A Rotary Induction Actuator for Kinesthetic and Tactile Rendering

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Abstract. Actuators with low inertia and high bandwidth are of great interest for haptic devices, as they improve the quality of force rendering and transparency. This paper describes, as a proof of concept, a new design in rotary induction motors, the Axial-DSIM (Axial Double-Sided Induction Motor). This motor has a simple design construction that consists of a thin and lightweight disc-shaped moving secondary (rotor) surrounded by fixed primaries on both sides that generate a rotating magnetic field that induces a force on the disc. The low inertia of this motor and its principle of operation make it possible to render high-fidelity torques with high dynamics.

Keywords: Design of haptic interfaces · Axial-DSIM (Axial Double-Sided Induction Motor) · Kinesthetic and tactile device

1 Introduction

Nowadays, the field of haptics is experiencing substantial growth; interest in haptic interfaces has increased considerably given their wide range of applications, including teleoperation, rehabilitation, education, games, arts, sciences, etc. However, the mechanical structure of most existing interfaces limits the transparency and rendering of haptic interactions [2]. The type of motor-drive system in a haptic interface is the predominant factor behind its selection. For instance, haptic devices that can produce high forces will not usually be capable of producing tiny and precise ones. The actuator, in this case, will be relatively large and massive; as a result, its large inertia will mask the perception of small forces. A small motor with low inertia, on the other hand, will be capable of producing weak and precise forces, but not large ones due to its small size [5].

An ideal haptic interface should be designed to cover the bandwidth of human haptic perception, and to faithfully render and scale forces without any structural distortion. The fidelity of a haptic interface is expressed as its transparency, which is obtained when the haptic signals rendered by the device are not distracted or scrambled by its mechanical dynamics [4]. Consequently, the ideal

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haptic interface should exhibit low inertia, low mass, low friction, and a high structure stiffness while generating force with high dynamic range [8]. Thus, a lot of attention should be dedicated to the design, choice, and supply/control of the actuators used in the design of haptic interfaces.

This paper introduces the Axial-DSIM (Fig. 1) and details its design and some of its parameters and characteristics, and its advantages over other types of Eddy-current actuators previously introduced in the literature.

The Axial-DSIM seems to be an excellent candidate because the forcer (rotor, moving part, or secondary) is simply a thin sheet of conductor that could weigh a few grams only and upon which a force is exerted when placed in a traveling magnetic field.

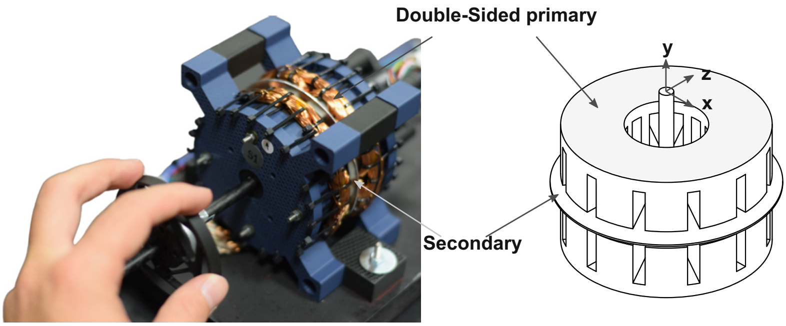

Fig. 1. The Axial-DSIM (Axial Double-Sided Induction Motor). The rotor's axis is coupled to a handle to transmit torque to the human operator.

2 Eddy-Current Based Haptic Devices

Eddy-current based actuators are appealing for haptics because of their low inertia. They have been employed in designing haptic interfaces but have not yet been commercialized. The primary goal behind the design of these interfaces is to reduce inertia and improve transparency [3,8,9], and [10].

In [8,9], and [3], rotary Eddy-current clutches are used in which a motor is used to rotate magnet-carrying discs around a non-ferromagnetic low inertia conductor to induce force on it; this complicates the control and makes the response time slower because to change the direction of the torque, it is necessary to change the direction of the motor that spins the magnet-carrying disc. And because the inertia of the motor and the magnet-carrying disc is high, the change in direction will be slower, resulting in a slower response time. In addition, when the magnets do not rotate and the handle is moved, viscosity is felt.

To have more flexibility in the control and a simpler mechanical design, we decided to replace the rotating magnet-carrying discs with a set of two electromagnets that surround the rotor. Thus, instead of having a fixed magnetic field that is moved mechanically, we will have a magnetic field generated by fixed electromagnets whose amplitude and speed are determined by the amplitude and frequency of the windings supply, which should result in a faster response time and a finer torque due to the higher actuation frequency.

3 Human Haptic Perception and the Design Requirements of an Ideal Haptic Interface

Knowledge gained on human haptic perception helped to understand how to develop and improve the design of haptic interfaces. The human haptic perception relates to two cognitive senses: the tactile sense and the kinesthetic sense. Both senses are very important for to manipulation and locomotion [1,4,12].

Haptic Interfaces are divided into two: Kinesthetic and tactile. Kinesthetic interfaces produce force feedback, and tactile interfaces deliver tactile feedback. Both types have progressed in recent years, but the two types are commonly addressed separately. That's mainly because kinesthetic actuators that render force feedback aren't usually capable of rendering tactile information through vibration over a large bandwidth. And vibrators that render tactile information naturally aren't capable of generating force feedback. Coupling the two displays is an essential feature to have in haptic interfaces, especially if they are intended to be used for teleoperation tasks. Obtaining both stimuli simultaneously is usually accomplished by mixing both types of haptic interfaces [6,7,9,11], and [12].

4 The Principle of Operation of the Axial-DSIM

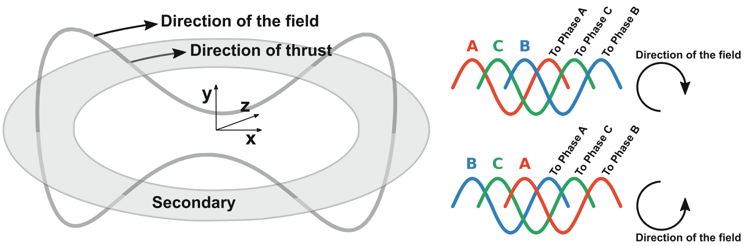

Fig. 2. The principle of operation of the Axial-DSIM.

When the primaries of the motors are fed with a three phased supply, a time traveling magnetic field will flow in the air gap between the two primaries and causes the secondary to move in the same direction as the field as illustrated in Fig. 2. When the time-traveling field passes through the non-ferromagnetic conductor, a current is induced in the conductor to oppose the change in the field by creating another magnetic field that opposes the change in the original magnetic field generated by the primaries. The induced current and the magnetic field of the primaries generate the force on the conductive plate. This is given by Laplace's law, which states that "A conductor through which a current flows and placed in a magnetic field is subject to a force." The frequency of the three-phase input supply determines the speed of the magnetic field, and the amplitude of the supply voltage determines the amplitude of the field. To reverse the direction of the magnetic field, i.e., the direction of the torque, the phase sequence must be altered from ACB to BCA by swapping the power supply of phase A with the power supply of phase B (Fig. 2).

5 Important Parameters and Considerations

The width of the air gap, i.e., the distance that separates the two sides of the primary, has a significant effect on the thrust and efficiency of the motor. When the length of the air gap increases, the efficiency and thrust decrease. Thus, the air gap must be as small as is mechanically possible. The smaller the air gap, the better the performance and thrust. The secondary thickness and conductivity are also important parameters to consider. The higher the electrical conductivity of the secondary, the higher the thrust produced. Here, aluminum was prioritized because it has the best weight to conductivity ratio. Keeping a small thickness secondary with a small air gap width is recommended. That falls to our advantage in minimizing the weight and inertia of the secondary. The input frequency is an important parameter as well. The frequency must be chosen in accordance with the magnetic characteristics of the primary core of the motor. The Axial-DSIM uses the SMC (Soft Magnetic Composite) "Somaloy 700HR 5P" that has fewer core losses at 60 Hz. Consequently, to output the maximum torque, the input supply frequency must be set to near the rated frequency of the primary core. And to decrease torque via frequency change, the supply frequency must be increased. At high frequencies, the windings' impedance rises, core losses rise, and the depth of Eddy-current penetration in the secondary decreases, resulting in torque reduction.

6 The Design of the Axial-DSIM

6.1 The Primaries

Aside from the primary core's material considerations, its geometry is also quite important. In the initial design that was intended to be sent to fabrication (Fig. 3 (a)), we wanted the primary to have an outer diameter of no more than 8 cm to avoid increasing the inertia of the secondary by increasing its diameter, and a deep slot with a small opening to reduce the slotting effect while yet allowing for the placement of coils with a sufficient number of turns. With SMC materials, complex shapes could be formed and fabricated at a lower cost than traditional silicon steel laminations. Making the mold is the most expensive aspect of the production process. Manufacturing a tiny amount is not cost-effective, which is why in this proof of concept, we have chosen as an alternative to use the

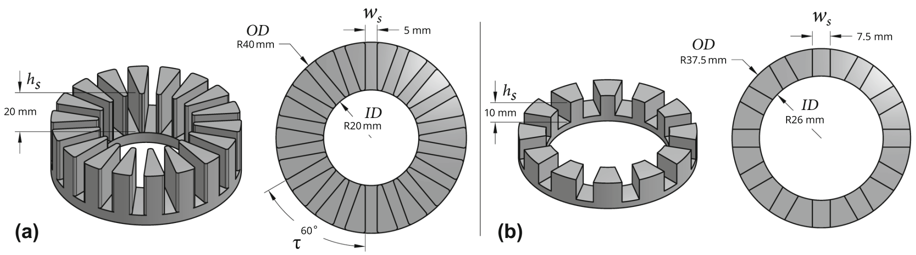

Fig. 3. (a) the initial intended design, (b) the design used in the experiments (primary used usually for single sided axial brushless DC motors).

primaries that are already used in the manufacture of single-sided axial brushless DC motors (Fig. 3 (b)). Although this primary core isn't perfect for an induction motor, it could be used to demonstrate the principle of actuation and its benefits.

6.2 The Winding Design

There are mainly two types of windings design: the one-layer planar (concentrated) non-overlapping windings and the overlapping double-layer windings. Induction motors often use overlapping double-layer windings, which provide a traveling field with fewer harmonic content as compared to the one-layer planar windings design. Here we have chosen to combine the two by adopting a three-layer planar, double-layer winding design (Fig. 4). This winding design is not recommended for single-sided configurations because the magnitude of the magnetic field generated by the phase closer to the air gap (third layer) is stronger than the amplitude of the field generated by the phase of the first layer. However, in a double-sided configuration that could be accounted for in the design by reversing the order of layers in the second side (Fig. 4). Each phase on each side consists of four sets of 60-turn coils connected in series (Fig. 5).

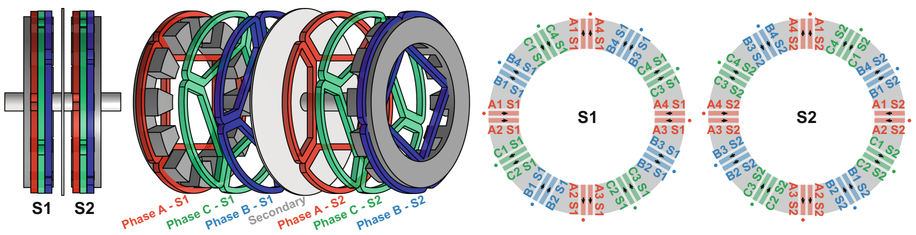

Fig. 4. The winding design of the Axial-DSIM (The three-layer planar, double-layer winding design).

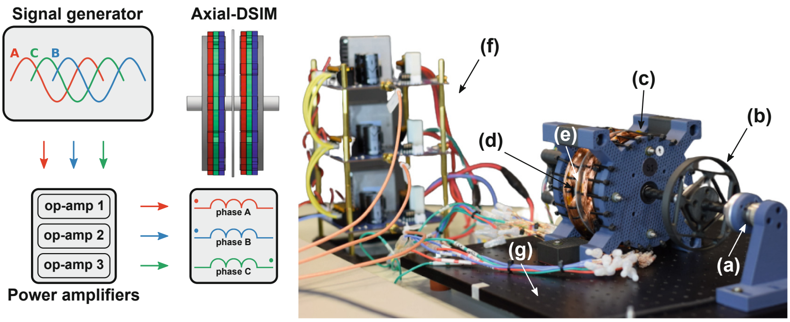

Fig. 5. The experimental setup. (a) the "ATI nano-17 force sensor", (b) the handle, (c) the first side of the stator, (d) the second side of the stator (3 mm apart from the first side), (e) the rotor (aluminum disc 80 mm in diameter and 1 mm in width), (f) the linear power amplifiers, and (g) the anti-vibration plate.

7 The Experimental Setup and the Shape of the Supply

Since the main interest is the quality of the rendered torque, the axis of the rotor has been attached to a high-resolution 6-DoF force sensor, the "ATI nano-17 force sensor". The motor and sensor are mounted on an anti-vibration plate to limit noise and vibrations coming from nearby equipment. The motor was supplied by three 120° phase shifted sine waves. The three sines were generated by a signal generator and amplified by linear power amplifiers. The shape of the power supply voltage greatly influences the quality of the rendered force and other factors such as noise and heating. The secondary disc is significantly less likely to overheat when the three phases are supplied with purely sinusoidal voltages. Therefore, as in HI-FI audio systems, we used linear power amplifiers fed with symmetrical linear power supplies. Linear power supplies have very low noise and ripple levels and react quickly to changes in voltage, resulting in a faster response time.

8 The Experimental Results

The Axial-DSIM could be controlled by a fixed-frequency/variable-voltage drive, a variable-frequency/fixed-voltage drive, or by variable-frequency/variable-voltage drive. This control flexibility falls to our advantage because it allows us to act on both the frequency and the amplitude to create intriguing and varied haptic renderings. Figure 7 shows the plot of torque and current per phase when the frequencies vary while the voltage remains constant. Hence, if a fixed-frequency/variable-voltage drive is to be used, the frequency should be adjusted at the primary core's rated frequency, which is 75 Hz, as seen in the plot of Fig. 7. Figure 8 shows the reaction time the motor takes to change the direction of torque. The change in direction was simply performed by swapping the power supply of phase A with the power supply of phase B. Given the Axial-DSIM's compelling dynamics, we chose to modulate the amplitude of the input supply to add vibrations to the constant force (Fig. 6).

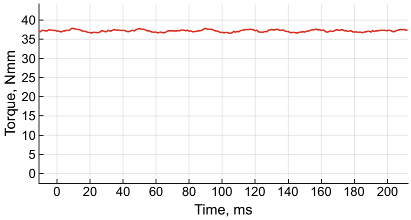

Fig. 6. Shape of constant torque generation as a function of time.

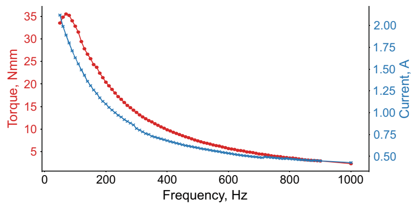

Fig. 7. Measured torque and current per phase as a function of frequency.

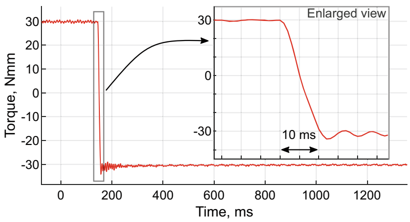

Fig. 8. Axial-DSIM reaction time to changes in direction of torque, the change from 30 Nmm to −30 Nmm took about 10 ms.

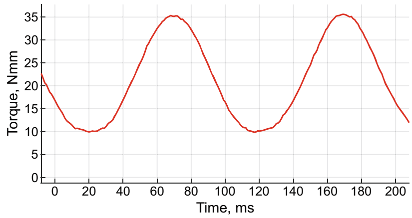

Fig. 9. Shape of the torque generated by the Axial-DSIM when supplied with a three-phase amplitude modulated signal; here a vibration 10 Hz was added.

In Fig. 9, we can see the shape of the torque exerted on the rotor when the Axial-DSIM is supplied with a three-phase supply 100 Hz amplitude modulated by a sinusoidal wave 10 Hz. The motor's vibration bandwidth is quite large; vibrations up to 1000 Hz Hz can be rendered and perceived. The maximum torque that can be generated with this design is about 100 Nmm. The maximum torque could be significantly increased if the primary cores were designed in the manner depicted in Fig. 3 (a).

9 Conclusion

The Axial-DSIM, a prototype haptic actuator with a low inertia rotor, was designed and built. The basic principle of the motor's operation was presented to familiarize the reader with the physics behind its operation. The experiments performed have proved that the Axial-DSIM is indeed interesting for haptics due to its wide range of rendering abilities that no other type of actuator of only one kind could provide. The Axial-DSIM's response time to change is the direction of thrust, and its ability to render vibrations over a large bandwidth demonstrates that the motor is ideal for both kinesthetic and tactile perception. The simplicity of its design and control makes it more interesting than magnet-carrying Eddy current coupling devices. The Axial-DSIM is not as energy efficient as a brushless DC motor because it lacks permanent magnets in its rotor. However, the uniqueness of the Axial-DSIM resides in its simple sheet of non-ferromagnetic conductor rotor that enables having low inertia and no cogging. In addition, the Axial-DSIM does not require an encoder for torque generation.

The main goals for future work include the further optimization of the motor and its design, the coupling of the Axial-DSIM with a slave micro-manipulator to perform micro teleoperated tasks (the specificities of the motor make it ideal for use in applications such as micro-teleoperation where high dynamics and vibrations are present), and the use of the motor to conduct studies on the perception and discrimination of force and vibration.

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