NEW DESIGN PLATFORM FOR COMPARISON AND SELECTION OF MOTOR TECHNOLOGIES FOR HIGH PERFORMANCE MOTION SYSTEMS

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Abstract: The large variety of motor technologies and corresponding control schemes available today to the design engineer and the dramatic pressure to reduce development time in industrial projects have created the need for performant design tools which allow to realise, already at a level of preliminary simulation, the complete motion system. After a first review of the selection criterias and the characteristic offered by the different motor technologies, the paper will illustrate an original global approach, allowing to simulate, optimise and implement, with an adequate hardware , a complete motion systems.

1. Introduction

The choice of the most adequate motor technology in the design of a high performance motion system is a key issue as normally each application presents specific requirements. However, besides the motor intrinsic characteristics, a multitude of other factors, such as the interdependence of the different components of the motion system, do affect its global performance. In this context, a particular attention has also to be paid to the sensitivity to the different parameters, in order to have a robust and cost effective design. It is therefore essential, in order to avoid repetitive iterations, particularly in the hardware realisation, to dispose of performant development and simulation tools in order to compare, already at the design stage, the performance of the different potential solutions. The aim of this paper is to illustrate, on the basis of a performant development platform, how such development tools can assist the designer in the multi criteria optimisation process of his particular application.

2.1 Characteristics and features of different motor technologies

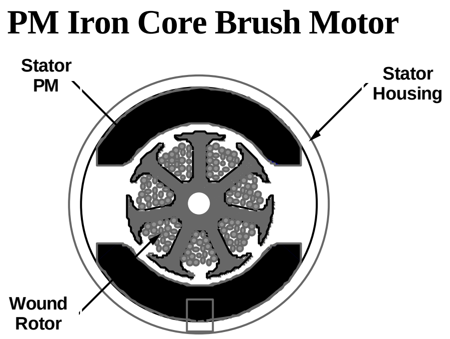
The designer of motion systems has basically, for a given application, the choice between a large palette of motor technologies. For small electrical drives, such as positioning systems requiring a motor power below one-two hundreds Watts, we can mention in a non exhaustive way:

- iron core DC motors
- ironless DC motors
- hybrid step motors
- disc magnets step motors
- brushless motors
- variable reluctance motors
- electromagnetic (tin-can) step motors
- linear motors
- ... ...

All the different motor technologies do present obviously advantages and drawbacks. These advantages and drawbacks are however relative, as they will be determinant only if they correspond to the specific needs of the application considered. Our purpose at this stage is to review and compare the advantage and drawbacks of some competitive technologies and to discuss some criterias of comparison which will illustrate the variety of specific constraints of different applications fields.

The generic comparison between the different motor technologies remains however relative as the various figures of merit are influenced by the motor size. However, in order to establish a list of relative criteria for motor selection, we will mention the most known advantages and disadvantages of each technology.

3.1 DC motor technology



This technology belongs to one of the basic technologies of classical electrical machines. A multitude of such motors exist today, with power ranging from fractions of Watts up to 10 kW and more. We will however limit our considerations to small motors (the so called subfractional horse power motors), which are mainly of the permanent magnet type.

The advantages offered by this motor technology can be summarised as follows:

the simplicity of the command: the motor can be activated from a simple voltage source (in opposition with brushless or step motors, which require an adequate control electronics)

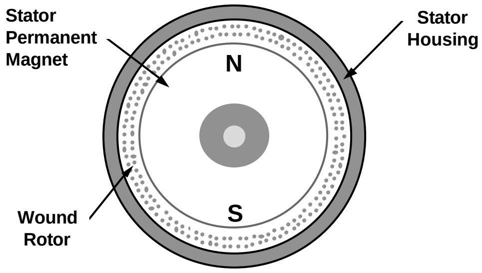
- the simplicity of their regulation: the no load speed is nearly proportional to the voltage, the torque is proportional to the current
- the wound rotor offers a big flexibility in terms of choice of motor characteristics (armature resistance, torque constant) by the change of wire diameter and number of turns
- the thermal time constant allowing temporary overload conditions
- the higher natural inductance, suitable for PWM electronic power amplifiers

As main drawbacks we can be mention, particularly for the small motors:

- the friction losses associated with the mechanical commutation system, which relative importance increases when the motor size decreases
- the relative low efficiency, especially for small motors (30 -40 % for motors below 1 Watt)
- the rotor inertia, which can , depending upon the applications, limit the system dynamics
- the residual torque (cogging torque) creating preferential rest positions
- the risk of demagnetisation in case of overcurrent at low temperature (Ferrite magnets)

3.2 Ironless DC motor technology

PM Ironless DC Brush Motor



The ironless technology is also a well known motor technology based on a particular self supporting skew winding which realises the rotor. The stator magnet is placed in the interior of the rotor. This particular technology offers the following advantages:

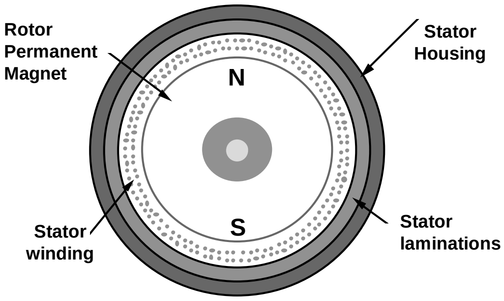
- the ironless rotor, characterised by a very low inertia, allowing high dynamic characteristics
- the absence of residual torque, due to the ironless rotor structure
- the absence of magnetic saturation allowing interesting peak torques
- the low inductance of the windings, allowing the use of precious metal commutation systems
- the small friction , due to this same precious metal commutation system
- high power/volume and high power /weight particularly in small sizes

As main drawbacks, we can mention:

- the low rotor thermal inertia, limiting the overloading capability
- the small inductance, which can limit the use of PWM amplifiers
- the higher copper losses at the same torque level than an equivalent iron core DC motor, especially for powers over 30-40 Watts

3.3 Brushless motor technology

PM Ironless Brushless DC



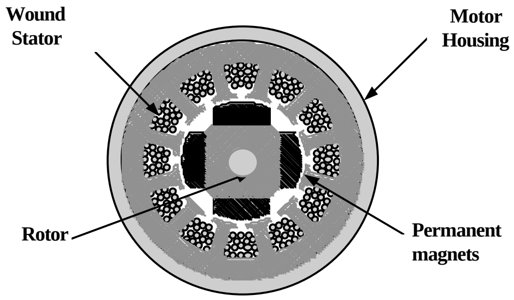
Brushless motors are characterised by a stator comprising a polyphased static winding and a rotor equipped with permanent magnets. The statoric windings are fed by an electronic power driver in function of the rotor position, detected either by position sensors (Hall effect devices) integrated in the motor or by sensorless detection circuit external o the motor. There are many different versions of brushless motors, but, for incremental and positioning applications, we can distinguish between two main families:

- slotless (ironless)brushless motors
- slotted (iron core)brushless

Brushless motors are characterised by the absence of any mechanical commutators. Their main advantages are:

- reliability and long life , due to the absence of any mechanical wear (except the bearings)
- no maintenance requirements
- high speed capabilities
- very precise speed regulation by using the commutation sensors (phase lock loop operation such as in disk drives)
- no commutation sparking

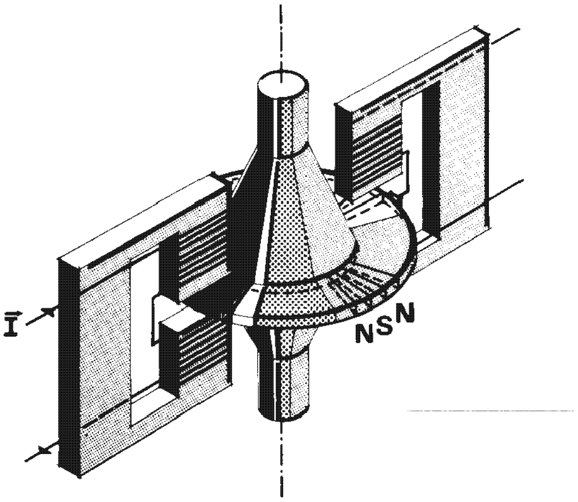
Iron core Brushless DC



The main drawbacks of brushless motors are of different nature:

- the necessity to dispose of an electronic driver adapted to the application requirements
- the relative additional cost represented by the drive electronics
- the slightly bigger volume in comparison with the DC ironless motor, especially in the small sizes
- the lower global efficiency for smaller motors (iron losses, hysteresis losses, power electronics losses).

3.4 Main characteristics and benefits of the step motor technology



The step motor is an electromechanical device characterised by its ability to realise a double function. This type of motor permits to convert electrical power into a mechanical power by the generation of a rotating torque and to convert a digital information (command pulses) in a displacement of a corresponding number of steps.

Although the different motor technologies may present various structures (disc magnet step motor, hybrid step motor, « tin can « step motor, VR step motor »), a step motor consists generally of a polyphased stator and a rotor with a permanent magnet which can be associated, depending upon the motor type, with a variable reluctance structure. The rotor windings are fed sequentially by an electronic driver.

As typical advantages of step motors we can mention:

- the possibility to realise « open loop » positioning systems without any need for additional sensors
- the relative high torque per volume unit, due to the particularity of the magnetic circuit (« magnetic gearing effect)
- the natural resolution which can reach several hundreds of steps per revolution
- the high acceleration capabilities related to a very low inertia in the case of the disc magnet motor
- the presence of a detent torque, holding the load in a given position also in absence of current in the windings

the possibility to increase the resolution by microstepping techniques

- the compatibility with digital command delivered by microprocessors

The main drawbacks are:

- the oscillatory behaviour corresponding to the intrinsic characteristic of this type of motor
- the corresponding oscillation when stopping at a specific position
- the dynamic instabilities in the mid range frequencies of the torque - speed curve
- the sensitivity to parameters variations such as inertia and friction
- the iron losses , especially at high speeds, due to the high number of pole pairs
- the relative low efficiency, determined by the open loop operation
- the high inductive behaviour, limiting the current which can be injected in the motor windings at high speed.
- the higher noise as compared with DC motors

4.0 Evaluation criteria of competitive advantages

The various characteristics and advantages of the different motor technologies cannot represent alone the selection criteria for the choice of a motor. Every specific application represents in fact different needs which have to be evaluated and to be compared with the possibilities offered by the various motors types.

Therefore our purpose is to mention, in a non exhaustive way, some typical applications requirements and to illustrate practically the particularities of the different technologies which can be considered for these applications. We have to mention that the motor size can influence in a non negligible way the comparison criterias.

4.1 Speed range

a) low speed

- **DC ironless motor:** very regular operation, due to the absence of residual torque and low starting voltage
- **DC iron core motor** : more irregular operation, due to higher friction and cogging torque
- **brushless motors:** in its ironless version, similar characteristic as an ironless DC motor. The lower number of phases, iron and hysteresis losses and the starting voltage of the electronics may introduce some irregularities. The slotted version could also be handicapped by cogging torque.
- **step motor:** driven in full or half step mode, this motor presents an oscillatory behaviour due to its incremental nature. With microstep operation, depending on resolution and torque harmonic distribution, very smooth operation can be achieved.

b) high speed

- **DC ironless motor:** this motor has by principle no iron losses due to the specificity of its magnetic circuit. The behaviour of the mechanical commutator is generally the limiting factor at high speeds.
- **DC iron core motor: the rotor presents iron losses** which increase with the speed squared. Mechanical commutation can also introduce limitations in speed
- **brushless motors:** by the absence of mechanical contact, except the bearings, this motor presents high reliability at high speeds. Iron losses are generally the limiting factor.
- **step motors:** these motors can also be used , due to the absence of mechanical commutator, at high speeds. The high number of pole pairs are responsible for sensitive iron losses which can cause overheating. Dynamic instabilities can also limit the useable speed range.

4.2 Motor losses

a) no load operation

- **DC ironless motor:** the low inertia, the small weight and the low friction associated with the rotor has a very positive impact on the motor losses. This technology presents generally speaking very low losses.
- **DC iron core motor:** friction losses are generally more significant, especially for small size motors, due to the mechanical commutation system.

brushless motor: the presence of an electronics, which requires also a permanent supply, and the iron losses places this motor between the two technologies.

- **step motor:** has significant iron losses and is characterised, due to its open loop nature, by a lower efficiency.

b) operation with load conditions

- **DC ironless motor:** Joules losses are proportional to the torque squared and high efficiencies can be achieved especially in small and medium sizes. Torque capacity can be increased by the use of a gearbox
- **DC iron core motor:** presents also Joule losses proportional to the torque squared, but additional losses are generated by friction in the commutation system and by iron losses.
- **brushless motors:** present also Joule losses and iron losses. The global efficiency is also influenced by the voltages drops generated by the drives electronics.
- **step motor:** the torque capability of this motor is in principle higher due to the « magnetic gearing » effect. Iron losses are however non negligible already at medium speeds, and the nature of the electronic driver (chopper amplifier) can also introduce additional losses.

4.3 Resolution DC ironless and iron core motors:
The resolution is related to the type of encoder used. With topical encoders, resolutions up to 2000-4000 increments per revolution can be achieved. In the case of iron core motors, the residual torque can affect the resolution.

brushless motors: resolution is also related to the type of position encoder.

step motors: by its synchronous nature, a step motor offers a resolution which is directly related with the number of steps per revolution. Disc magnet motors offer, due to the optimised sinusoidal torque characteristic, a natural resolution which can be increased by a factor 4-16 in microstepping mode.

4.4 Dynamic response:

- **DC ironless motor:** very good dynamic response, related to the very low rotor inertia. The absence of magnetic saturation allows to generate very high acceleration torques.
- **DC iron core:** higher inertia, which can limit the dynamics
- **Brushless motor:** better dynamic than the DC iron core motor(depending upon magnet type).
- **step motor:** disc magnet motors present, due to their low rotor inertia, a very good dynamic performance

Motor technology	*DC ironless*	*DC iron core*	*Brushless DC*	*Disc magnet stepper*	*Hybrid stepper*	*Tin can stepper*
Criteria						
no load current	●●	❍	●	❍	❍	❍
efficiency small	●●	❍	●	❍	❍	❍
medium	●	●	●	❍	❍	❍
high powe	❍	●●	●●	●	●	❍
low speed	●●	●	●	●●	●	❍
residual torque	●●	●/❍	●/❍	●	❍	❍
starting voltage	●●	●	●/❍	❍	❍	❍
speed accuracy	●●/	●/❍	●●	●●	●	❍
dynamics	●●	●	●●	●●	●	❍
natural resolution	❍	❍	●/❍	●●	●●	●/❍
stability	●●	●●	●●	●/❍	●/❍	●/❍
noise	●●	●	●●	❍	❍	❍

Table I : Comparison of the figures of merit and corresponding benefits for various motor technologies

●● very performant ● medium performance ❍ little performance

5.0 S.O.A.P. : a global design platform for motion systems

The different characteristics mentioned in the table I are only general guidelines, related to a given motor size. Other elements such as the power electronics, the feedback sensors, the mechanical transmission and the control algorithm, if any , have to be taken into consideration for the evaluation of the global performance of a motion system.

A particular development tool named S.O.A.P. (System Optimisation Assistance Program)has been developed to address the problematic of direct graphical design and programming of electrical drives and motion systems. (cf Fig. 1). This development platform offers a user friendly graphical interface permitting the quick modelisation of complex motion system structures, comprising various motors technologies such as DC ironless, DC iron core, stepper and brushless motors. The corresponding numerical simulation allows the prediction and comparison of potential design performances. Moreover, complex control algorithms can be evaluated, compared and directly implemented in an hardware experimental platform.

The S.O.A.P. platform enables the designer to rapidly:

- define the specifications for the motion system associated with the case to be studied
- select and evaluate the motion system architecture
- select and optimise the different system hardware components
- modelise, simulate and optimise the off-line dynamic behaviour of the system
- generate and implement the real time control algorithm
- implement the complete motion system
- measure and analyse the real system behaviour

The development platform offers adequate expert models for the various motor technologies. As a consequence, a direct comparison between different potential solutions and their performance is already possible at an early stage of the design.

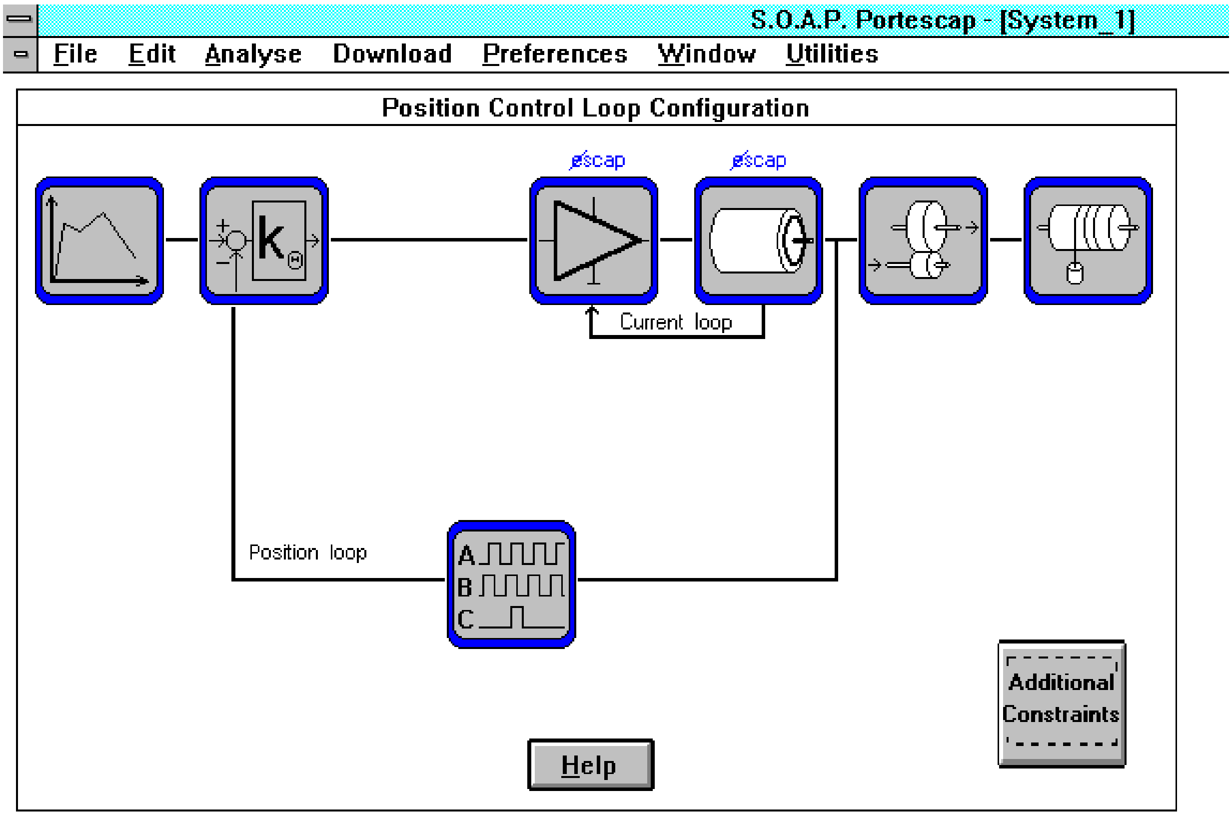


Figure 1: Graphical interface of the development platform S.O.A.P

6.0 Sensitivity analysis to the system parameters

Let us consider a typical servo positioning loop consisting of a DC ironless motor combined with an optical encoder feedback, as represented in figure 1.

The dynamic behaviour of the system and his performance can be normally predicted by an adequate simulation. Conventional simulation tools do however utilise more or less idealised models for the different elements. In some cases, this implicit assumptions can influence the real system implementation, as the real performance may differ from the predictions.

We can mention some factors which can contribute to variances of the system behaviour for the different elements, such as:

Motor
- non linear friction
- cogging torque
- iron losses
- hysteresis torque
- resistance variation with temperature
- magnetisation variation with temperature

Load and transmission
- non linear loads
- non linear friction
- compliance
- back-lash
- time dependent load torque
- speed dependent load torque
- position dependent load torque

Power amplifiers
- saturation
- offset
- bandwidth
- input voltage saturation

Encoder
- resolution

Analogue tacho
- ripple

A/D and D/A interfaces
- resolution
- sampling time
- offset
- saturation

Digital controller
- type of algorithm
- calculation resolution
- round off errors
- sampling time
- saturations/scaling effects

6.1 Case study I: Sensitivity to parameters

For the purposes of illustration of the approach let consider the following system

Motor type:	**DC ironless 35NT2R82 330P**
torque constant	k_t= 23.9 mNm/A
resistance	R = 0.84 ohms
rotor inertia	J_r = 70gr.cm^2
Power amplifier	
linear amplifier	
gain	2A/V
bandwidth	2kHz
supply voltage	35 V
Load and transmission	
Load inertia	J_m=70 grcm^2
direct transmission	
Feedback devices	
Optical encoder	500 lines

In order to determine an optimal hardware configuration, optimising the performance/cost ratio, this system has been simulated and tested in various configurations by changing the different parameters such as:

Parameter	Values		
• sampling time [µs]	100	200	500
• A/D resolution[bits]	12	10	8
• encoder [lines]	500	1000	2000

The results are synthesised in the following tables

Table Ia : Sensitivity to the encoder resolution

Parameter	Test 1	Test 2	Test 3
Sampling period [µs]	200	200	200
Encoder resolution [lines/rev]	4x500	4x1000	4x2000
D/A converter	12	12	12
Position error[deg]	2,18	2,23	2,18

TableII : Sensitivity to the D/A resolution			
Parameter	Test 1	Test 2	Test 3
Sampling period [µs]	200	200	200
Encoder resolution [lines/rev]	1000	1000	1000
D/A converter	12	10	8
Position error [deg]	2,21	2,23	2,21

TableI : Sensitivity to the sampling time variation			
Parameter	Test 1	Test 2	Test 3
Sampling period [µs]	100	500	200
Encoder resolution [lines/rev]	1000	1000	1000
D/A converter	12	12	12
Position error [deg]	5,56	2,21	1,08

If we consider the dynamic following error as a criteria in this case, we see that the most critical factor in this example is the sampling time associated with the control algorithm. The encoder resolution and the resolution of the D/A converter have less influence, and therefore the cost of these components can be optimised. The following figures illustrate two cases, where the sampling time has been selected to be 100µs and 500µs.

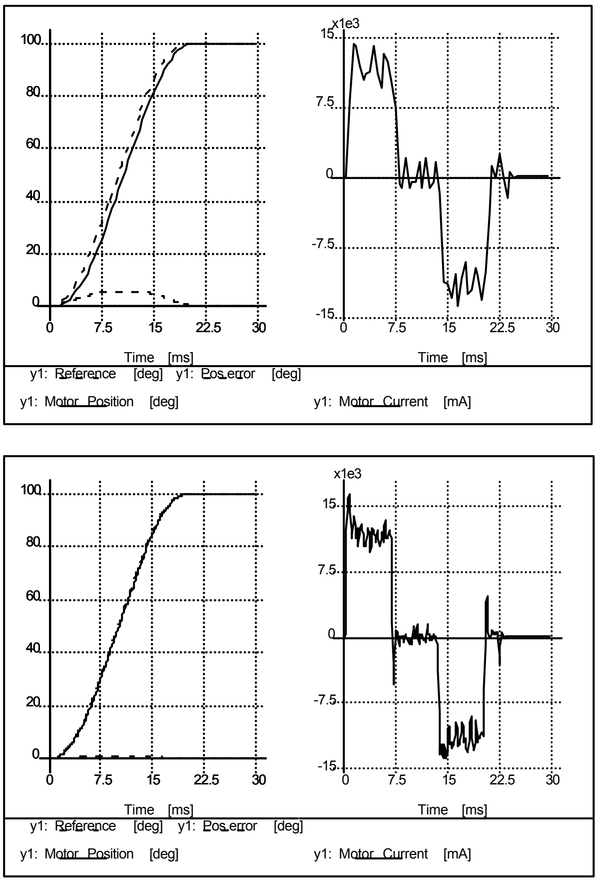


Figure 2a and 2b: dynamic response of the system described in paragraph 6.1 with sampling times of 500 and 100µs. Notice the improvement in the dynamic following error.

6.2 Case study II

Let us consider the case where a mass of 200 gr. has to be displaced linearly over a distance of 100 mm in 100 ms with a parabolic profile. The transmission considered for this case will be a two stages belt transmission which ratio can be adapted in the range of 1 to 4 and the radius of the second stage pulley can vary from 5 to 15 mm. As an example, a DC ironless and a stepper motor will be considered for the design

6.3 DC motor case

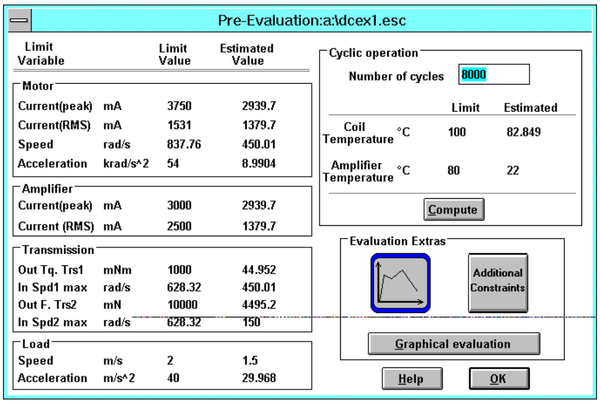
For the DC ironless motor , the retained solution consists of 28 mm diameter motor which characteristics are summarised as follows:

Motor type: DC ironless

Motor 28DT12 28 mm diameter

torque constant k = 32,50 mNm/A
resistance R = 6,20 ohms
rotor inertia J = 20 gr.cm^2
transmission ratio 3:1
pulley radius: r = 10 mm

The profile of the move is represented at the figure 4. The analysis of the dynamic variables such as motor current, transmission torque are summarised in the figure 3. We can particularly notice the thermal analysis which indicates that the motor windings will reach a temperature of 85 degrees when the move is repeated continuously every 200 ms. The thermal model associated with the motor includes the internal losses of the motor itself, such as bearings and commutation friction and, in the case of iron core DC motors, the iron losses.



Pre-Evaluation:a:\dcex1.esc

Limit Variable		Limit Value	Estimated Value
Motor			
Current(peak)	mA	3750	2939.7
Current(RMS)	mA	1531	1379.7
Speed	rad/s	837.76	450.01
Acceleration	krad/s^2	54	8.9904
Amplifier			
Current(peak)	mA	3000	2939.7
Current (RMS)	mA	2500	1379.7
Transmission			
Out Tq. Trs1	mNm	1000	44.952
In Spd1 max	rad/s	628.32	450.01
Out F. Trs2	mN	10000	4495.2
In Spd2 max	rad/s	628.32	150
Load			
Speed	m/s	2	1.5
Acceleration	m/s^2	40	29.968

Cyclic operation

Number of cycles: 8000

		Limit	Estimated
Coil Temperature	°C	100	82.849
Amplifier Temperature	°C	80	22

Figure 3: Preevaluation of the dynamic operating conditions for the DC motor.

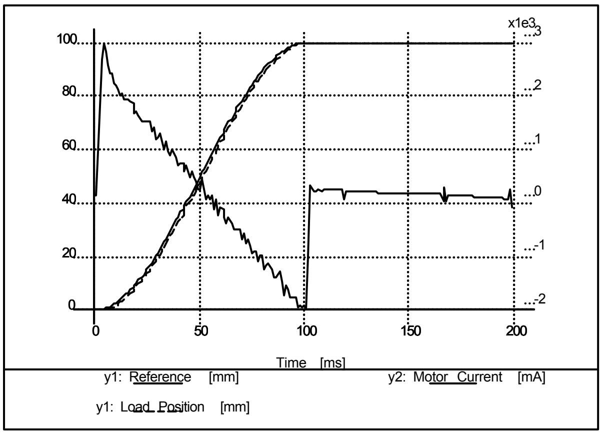


Figure 4: Simulation of the move of a DC motor with a parabolic profile

The feedback device considered in this case is a 500 lines quadrature encoder with edge count and a discrete PID controller with feedforward with a sampling time of 1 ms. The dynamic following error stays within 1 mm during all the move.

6.3 Step motor case

In the case of a step motor, which is normally considered as an open loop system, the designer has to verify that, according to the system parameters, the maximal dynamic torque required to accomplish the move does not exceed the maximal dynamic torque avalaible. The design tool offers in this respect an useful feature, as the theoretical maximum torque can be calculated by taking into consideration the motor intrinsic parameters and the power electronics parameters (voltage, current, operating mode of the power stage). Figure 5 illustrates a direct comparison between the maximal dynamic torque which can be generated by the motor (the so called «torque-speed » curve) and the required torque during the move. It can be noted that the elliptical torque-speed requirement, associated with the parabolic profile, remains within the maximum dynamic torque characteristic.

Motor type: Step motor

Step angle	3,6 degrees
Holding torque	120 mNm
Phase resistance	4.40 ohms
Rotor inertia	12 gr.cm^2
Driver (half step)	36V, 1.3 A/ phase
Gear ratio + pulley radius	3:1 with 10 mm

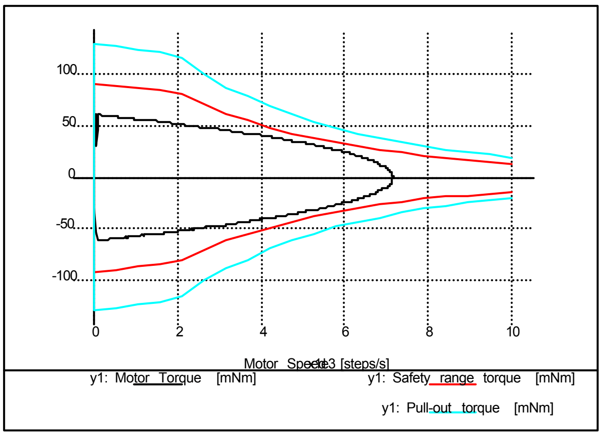


Figure 5: torque-speed locus for the step motor with a parabolic speed profile

7.0 Conclusion

The design of high performance motion systems is a typical multi-disciplinar approach, as knowledge in different fields such as electromechanics, power electronics and controls is normally a prerequisite. On the other hand, the different motor technologies do present specific advantages, which can make them suitable for different types of applications. The performance of the motor is however also strongly influenced by its interaction with the other elements of the system. The motor selection is therefore a multicriteria decision process. In this context, it is crucial to proceed to a global evaluation with performant in order to select the best motor technology and system architecture. This approach has been illustrated on the basis of a powerful design tool called S.O.A.P. (System Optimisation Program) which can assist the design engineer through all the development steps.

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