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Two synchronous permanent magnet machine frameworks for a direct drive active stick application

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Abstract *This paper deals with the comparison of two actuators with different frameworks for a direct drive active stick application. The set of specifications impose many constraints as torque, torque ripples, temperature etc… The high required torque per unit of mass and the small volume allowed oblige us to use synchronous permanent magnet topologies which have the best torque performances. We will compare a tubular linear synchronous permanent magnet actuator to a double airgap rotating synchronous permanent magnet actuator. We will calculate the torque with the Laplace force and the magnetic flux density without loads thanks to the Ampere law. Then we will make an optimization with the analytical expressions of the torques we get previously. We will make simulations on the optimized structures in order to validate the analytical model. Finally we will compare the two actuators in order to give the best compromise for the stick application.*

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Introduction

Many of the actual aircrafts use fly by wire with passive sticks to create force feedback. This force depends of the displacement angle of the stick compared to the natural resting position. Two passive sticks in the cockpit, on the left side for the pilot and on the right side for the co-pilot, create feedback force by compression of springs. It has been demonstrated that active stick technology can improve haptic sensation in comparison with passive solution. We can cite studies in [1, 2, 3] and also companies [4, 5, 6] dealing with this topic. Most of the time, the actuated stick is composed of a conventional rotating motor with a reducer. The requirements given by the aeronautical companies are highly restrictive: a high torque per unit of mass (around $3 \ (Nm.Kg^{-1})$), the lack of torque ripple, a low volume allocated, a low electric consumption and a low failure rate. Complying with all of these requirements is very difficult and there is currently very few industrial active devices.

In this article we will propose two active direct drive solutions (without reducer): the first one is a tubular linear permanent magnet (PM) machine and the second one is a double airgap rotating synchronous permanent magnet machine (with non-entire arc). In the first part we will describe the set of specifications of the active stick. In the next part we will develop the pre-dimensioning in order to reach an analytical expression of the torque. We will use a global approach to give a simple expression of the torque and to make an analytical optimization with fast computation time. In the third section, the simulations results are done on optimized structures. In the last section, we will compare the two actuators in order to determine which solution offers the best compromises.

Set of specifications

For this application we have to comply with a set of constraints such as dimensions, duplications, forces, stroke, speed, temperatures and force ripples constraints. The application requires that the system is redundant for each axis (pitch and roll). Thus, for each axis, two actuators are implemented in parallel and are embedded in a box of which dimensions are 175*150*60 (*mm*). The grip middle point distance d_{gmp} is the distance between the pivot and the point where the force F_p is applied by the pilot as in Fig. 1.
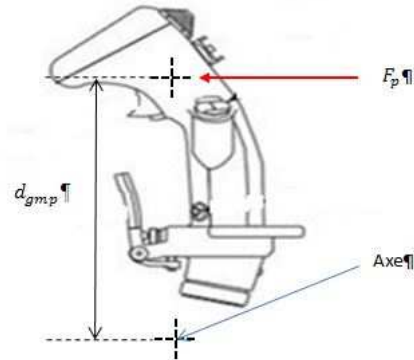

Fig. 1. Grip middle point distance

The maximum torque to be developed by each actuator is thus equal to:

$$C_p = F_p * d_{gmp} = 3.2 \ (Nm) \qquad (1)$$

In a passive stick the effort is a linear function of the displacement angle. But in the case of an active technology, the curve of the force in function of the displacement angle can be piecewise continuous as shown in Fig. 2.
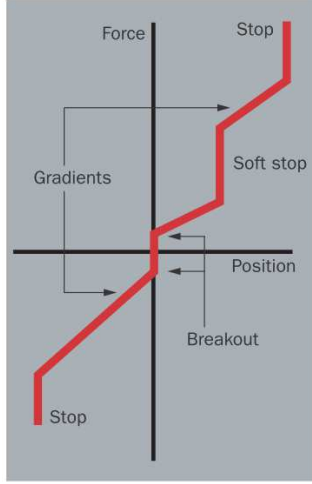
Fig. 2. Force vs position characteristic [6]

Pre-dimensioning

We will compare two different actuators, the first one, shown in Fig. 3, is a linear tubular synchronous permanent magnet machine [7]. The ring shape coils supplied by three-phase sinusoidal current are molded and tied to the stator at the ends. The stator has no teeth in order to reduce the saliency effect. The ring shape permanent magnets are radially magnetized.
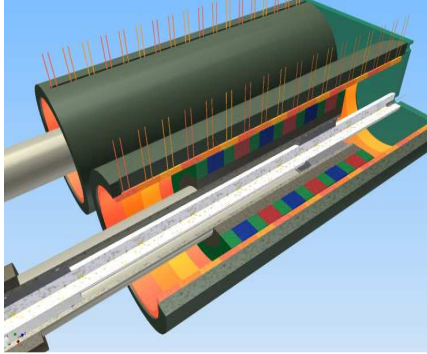

Fig. 3. Tubular moving magnet actuator [7]

The second kind of actuator is a rotating synchronous permanent magnet machine with two airgaps, shown in Fig. 4. The stator in iron is surronded by the coils which are supplied by three-phase sinusoïdal current. The inner and outer rotors are fixed by a plate and are composed of two iron yokes and magnets radially magnetized.

According to the kind of actuator (linear or rotating), the variable of displacement is a distance in meter or an angle in radian. We use the variable X which can be used for linear and rotating machine. X_R is the variable which allows to describe the rotor. X_S describes the stator and X_{RS} describes the position of the rotor compared to the stator:

$$X_S = X_R + X_{RS} \qquad (2)$$

The waveform created by the radial magnetization pattern and the displacement of the rotor is considered as strictly sinusoidal. We can traduce this mathematically by:

$$\boldsymbol{J_m}(X_R) = \hat{J}_m . \sin\left(\pi \frac{X_R}{X_{pitch}}\right) . \boldsymbol{e_r} \qquad (3)$$
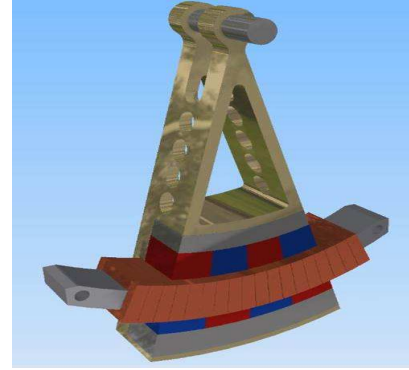

Fig. 4. Double airgap synchronous machine

Copper wire of the stator is crossed over a current I. We define two currents densities J_{coil} and J_{slot} which respectively represent the current densities in a coil and in a slot expressed in $(\mathrm{A.mm^{-2}})$. The magneto-motive force nI with n the number of turns per slot is equal to:

$$k_f . J_{coil} . S_{slot} = nI \qquad (4)$$

where k_f is the slot fill factor equal to the ratio $\frac{S_{coil}}{S_{slot}}$.

We can calculate the linear force and then the torque thanks to the Laplace force:

$$\boldsymbol{dF_L} = I . \boldsymbol{dl} \times \boldsymbol{B_e} \qquad (5)$$

where $\boldsymbol{B_e}$ is the pseudo-vector of magnetic field in the airgap without load, I the total current in the coil, $\boldsymbol{dl}$ an infinitesimal part of the current trajectory and $\boldsymbol{dF_L}$ the infinitesimal Laplace force. To reach the total force applied over the contour we need to integer around the windings.

$\boldsymbol{B_e}$ is calculated with the Ampere law and is equal to a coefficient K_e which only depends of the pattern geometry and of the radius r multiplied by the polarization waveform created by PM:

$$\boldsymbol{B_e}(r, X_R) = K_e(r) . \boldsymbol{J_m}(X_R) \qquad (6)$$

Finally, we get the total force of the linear actuator or the total torque of the rotating machine by the calculation of the average of the force over the surface of each coil. If we consider a *m*-phase sinusoidal current, the force is given by:

$$F_m = \frac{2p}{S_{coil}} \int_{R_i - e_{ci}}^{R_i} \sum_{\lambda=1}^{m} \int_{(\lambda-1)*\frac{X_{pitch}}{m}}^{\lambda*\frac{X_{pitch}}{m}} F_L{}^{\lambda}(r, X_s, t).dS \qquad 7)$$

$$C_m = \frac{2p}{S_{coil}} \int_{R_i - e_{ci}}^{R_i} \sum_{\lambda=1}^{m} \int_{(\lambda-1)*\frac{X_{pitch}}{m}}^{\lambda*\frac{X_{pitch}}{m}} r.F_L{}^{\lambda}(r, X_s, t).dS \qquad (8)$$

where p is the pole pairs number, R_i the inner radius, e_{ci} the thickness of a coil and $F_L{}^{\lambda}$ is the instantaneous force developed by each coil supplied by a sinusoidal current.

Finite Element simulation results

Fig. 5 gives the radial component of the magnetic flux density in the double airgap machine by Finite Element Method (FEM) software.
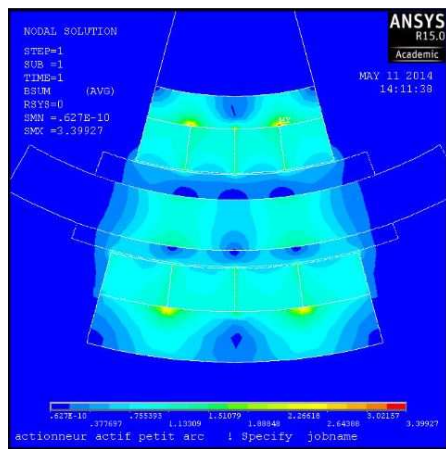

Fig. 5. Radial component of the magnetic flux density

Fig. 6 gives the force in single phase opposite continuous current in function of the stroke for the linear structure. With a three phase sinusoidal supply, the total force reached is almost constant and equal to ¾ of the peak force value of Fig. 6.
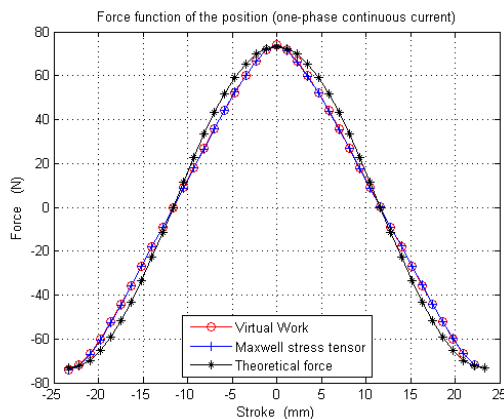

Fig. 6. Force in single phase opposites continuous current in function of the stroke

Comparison of the two actuators

Table 1 compares the main characteristics of the two frameworks.

Table 1: Comparison of the two actuators

Parameters	Linear machine	Rotating machine
Torque (Nm)	3.2	3.2
Mass (kg)	0.93	1.19
Volume (m^3)	2.5e-4	1.8e-4
Magnet volume (m^3)	2.12e-5	2.37e-5
Copper volume (m^3)	2.48e-5	6.13e-5

Conclusions

In this paper, we present two topologies of direct drive actuated stick for an aeronautical application. The calculation of the force and the torque developed by each actuator is based on an analytical approach. With the help of FEM simulations, the analytical calculations are checked for optimized structures. The conclusion will allow us to give the advantages and disadvantages of each framework in order to be able to choose the best one for this application.

Aknowledgement

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