EUROPEAN ELECTRIC SPACE RATED MOTORS HANDBOOK

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1 INTRODUCTION

As soon as a space mechanism has a moving part, a motor is required to activate the motion. The motor can be a passive device (i.e. spring) but more often an electrically powered motor is considered. In this case, the problem is to find the optimal technology, optimal in terms of motor performances, reliability, material adequacy with the space constraints, system complexity and overall costs.

The motor handbook [1] presented in this paper has been written in the frame of an ESA contract aiming to provide to mechanism designers an aid for the selection and/or identification of a suitable motor for specific applications. It addresses frameless motor units since the problems limited to the motor housing/bearing can be seen as “conventional” problems for space mechanism designers.

This paper summarises the content of the motor handbook, namely :

- a short description of the different existing types of motors ;
- a summary of the impact on the electronic driver complexity of the selection of a given type of motor ;
- comments on the impact of the space environment on the motors design ;
- a summary of the typical space applications linked to the different motor technologies ;
- a short guide-line for the mechanism designer on “how to specify a motor to a motor manufacturer” ;
- comments on the specific tests normally required at motor unit level ;
- data-sheets of existing space qualified motors (or readily qualifiable), from different motor manufacturers.

Finally, the comparison of motor technologies is made in a general context and thus the numbers and limits given in this paper shall be considered as “guidelines” and not as absolute limits which can not be adjusted on a case by case basis. Likewise, in this paper, a motor specialist may find comments which are at a given extend incorrect : the idea is to give a feeling to mechanism designers and not to have too complex explanations, correct for the specialist but not understandable for the targeted reader.

2 ROTATIVE MOTORS

This chapter addresses the rotative motor technologies generally considered in space applications. It gives an idea on the intrinsic limits of the technologies and serves as an introduction to the synthesis made in a further chapter.

Different motor configurations can always be considered (i.e. external rotor, way of fixing a magnet, need of a protective sleeve, limited angle torquers) but they are not addressed hereafter. Likewise, alternative technologies such as piezo-electric, paraffin and shape memory alloys motors are mentioned in this paper but are not addressed in details.

2.1 Stepper motors

The key advantage of the stepper motor technology is the simplicity of the electronic driver and the resulting incremental stepping motion, matching many mechanisms requirements. It makes of it a simple brushless solution which often does not require a dedicated position sensor.

There are many different options to design a stepper motor but the preferred ones, in space, are generally the following :

- the hybrid stepper motor (figure 1) ;
- the reluctance stepper motor ;
- a permanent magnets synchronous motor with a specially large number of poles.

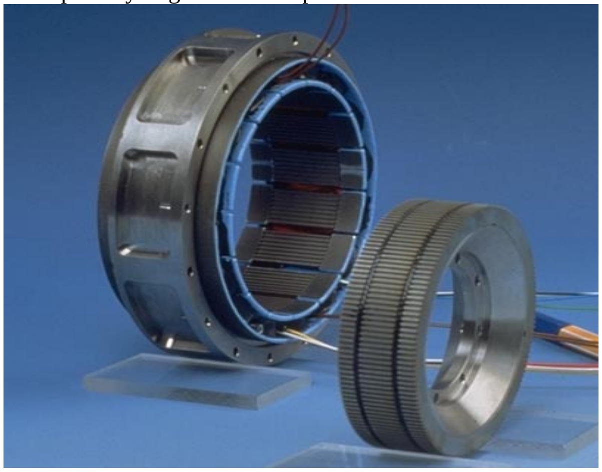


Figure 1 : hybrid stepper motor (ETEL SA.)

The hybrid stepper motor design has a very high torque/power ratio, pending on the use of small stator-rotor mechanical airgap (typically lower than 0,1 mm radius and ideally down to 0,05 mm). This small airgap leads to non-negligible mechanical design constraints, such as having tight overall machining tolerances and a stiff bearing/shaft arrangement, avoiding stator-rotor mechanical interferences due for example to the radial force created by the stator-rotor magnetic attraction.

The torque/power ratio is generally the best when the motor is used at low speed (i.e. a few steps/second) and at low power. Indeed, the increase of the speed often reduces the torque capability (unless an adequate electronic driver is used) and the increase of the power induces magnetic saturation, generally significant with this technology. The latter has also the consequence to limit the motor short term peak torque capability, since a power/thermal overload does not necessarily imply a significant increase of the torque capability.

Hybrid stepper motors have a number of full steps per turn typically ranged between 50 and 1200 steps/turn, for motors with a 15 mm and 150 mm external diameter respectively. Note that the larger the motor, the higher the possible number of steps per turn, but a large size motor can not have a too low number of steps per turn.

In term of working speed, a working frequency lower than 10 steps/second can be considered as low. Speed ranged between 10 and 200 steps/second are still low but need a check of the speed influence on the torque behaviour, while speed higher than 200 steps/second shall be carefully considered. It is nevertheless common to see stepper motors going up to a few thousands of steps/second in industrial applications.

Finally, hybrid stepper motor users shall be aware of particular working characteristics of this technology :

- torque exceeding 5-10 Nm are marginally considered with a stepper motor ;
- in open loop, the position accuracy of a stepper motor is limited by the relatively low angular torque stiffness (Nm/rad) of the motor ; a position error going up to one full step can theoretically be noticed, even when the motor is driven in micro-steps ; this point must be clearly understood if an accurate positioning is expected.
- the number of energised steps per turn is in some cases different from the number of unpowered stable steps per turn (often 4 times less unpowered steps). This depends on the specific motor magnetic design and leads, in some cases, to add a magnetic braking device to ensure that the motor stays in position when the power is switched-off, not relying on the mechanism friction.
- it is a noisy technology, creating generally significant speed ripple and micro-gravity disturbances. To try to improve these characteristics by electronic means often spoils the advantages of the technology and then a brushless DC motor can quickly become a more suitable solution. If of concern, this point shall be discussed in details on a case by case basis.

The second stepper motor design option is the reluctance design, which has a very poor torque/power ratio (typically five times lower than the hybrid technology) but presents a design simplicity which makes it attractive to ease the manufacturing process for extreme temperatures applications. Since in cryogenic conditions the power budget becomes often a marginal problem (copper resistance and related power losses significantly lower than at + 20°C), this design has been used in several very low temperature missions (i.e. ISO). This technology shall nevertheless be seen as a marginal option.

Finally, in some cases, a stepper motor is made by considering a permanent magnet synchronous motor (brushless DC motor) with a specially large number of poles, allowing to use this motor technology in open loop with a good torque/power capability and an increased working speed. It often allows to have a coincidence between the powered/unpowered number of steps per turn. This technology is marginally used on a global point of view.

2.2 Brushless DC motors

A permanent magnets synchronous motor (often called “brushless DC motor”) is an efficient solution for mechanisms drive. It shall be seen as a technology complementary to the stepper motor one, reaching performances out of the stepper motor working ranges while less efficient in the same working area. Indeed, it has a slightly lower torque/power capability and needs in any case a position sensor (even if simple). The electronic drive of a brushless DC motor is more complex than the one of the “simplest” stepper motor driver (open loop, full step) but has rapidly a similar complexity if the stepper motor is tentatively driven more efficiently. The system complexity is in any case identical if the mechanism needs for other purposes a position sensor to be processed by the control electronics.

Three brushless DC motor designs are generally considered :

- the low speed designs, with a generally large outside diameter and a short axial length, generally called “torque motor” ;
- the high speed designs (figure 2)
- the high or low speed designs which provide specifically smooth speed/torque characteristics, called “toothless brushless DC motor”, due to a dedicated magnetic feature.

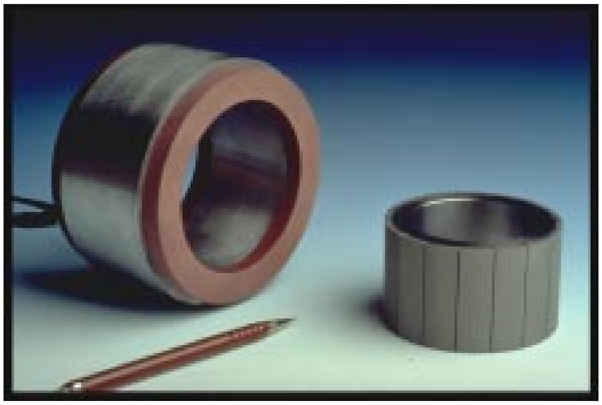


Figure 2 : brushless DC motor (ETEL)

The torque/power ratio of brushless DC motor is high even if for the “torque motor” working at low speed, it is lower (- 25 %) than the one of a stepper motor, designed with a small airgap (typically < 0,8 mm) and working in the same speed range. The brushless DC motor stator-rotor mechanical airgap is typically close to 1.0 mm and is generally easy to handle at system level, in term of both mechanism design tolerances or mechanical integration. With brushless DC motors, the stiffness of the mechanism shaft is generally not a major issue.

Since the brushless DC motor is used in closed-loop, the torque/speed characteristic is not any more a concern and a given torque can be obtained at any working speed, pending that the power allowance is in line with the requested mechanical/total motor input power. Working speeds below 15'000 rpm are common in space applications while a speed going up to 200'000 rpm has been considered for a specific space application (ISS – MELFI). Mechanism designers often run brushless DC motor at speed close to 3000 rpm. For position control, the position resolution or accuracy is set by both the drive electronic and the position sensor, the motor being not the key design driver except in specific very demanding applications. The same applies for the speed performances (speed, ripple, offset, settling time).

In term of short term-peak torque overload, brushless DC motors have a significant capability, with a peak torque value which can be more than five times the nominal demand (maximum limit is fixed by the risk of magnets demagnetisation). The typical space needs in term of peak torque demands are below 2-5 Nm, while occasionally higher torque are requested (50 Nm for NEUROLAB, 1200 Nm for MARES/ISS).

The torque/speed noise of the brushless DC motor technology is an order of magnitude better than the one of the stepper motor. Nevertheless, if it still shall be improved, two options or a combination of both can be considered :

- to use the above-mentioned “toothless” technology [2], which eliminates the generally stiff (Nm/rad) detent torque and provides a limited content of torque ripple harmonics. The main drawback of the toothless design is an increase of the motor mass/size or power consumption (typically + 30 % compared to a classical brushless DC motor design) :
- to use an improved electronic driver, starting from a sinewave current control and going up to a “tailored” current harmonics controller for the more demanding applications [3].

2.3 Brush DC motors

A brush Dc motor is magnetically made identically to a brushless DC motor, except on one important specific point : the winding is placed on the rotating part while the main magnetic excitation (generally magnets) is on the fixed part.

The main impacts are :

- the problem of energising the rotating part involves the use of brushes ;
- the motor, for the user, can be energised by a DC voltage.

Otherwise, the motor performances are globally identical to the one of a brushless DC motor, in term of motor mass, size, torque ripple, power budget. Nevertheless, the fact that the brushes replace the power bridge and the commutation position sensor (the simplest one, as for example Hall sensors) involves two significant technical advantages :

- the mass/size/power consumption of the brushes is lower than the one of the corresponding power bridge electronic;
- the mechanism designer (generally with a mechanical background) has not to manage relatively complex electronic problems and has a simple DC electrical interface.

These advantages have to be moderated as follows :

- the drawbacks of the brushes in space environments are major and often forbid the use of the brush DC motor (i.e. brushes behaviour under vacuum, maintainability, wear, disruptive voltages – arcs - restartability after a dormant period) ;
- In any case, on a system point of view, a brush DC motor needs often an electronic management (EMC filter, system communication, position or various sensor processing, power bus conditioning such as generation of auxiliary voltage supplies, management of the redundancy) : to add the delta electronics required for the brushless technology is not a major system problem.

On this baseline, the difference between brush and brushless DC motors on a global system electronic point of view is not so significant. The main problem is due to the fact that electronics parts are often split in a way that the use of a brush DC motor simplifies significantly the electronic tasks close to the mechanism designs and, as the work share is made, implies the saving of an additional electronic box. This way of sharing may often be due to the past DC motor heritage. Nonetheless, it is a simplification for anyone to have a motor which manages itself its power distribution.

As a general conclusion on the brush DC motor, the latter has to be preferred as far as the brushes major drawbacks in space environment can be acceptable. Nevertheless, the use of a brushless DC motor does in many cases not lead to too significant drawbacks if properly managed at system level. Finally, the mechanical performances of the brush DC motor shall be compared to the one of the brushless DC technology. The trade-off between the latter and the stepper motor technology has been made in the previous paragraph and can consequently be used for the brush DC motor.

2.4 Alternative technologies

Other technologies could be considered on a case by case basis for space applications, but shall in general be considered as non efficient or non mature compared to the already presented options :

- AC induction motors : poor efficiency (< 50 %) in the motor sizes generally considered in space ; often used on earth/aeronautic to drive fans or pumps, when an AC power supply is available (50 Hz or 400 Hz). Since the latter is generally not available in space, a brush or brushless DC motor shall be preferred ;
- Switched reluctance motors : low cost and robust motor for industrial applications. Low efficiency (< 50 %) Require an electronic identical to the one of a brushless DC motor. The latter shall in general be preferred.
- Hysteresis synchronous motor : good alternative for high speed/low power applications (i.e. gyroscopes), when an AC voltage is available. Otherwise, brushless DC motors shall generally be preferred ;
- Rotative piezo-electric motors [4] : technology which provides a good alternative to stepper motors on a performance point of view. Shall still demonstrate its behaviour under space environments and has in any case a limited working lifetime (several hundreds of working hours on earth) compared to more classical solutions ;
- Paraffin [6] and shape memory alloys [7] motors : rotative designs based on such technologies are generally made with an adequate mechanism which converts into rotation the linear motion produced by a thermal effect (can not be seen as a direct drive solution). Paraffin technologies have today a good space heritage and are massively used in the industrial market (i.e. cars manufacture). Shape memory alloys motors are more recent but have already penetrated the space market.

2.5 Rotative motors summary

The trade-off summarised in this paper identifies four main motor technologies, based on the comparison of their respective performances (torque, power, speed, mass and sizes), summarised in table 1. They are namely :

- stepper motors,
- brush DC motors,
- brushless DC motors,
- piezo-electric motors.

The first technology is a motor which can be used in open-loop in term of position control, while the others need at a given stage a position feedback (sensor or mechanical end-stops), if not simply used in speed loop. This criteria often allows already to select the stepper motor as the best candidate if :

- the motor must be stopped in several angular positions (for example for an optical calibration unit, with different prisms to be placed into a light beam) ;
- the required position accuracy is in line with the one of an open-loop stepper motor ;
- the required step increment (resolution) is in line with a stepper motor used in full or micro-steps mode ;
- the speed/dynamic behaviour is not too demanding (i.e. maximum speed, transfer and stabilisation time) ;
- micro-gravity or speed disturbances are acceptable during shaft motion.

If one of those criteria is not satisfied, the choice is less obvious since the stepper motor alone can not fulfil the requirement. It means that using it requires an increase of the system complexity and then the use of one of the other technologies becomes often more logical. The latter is emphasised if for system reasons a position sensor is in any case required (often the case), with its processing electronic available.

The first step is to check if by changing the mechanism mechanical design (i.e. gear ratio, lead screw pitch, length of a lever) it is possible to solve the problem. If not, the second step is to look at the alternative technologies.

In this case, a first selection can be made by deciding if the brushes drawback are acceptable. If so, the brush DC motor shall be preferred (see nevertheless § 2.3 comments). Likewise, the piezo-electric motor can be rejected if (1) its lifetime or space heritage is not assumed to be sufficient ; (2) its working speed is large enough for the required application. In short, the selection among the three “non stepper” motors is in general relatively simple. If not, the trade-off is more complex and shall be treated on a case by case basis. The same applies if the logic described in this paragraph can not be followed.

2.6 Typical applications

For the key technologies, the following typical applications can be mentioned (author less familiar with space brush type motor applications) :

stepper motor :
Solar array drive, Antenna pointing, Ion thruster orientation ; cover opening, sample positioning, calibration unit, valve actuation, gearbox drive ; mechanical switch, scan unit, deployment mechanism.

brushless DC– torque motor :
High dynamic or accurate antenna pointing ; robotic ; valve actuation ; scanning mechanism ; inertial wheel.

brushless DC– toothless motors :
High dynamic antenna pointing ; inertial wheel ; constant speed motion ; scanning mechanism, attitude control, sealed motor.

brushless DC– high speed :
Pumps, gyroscope, valve actuation, fan, compressor, water separator, geared mechanisms, sealed motors.

brush DC motor :
Solar array drive.

3 LINEAR MOTORS

Direct drive linear motors are regularly used in space mechanisms and are shortly addressed hereunder. In general, the magnetic conception is similar to the one of their more classical rotative counterpart and the disadvantages/advantages of the latter can be derived to the linear design. Linear technologies can be split into two different families [8] [9], depending on the length of the linear stroke.

3.1 Short stroke linear motors

The stroke of these motors is typically lower than 50 mm and the fact that the winding is single phase eases the electronic control.

We have :

- **moving coil motors** (figure 3) : many different design options are available, depending on the expected performances [9] [8]. This technology is massively industrially used for several decades and is regularly considered in space mechanisms (i.e. SOHO, MIPAS, METOP, IASI). The main advantages are its good linearity (force versus current) and the fact that the mechanical guidance can be very smooth and reliable (i.e. blades) avoiding the use of linear bearings and the related lubrication/wear issues. These motors are very dynamic but this advantage is generally not a key issue in space. As a drawback, moving coil technologies are heavy compared to alternative solutions. The fact that the power losses (heat) are on an “airgap coil” is occasionally a problem in vacuum, even if manageable.

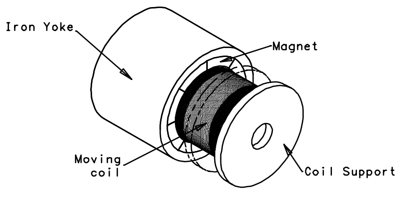


Figure 3 : moving coil motor (ETEL)

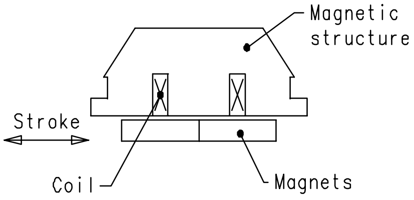


Figure 4 : moving magnet motor (ETEL)

Figure 5 : SAX, Huygens and ISO electromagnets (ETEL)

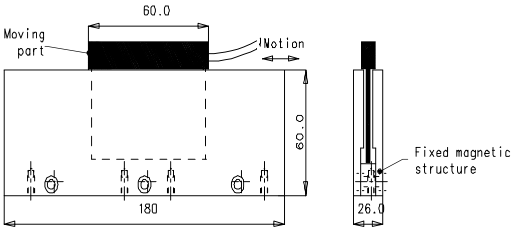


Figure 6 : long stroke moving coil linear motor

- **moving magnet motors** (figure 4) : this technology has a ratio force/mass significantly better than the one of the moving coil technology. It should consequently be preferred for space mechanisms but is practically not used due to both its (1) highly non linear and disturbed force characteristic ; (2) the more difficult mechanical guidance (linear ball bearings) and related wear. Finally, due to the latter and to the fact that its dynamic behaviour is limited, it is more often in competition with traditional solutions such as the combination of a rotative stepper motor with a lead screw.
- **electromagnets** (figure 5) : well known technologies, commonly used into the space and industrial markets.
- **piezo-electric motors** : commonly used over limited stroke (a few micron). Longer stroke designs today available but still not industrially mature compared to alternative technologies.
- **paraffin and shape memory alloys actuators** : see comments made on paragraph 2.4.

3.2 Long stroke linear motors

For strokes longer than approximately 50 mm, two or three phases motors shall then preferably be used instead of the previous single phase designs (significant mass saving). In this case, all the rotative motor designs presented in paragraph 2 can be derived into a linear versions. For different reasons, the design which presents the best potential and maturity for space mechanisms is the “polyphased" moving coil linear motor” (figure 6). For more explanations, see [1] [8] [9].

4 IMPACT OF THE SPACE ENVIRONMENT

The specificity of the requirement linked to space applications is the following :

- extreme working temperatures, ranged somewhere between – 270°C and +250 °C, depending on the application ;
- vacuum and non vacuum working conditions ;
- frequent humid environment at least during tests ;
- vibration and shock loads.

The motors commonly considered for terrestrial applications have generally three main problems :

- materials are not suitable for vacuum conditions and present flammability/toxicity levels regularly out of requirements ;
- manufacturing process have no heritage with respect to the specific space environment ; a part/process which works under normal industrial conditions may fail when subjected to space constraints ;
- thermal expansion effects shall obviously be part of the motor design drivers.

A space rated motor takes these parameters into account. The trade-off for using parts with a lower standard shall take the following factor into account :

- PA/QA and engineering efforts linked to the use of a non qualified part (a few engineering days cost rapidly the price of a space unit).
- material justification effort and qualification tests, if any ;
- manufacturing process qualification with respect to the specific environment ;
- number of industrial units to be used for qualification (up to a few hundreds in a known space program) ;
- risk management at project level.

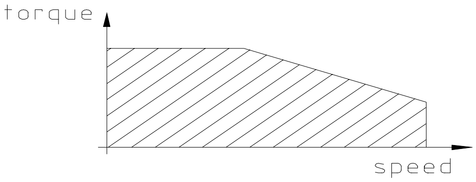
A space rated motor does not require any test at unit level.

5 MOTOR SIZING

5.1 Minimum content of a motor requirement

A motor specification shall include the following parameters, to allow the design of the magnetic/electric part.

1. the torque versus speed curve must be provided including any possible motor working point (figure 7). The duty cycle of each working point shall be known. This curve shall already include every motorisation margin factor required at system level.



2. *Figure 7 : motor working area*

2. the maximum RMS torque value which can be permanently requested. By permanently is meant more than the motor thermal time constant (between a few seconds for small motors and a few minutes). For torque values larger than this RMS torque value on figure 7, an indication of the duration of occurrence shall be provided if it lasts for more than approximately one second.
3. the expected detent torque value (no current torque) or, as a minimum, the maximum expected value. This parameter shall not be over-specified since difficult to manage.
4. the maximum available total motor input power. If applicable, maximum short term/long term power shall be distinctly specified, with an eventual link to figure 7 working curve.
5. the dimensions not to be exceeded by the motor. At least, the maximum diameter and axial length shall be provided, as well as the expected dimension of the motor hollow shaft, if any. The output cable location/definition shall also be provided.
6. the maximum mass.
7. the extreme working/non working temperatures.
8. the type of electronic driver used with in particular : (1) if it is a current or a voltage supply ; (2) the number of motor phases simultaneously energised for square wave drivers (one or two phases “on”).
9. the level of the supply voltage (DC), at motor level, including the worst cases tolerances.
10. the peak motor phases current value accepted by the electronic driver (not always obvious to know from the power and voltage definition).

The last three points can be replaced by specifying the motor electrical parameters, namely the resistance (Ω), the inductance (mH), the back-emf constant (Vs/rad) and the torque constant (Nm/A). tolerances on these parameters shall be ± 10%, ± 30%, ± 10% and ± 10% respectively.

5.2 Inputs for a preliminary motor sizing

For a preliminary motor selection, the following parameters shall as a minimum be defined, even if there are only ROM values :

- the torque need (point (1) and (2) of § 5.1), with at least a peak end a RMS value
- available power
- maximum mass/dimensions
- extreme working temperatures

6 MISCELLANEOUS POINTS

Various other points are addressed in the motor handbook [1] :

- indicative dipolar moments values. For example : it is in general below 0,1 Am^2 for (1) brushless DC motors ; (2) brush DC motor ; (3) stepper motors with an even number of rotor magnets (number of so called “stacks”). It is close to 0,5 Am^2 for (1) stepper motors with an uneven number of rotor magnets ; (2) moving coil motors ;
- a description of the calculation of a motor power budget, including comments on : (1) temperature influence ; (2) impact of considering a “voltage supply” instead of a “current supply” ;
- data sheets of existing motors which have a space heritage should be appended to the motor handbook. These data sheets come from the various suppliers who have responded to ESA request but are not easy to compare since often based on unclear definitions.

7 CONCLUSIONS

An overview of the content of the space rated motor handbook [1] is presented in this paper. It should be useful for a mechanism designer already aware of the problems linked to the motor selection and is an introduction to the motor handbook for the others.

8 REFERENCES

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