At high frequencies, the copper loss increases...
due to the the skin and proximity effects, which cause the AC resistance of the coils to increase \(^{(29)}\). Throughout the considered frequency range, the copper loss is up to app. 1.5 times larger for the voice coil than for the hybrid reluctance actuator. This is due to the fact that the AC resistance changes at different rates for the two actuators due to the different dimensional parameters of the coils \(^{(30)}\). The iron loss also increases with the frequency mainly due to the eddy currents and hysteresis in the ferromagnetic components. Notice that within the considered frequency range the iron loss is between 1.3 and 5.1 times larger for the hybrid reluctance actuator than for the voice coil actuator.

The total loss of the two actuators is shown in Fig. 9. Notice that for frequencies higher than 10 Hz, the total loss of the hybrid reluctance actuator is larger than that of the voice coil actuator, thereby resulting in a lower energy efficiency. This makes the studied hybrid reluctance actuator more suitable for operation at low frequency. Countermeasures to improve the performance of such actuator at high frequency include the employment of softer ferromagnetic materials or laminated ferromagnetic components, which are characterized by lower iron loss, as discussed in more detail in Sec. 4.2.2.

4.2.2 Dynamic Thrust Constant

In applications where hybrid reluctance actuators are employed (e.g. fast steering mirrors \(^{(18)}\)), the iron loss was shown to pose a limit for the achievable control bandwidth and positioning precision. To properly evaluate such behavior, a frequency-domain simulation is performed to compute the dynamic thrust constant \(K_f(j \omega)\).\(^{(14)}\)

\[
K_f(j \omega) = F(j \omega)/I(j \omega)
\]

of the two actuators. In experimental measurements, the frequency response and bandwidth are typically evaluated for small values of the input current to prevent saturation of the input amplifier. The frequency response of \(K_f(j \omega)\) is shown in Fig. 10 for both actuators. Notice that, while the magnitude and phase of \(K_f(j \omega)\) are constant for the voice coil actuator, a considerable magnitude slope (app. \(-14.4\) dB/dec) and a high phase lag (app. \(-71^\circ\) at \(f = 10\) kHz) can be observed in the case of the hybrid reluctance actuator. This disparity results from the different operation principles of the systems. In the voice coil actuator, the force is directly proportional to \(I\), as shown in (1). In the case of current drive, \(I\) does not depend on the inductance of the coil and is therefore not affected by the iron loss in the ferromagnetic stator. In contrast, in the hybrid reluctance actuator the force is proportional to the square of the magnetic flux in the air gap (see (2)), which is affected by the iron loss \(^{(19,20)}\). Consequently, the magnitude and phase of \(K_f(j \omega)\) decrease as the iron loss increases with the frequency (as shown in Section 4.2.1). This greatly influences the performance of the actuator, as the resulting phase lag can limit the achievable control bandwidth in systems requiring high positioning precision \(^{(17)}\). Additionally, the decrease in the magnitude of \(K_f(j \omega)\) means that the actuator exerts lower forces for the same current as the frequency increases. For a frequency higher than app. 1.5 kHz in Fig. 10, the thrust constant of the hybrid reluctance actuator is lower than that of the voice coil actuator.

Such drawbacks can be partially overcome by means of a careful material selection. For example, a softer ferromagnetic material, characterized by lower iron loss, can be employed for the ferromagnetic components of the actuator. For demonstration, the dynamic thrust constant is simulated by
employing a different electrical steel (10JNEX900, JFE Systems, Inc., Japan) for the stator and the mover. The material parameters, including the electrical conductivity $\sigma$ and the iron loss coefficients from the Bertotti model \(^{(10)}\) are listed in Table 2. Notice that the values of all the parameters are lower for 10JNEX900 with respect to 50JNE470. The resulting frequency response plot is shown in Fig. 11. Notice that, while no significant changes are observed for the voice coil actuator, both the magnitude slope (app. $-11 \text{ dB/dec}$) and the phase lag (app. $-55.5^\circ$ at $f = 10$ kHz) of $K_p(j\omega)$ are reduced in the case of the hybrid reluctance actuator. Finally, the frequency threshold is also increased of app. $1.8$ kHz to app. $3.3$ kHz. This can be further improved by replacing the solid ferromagnetic components with laminated parts, consisting of several isolated layers of sheet material, as typically done in the case of transformers \(^{(34)}\) and also reported for hybrid reluctance actuators \(^{(33)}\).

In summary, the presented results show the ability of FEA to model the behavior of electromagnetic actuators both in the spacial and in the frequency domain. The hybrid reluctance actuator is shown as an efficient device to achieve a large output force. However, this comes at the cost of a high negative stiffness, as well as unwanted decrease of the thrust constant and a phase lag at higher frequencies. Such behavior is due to the iron loss in the ferromagnetic system components and can be at least partially improved via a careful material selection (see Fig. 11). Overall, the resulting trade-off between thrust constant, linearity and frequency response can be critical in applications requiring both high scanning speed and high positioning precision, such as fast steering mirrors \(^{(25,33)}\) and flexure-guided scanning systems with nanometer resolution \(^{(37)}\).

5. Conclusion and Future Work

In this paper, FEA is employed to accurately compare the properties of a hybrid reluctance actuator and of a voice coil actuator for high-precision applications. For detailed analysis, both spacial- and frequency-domain simulations are carried out to evaluate the force, thrust constant and power losses of the actuators. The simulation results show that the studied hybrid reluctance actuator can achieve between 3.7 and 9.6 times higher thrust constant compared to the studied voice coil actuator. However, the position-dependent force causes a variable negative stiffness with values between $-4 \times 10^3$ N/m and $-3.7 \times 10^3$ N/m. Additionally, the energy efficiency of the hybrid reluctance actuator is shown to degrade at high frequencies, as the total loss rises above that of the voice coil actuator. This results in a decreased performance, as the magnitude of the thrust constant decreases below that of the voice coil actuator beyond a certain frequency ($f \approx 1.5$ kHz) and a high phase lag ($\phi \approx 71^\circ$ at 10 kHz) is induced. Finally, it is demonstrated that this behavior can be improved by selecting a softer ferromagnetic material for the actuator components, as the frequency threshold is significantly extended to app. $3.3$ kHz and the phase lag reduced to $-55.5^\circ$ at $10$ kHz.

As part of future work, optimization studies will be performed based on the identified comparison parameters for different dimensional and geometric configurations of voice coil and hybrid reluctance actuators.

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References


Table 2. Material parameters of the employed steel types

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<thead>
<tr>
<th>Parameter</th>
<th>50JNE470</th>
<th>10JNEX900</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical conductivity ($\sigma$)</td>
<td>$2.8 \times 10^6$</td>
<td>$1.2 \times 10^6$</td>
<td>S/m</td>
</tr>
<tr>
<td>Hysteresis coefficient ($K_h$)</td>
<td>385.9</td>
<td>133.5</td>
<td>W/(Hz·T$^2$)</td>
</tr>
<tr>
<td>Classical eddy coefficient ($K_e$)</td>
<td>$60 \times 10^{-3}$</td>
<td>$1.3 \times 10^{-3}$</td>
<td>W/(Hz·T$^2$)</td>
</tr>
<tr>
<td>Excess coefficient ($K_i$)</td>
<td>15.8</td>
<td>1.26</td>
<td>W/(Hz·T$^3$)</td>
</tr>
</tbody>
</table>
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