HIGH – SPEED STEPPER MOTOR FOR MECHANISM
SAGEM STEPPERS MOTORS : 27PP and 35 PP

Jean-François Oudet*,

SAGEM*
Unité de Fabrication Senseurs Inertiels
Route de châteauroux,
BP 3247 - 03106 MONTLUÇON CEDEX.
Phone : +33(0)4.70.28.75.34
Fax : +33(0)4.70.29.06.55
Email : jean-francois.oudet@sagem.com

François Pagnon**

SAGEM**
Ponant de Paris,
27, rue Leblanc,
75512 PARIS CEDEX 15
+33(0)1.40.70.63.16
+33(0)1.40.70.67.00
francois.pagnon@sagem.com

ABSTRACT

The hybrid stepper motor are particularly well suited for motorization requirement in space mechanism. These applications are characterised by accurate positioning and slow speed or quasi-steady state, and are usually based on open loop control. Hybrid Stepper Motor driving is usually easy.
A high speed stepper motor size 35 was developed to satisfy this requirement.

The first step consisted in the study and theoretical prediction of performances.
In order to increase the maximum speed, the back electromotive force (Back E.M.F) had to be reduced, by actions on the iron losses and windings definition in the magnetic circuit.

The second step consisted in laboratory tests, to confirm that the new stepper motor is able to perform in open loop 100 rotations in 8 seconds, with a repositioning precision better than 1mrad.

Further developments include a second high speed stepper motor size 27, that has confirmed the results obtained in the new definition.

1. INTRODUCTION

In the frame of a preliminary project carried out by CNES for SPOT, SAGEM has conducted a study to develop a new motor combining a high positioning precision with an increased dynamics, allowing a quick rotation of the telephotograph instrument.

(see figure 1 : Motorised deployment system "SYDEM")

Figure 1 : Motorised deployment system "SYDEM"

This paper submit four points :

- Principle of high speed stepper motor.

- Tests on first speed stepper motor size 35 manufactured.
- Identification and analyse of the deviation between tests results and simulation.
- Prediction of performance on new speed stepper motor 27PP and tests results

These new motors will naturally be based on space proven materials and manufacturing means, and will be produced according to SAGEM space procedures.

The aim is to confirm the prediction, and the capability to give technical elements for a generic definition of a family of high speed hybrid stepper motors.

2. Principle of high speed stepper motor

Hybrid stepper motor :

Hybrid stepper motors are brushless synchronous motors usually dedicated to open loop applications. They naturally generate controlled movements in position and speed. The usual applications are mainly for unfolding, orientation, accurate pointing or positioning mechanisms. These motors can either be used in direct drive mechanisms or associated with a gearbox. Their specific characteristics are required in numerous high performances space mechanisms :

- High incremental resolution (i.e. 0.3° full step) enhanced by microsteps command possibilities.
- Very high torque capability per power unit (motor constant in Nm/√W) and per mass unit (0.8 Nm/√W/kg),
- High angular stiffness thanks to the natural high number of poles (up to 300),
- Excellent positioning accuracy and stability on steps and microsteps,
- Possibilities for open loop continuous rotation at very low speeds (down to 0.001 rpm) and with a good instantaneous stability.

Two main divergent objectives are requested in most used motorization applications :

- Motor with a high torque capability per mass unit (torque harmonic content without importance),
- Motor with a good speed stability in synchronous mode (lower harmonic content).

Figure 2 : Steppers motors Sagem 27PP

Requirement for deployment mechanism :

Maximum Rotate speed	:	1600°/s
Maximum Acceleration	:	530°/s
Holding torque	:	0,3 Nm
Inertia	:	$1{,}56.10^{-4}$ Kg.m^2
Maximum voltage	:	70 V

High speed stepper motor :

For a mechanical system with a stepper motor, it's possible to improve dynamic behavior with modification of the motor, supply and mode of driving.

Possibilities to improve dynamics behavior :

- Current command supply improvement
- Driving of the motor in synchronous mode
- Definition of an acceleration / deceleration ramp
- Development of a laminated magnetic circuit in order to reduce the eddy current losses.
- Reduction of winding inductance.

<u>Electrical equations</u> :

Classically we have on each phase :

$$Uj = Rj\ Ij + \frac{d\Psi j}{dt}$$

with :

- Uj phase voltage (j),
- Ij phase current (j),
- Rj phase resistance (j),
- Ψj flux in each phase (j)

The first part is the voltage on the winding resistance. The second is the induced electromotive force who can be written with winding inductance and currents hereafter defined.

$$Uj = Rj\ \ Ij\ + Lj\ .\ \frac{dIj}{dt}\ - Kej\ \theta\ \sin\ (p\theta + \varphi j)$$

with :

- Lj the winding inductance.
- Kej phase constant electromotive force.

For a dynamic use and a synchronous command, the motor comportment can be approached by numeric simulation with :

$U\alpha = RI\alpha\ +\ LI\alpha\ - K\theta \sin p\theta$
$U\beta = RI\beta\ +\ LI\beta\ - K\theta \cos p\theta$
$J\,\theta = T -\ Tmf - Tf$
$I\,\alpha = Io \cos \omega t$
$I\,\beta = Io \sin \omega t$
$T = KIo \sin (p\theta - \omega t)$

with :

- R,L phase resistance and inductance,
- U,I phase voltage and current,
- θ, θ angular speed and acceleration,
- J total inertia,
- Tmf total motor friction torque,
- Tlf load friction torque.

	Standard motor	Speed motor
R (Ω)	360	43.8
L (mH)	1440	17
K (Nm/A)	6	0,62
I (A)	0,055	0,562
RI (V)	19,8	2.1
LωI (V)	199	24
Kω.dr (V)	167	17.3
U phase (V)	~ 386	~ 43.4

3. Tests on first speed stepper motor manufactured in size 35.

This tests are performed with CNES collaboration. The inertia is 15,7 10^{-5} kg.m² and the number of micro steps is 64.

Maximum speed tests

Speed in function of the voltage :

For I constant (0.5 A), the voltage moves to 30V until 60V, the measured speed increases to 29 rd/s until 79 rd/s for a maximum estimated value to 46 rd/s until 102 rd/s. Other test show us that the motor is able to obtain higher speed, but the oscillation amplitude, measured on speed curve diverges and the motor falls out of step. The motor loses the position when the available torque isn't high enough to compensate acceleration caused by level oscillations.
The torque constant of the motor « K » is 0,59 Nm/A measured and 0,63 calculated.

Speed in function of the current :

Many current variation show that the maximum speed $\dot{\theta} = 89 \quad rd/s$ is obtained with I = 0.4A and U = 63 V. If the current is lower than 0,3A the maximum speed isn't reached because the available torque isn't high enough to match the friction torque and the accelerations caused by oscillations.

Maximum acceleration tests :

Acceleration in function of the voltage :

Voltage hasn't any impact on the motor acceleration.

Acceleration as a function of current

With a low speed we can obtain the estimated acceleration, but with high speed, current haven't enough time to establish in the coils. It's necessary to consider the iron losses because they create an additional resistant torque.

4. Identification and analysis of the deviation between tests results and SIMEPS simulations.

The earlier tests showed the difference between the high speed stepper motor behavior and the SIMEPS simulation at high speed, because the model parameters used until now are appropriate only for low speeds. It was necessary to carry out complementary tests at high speed to define exactly the difference of performance.
First of all it is interesting to make the energetic balance and identify the different motor losses.

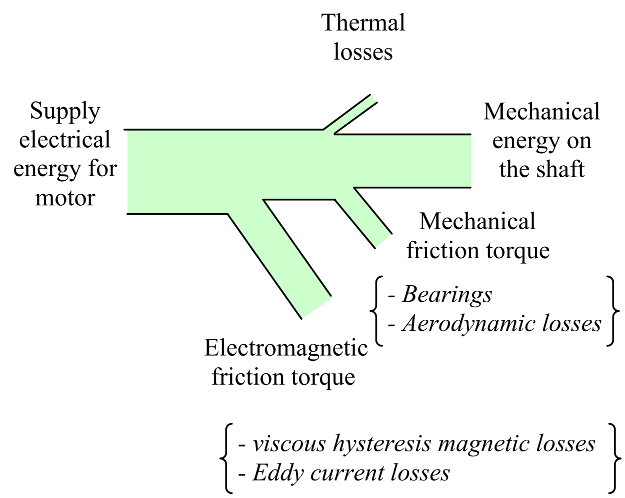


Figure 3 : motor energetic balance

The mechanical friction torques are considered constant on the speed interval. The aerodynamic losses are negligible taking in account a maximum speed of 116 rd/s.
On the other hand the magnetic losses are important at high speed. The high frequency leads to important modifications principally caused by the eddy current losses.

Iron losses tests :

Iron losses is the result of an alternative flux on the ferromagnetic alloy, the addition with hysteresis losses and eddy current losses.

For the measurement, the motor is not electrically supplied.
The winding is open and the shaft is mechanically set at a speed $\dot{\theta}$ by an external motor with control driving .

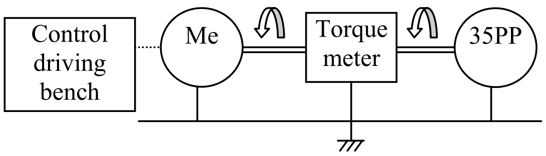


Figure 4 : Iron losses control bench

The torque-meter on the bench measures the friction torque created by iron losses additional with bearings friction torque. It's necessary to substract 0.008 Nm of bearings from measurement, in order to keep only the iron losses.

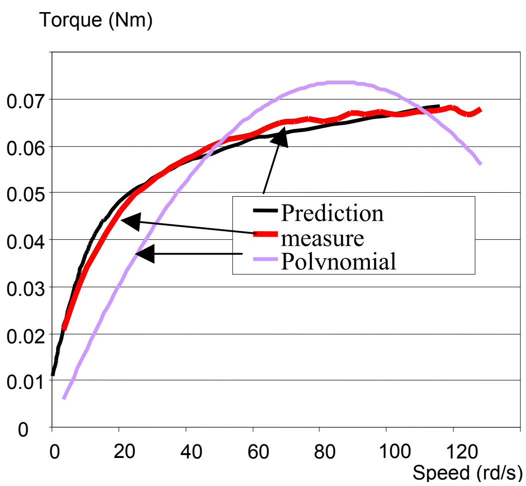


Figure 5 : Results of iron losses

The measurement of iron losses confirms SAGEM prediction at high speed.

A polynomial representation is obtained with following coefficients :

Kcfo = 0.001705 Nm/rd.s^{-1}
Kcf1 = 0.000010 Nm/rd.s^{-2}.

This results show that iron losses calculation on low speed with an equation order 2 (Kcf0 and Kcf1) isn't appropriate to high speed for a stepper motor.

Variation torque function of the speed

The motor is supplied with a current about 0.55 A and 64 µpas/pas.
A brake torque is set on the stepper motor shaft. A couple-meter measures the torque when the stepper motor falls out of step.

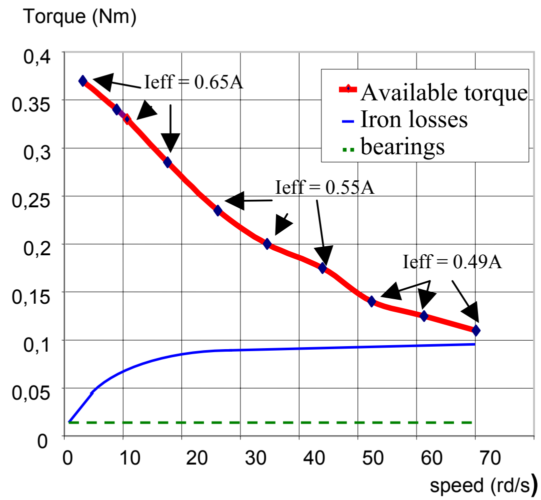


Figure 6 : 35PP Speed : Dynamic torque

The holding torque measured is 0.37 Nm for a current to 0,65 Arms in microsteps. Variations of the current are caused by the current control command means available.

There are the friction torque created by iron losses and the friction torque caused by bearing

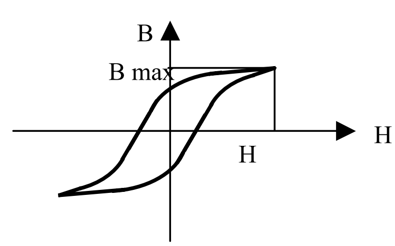
Available torque (Ta) on the shaft can be written as:

Ta = $T(\omega) - Tf(\text{iron losses}) - Tfb(\text{bearings})$

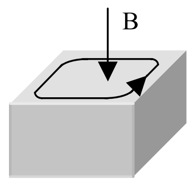
Analysis of iron losses and calculation parameters :

The main difficulty is the determination of iron equivalent winding parameters. This paper presents a method to determine the resistance and the leakage inductance, as a function of iron losses torque measurement. These parameters are both a function of frequency.

The Hysteresis losses are the result of a transformation of material organisation with a variation of direction or strength of the magnetic field.

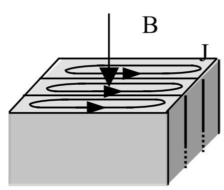


The Eddy current losses are the result of temporal flux variation with electromotive force in the mass. This back E.M.F. generate a short-circuit current on the iron material along the normal plane of the direction flux.



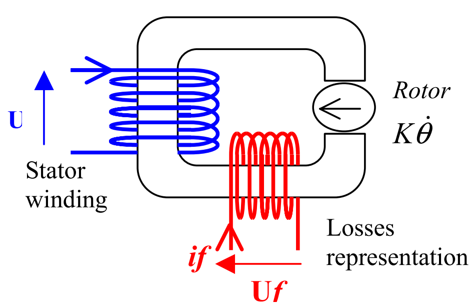
The iron losses composed by Hysteresis and Eddy current losses are generated by the same field and magnetic induction.

When the 35PP high speed stepper motor was designed, the iron losses were limited by use of a laminated magnetic circuit. This last point increases the electrical resistance of the stator.



To study iron losses, we can associate the Eddy current, induced current on the laminated magnetic circuit, by short-circuit coils

We can drawing hereafter the rotor and stator with iron losses :



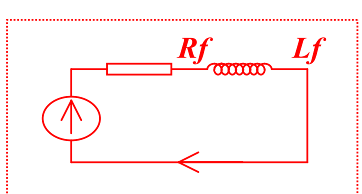


Figure 7 : Iron losses electrical representation

We can represent the eddy currents by a winding with n rounds of a coil, a resistance Rf and an inductance Lf.

When the motor is rotating, there is an additional mutual inductance Mf. This inductance is a virtual winding seen by stator's winding with a resistance R and an inductance L.

We can write the Ohm's law for the 2 windings :

$$U = Ri + \frac{Ldi}{dt} + K\dot{\theta} + Mf\,\frac{dif}{dt}$$

$$Uf = Rif + \frac{Ldif}{dt} + K\dot{\theta} + M\,\frac{di}{dt}$$

Evaluation of Eddy current :
- Eddy current losses are represented by short-circuit coils : $Uf = 0$
- The stator winding is in open loop : $I = 0$.

The iron losses are measured with a mechanical drive on the rotor (other motor) and the winding is in open loop.

Figure 8 : Stepper motor SAGEM size 35.

Source : $K\dot{\theta} = Eo$

$$\Rightarrow \qquad if = \frac{-Eo}{Rf + jLf\omega} \qquad \textbf{(2)}$$

Evaluation of friction torque provocated by iron losses.

$Cf = K\,.\,if$

with : $\omega = p\dot{\theta}$

$$\|Cf\| = \frac{K^2\dot{\theta}}{\sqrt{Rf^2 + (.Lf.p\dot{\theta})^2}}$$

This approach give a tendency on the iron losses evolution. We can retrieve a symbolic "eddy time constant".

$$\tau f = \frac{Lf}{Rf}.$$

Rf and Lf move with frequency but the speed increases more quickly $\dot{\theta}$.

This theoretical approach gives an equation close to the real iron losses evolution in dynamic.
But the "Eddy time constant" dubbed τf is composed by variable frequency elements not measurable. We can't consider τf as a constant.

For simulation, we need to have an iron losses with easy parameters to calculate dynamic performances.
It's easier to define a polynomial equation representative of iron losses.

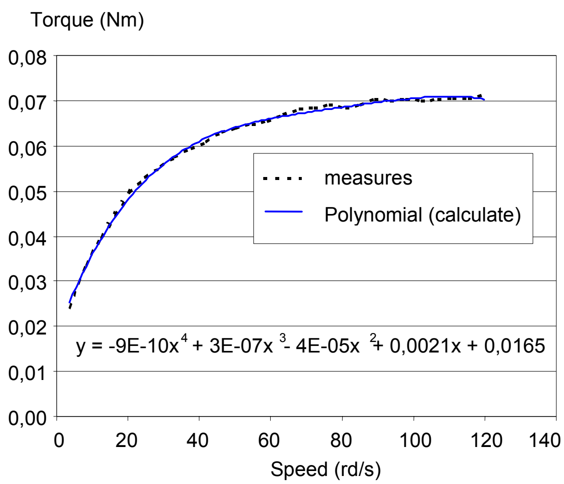


Figure 9 : Iron losses (Calculated / measured)

An equivalent iron losses representation calculated by a polynomial equation order 4 is easier.

$$Cf = -9.10^{-10}x^4 + 3.10^{-7}x^3 - 4.10^{-5}x^2 + 2{,}1.10^{-3}x + 0.0165$$

With "0.00165" constant for hysteresis losses.

4. Prediction of performance on new speed stepper motor 27PP and tests results

To confirm this theoretical approach, with CNES collaboration, we manufactured and tested a new high speed stepper motor size 27.

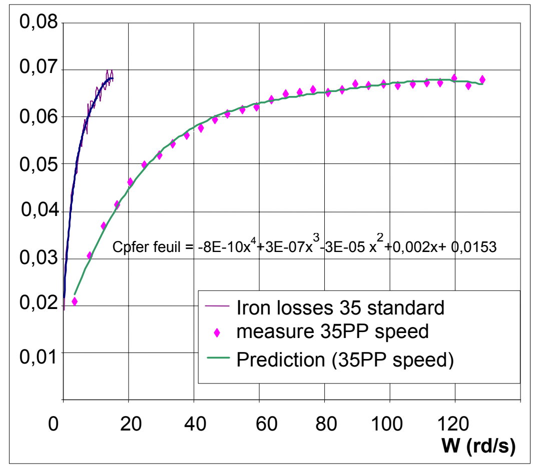


Figure 10 : Iron losses (Polynomial / measured)

SAGEM has calculated the predicted parameters regarding the iron losses on the new high speed 27PP.

The method consists in establishing at first, the relationship between the iron losses on the massive stator (standard 35PP) and the laminated magnetic circuit (speed 35PP).

The geometrical shape and the thickness of the magnetic circuit is the same between the laminated and the massive stator. The main difference is simply the iron losses.
With an analysis performed between the iron losses evolution of standard model and laminated stator, we could obtain an extrapolation to define a prediction of iron losses, for the new speed stepper motor.

5. Conclusion

The design of new high speed stepper motor allowed SAGEM to verify the method to calculate parameters for any high speed stepper motor.

The objective was to increase the speed maximum with a design to decrease the iron losses it's a successful.

THE HIGH SPEED STEPPER MOTOR OPTIMISED 27PP SAGEM, CAN ROTATE TO 7300°/S WITH A POSITIONING BETTER THAN 1MRAD.

6. Further prospects

These recent developments, sponsored by CNES, reflect continuous commitment of SAGEM in the development and manufacturing of improving products.

They show an interesting alternative to brushless motors for high speed command of mechanisms, saving the cost of development of specific electronics.

They also offer a simpler open-loop control electronics, a very high positioning accuracy, a controlled harmonic content, a high torque capability per power and mass unit.

More generally, SAGEM is constantly improving it's offer on space motors :

- Improved technical characteristics
- Specific motors for larger quantities eg. constellations
- Customised motors for specific applications

SAGEM has been developing and selling motors for space applications for 30 years. Space proven concepts and technologies are a key for this stability.

An established industrial basis, and a R&D capacity based on indigenous technology allows for this continuous improvement. Space motors and resolvers benefit from synergy with large productions of components for defence and civilian airborne industry.

Back to Contents