DESIGN AND TEST OF VERY LARGE DIAMETER, BRUSHLESS PERMANENT MAGNET TORQUE MOTORS FOR THE VERY LARGE TELESCOPE

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ABSTRACT

This paper describes the design and test of the drive systems for the four Very Large Telescopes (VLT) of the European Southern Observatory (ESO), currently under construction on Cherro Paranal, Chile. These huge and complex machines have exceptional requirements on movement smoothness and controllability. Direct drive was deemed necessary to get the best dynamic performance; an ad-hoc design was developed.

In this design, the Azimuth axis is powered by a 10 m diameter dual axial gap, brushless permanent magnet motor, with the design target of 250000 Nm peak torque and 210 Nm (less than 0.1% to peak) cogging torque. With the same architecture, the Altitude (elevation) axis is powered by two coupled 2.5 m diameter motors, with the design target of 72000 Nm peak torque and 60 Nm cogging torque.

The first fully operational telescope is nearing completion in Milan, Italy, where operational tests are being performed. The motor tests fully confirmed the expected performances, within 1% from specifications. A new version of the motor was also mounted on a large milling head for machine tool, now completing the first year of continuous operation.

Direct drive proved to be applicable to any motor size, guaranteeing high performance and elegant machine architecture, while also reducing overall system cost. A full line of large diameter torque motor was developed and full production is starting.

1. INTRODUCTION

The Very Large Telescope (VLT) project, operated by the European Southern Observatory, will consist of four of the largest optical telescopes ever built, each with a monolithic 8 m diameter primary mirror, which will also be able to combine their light output in a coherent optical path, to operate in interpherometric mode with the resolution of a telescope as large as the distance between the farthest units.

This extremely ambitious project, whose ultimate goal is to increase of an order of magnitude the size of the known universe, represents the utmost technical challenge in the motion control field as well.

Traditionally, large optical telescopes could never attain a very high angular resolution (at best in the 0.1 arcsec range), mostly due to optical aberration of the large primary mirrors and to atmospheric turbulence. In general, an increase in size would only worsen those plagues, so that the largest telescopes were often disparagingly referred to as "light buckets". The advent of novel techniques, such as active optics and adaptive control of the light path, with the promise to nullify atmospheric turbulence, put the possibility of a stunning 0.01 arcsec in imaging and an order of magnitude less in interpherometry resolution within reach. The impact of this potential on telescope attitude control can be appreciated considering that one of the VLT telescopes, with 20 m diameter and 400 metric tons mass, must be controlled within less than 0.4 μm increments on the 10 m diameter tracks just to achieve a 0.01 arcsec resolution.

For an observatory on a mountain top, wind gusts could be a cause of major concern, producing variable frequency disturbances on the telescope structure. As the maximum availability of this very expensive machines is of utmost importance, the observation performances must be maintained even while sustaining rapidly varying winds. Furthermore, the controllability at extremely low speeds is particularly important while performing long exposure observation.

All these performances would be meaningless if the structure were not perfectly stable: a particular emphasis is also placed on the thermal equilibrium of the active parts close to the optical path, to avoid blurring due to air convection, as well as to reduce any unbalanced force which could deform the structure and move the optical axis. See photograph n. 1 for a view of the assembly and test site.

2. OVERVIEW OF SYSTEM SPECIFICATIONS

The drive systems for telescopes must be able to guarantee a tracking accuracy in the same order of magnitude of the optical angular resolution, in spite of a structure which, because of its size, cannot be infinitely stiff and inspite of unbalance or sudden loads, such as wind gusts. This mandates a wide **bandwidth** for the whole drive system.

Concentrated loads imply lower equivalent stiffness and increased design complexity. This drawback is typical of a conventional drive architecture: few transducers deliver force/torque on few, even one, points. Moreover, in a conventional gearbox, the load is carried by a few teeth, whose stiffness rules the system: this leads to larger, heavier and cumbersome gearboxes, with low gear ratio. Bandwidth does not generally remain limited by the performance of the electrical members, but by the mechanical linkage: the first resonance of the mechanical assembly is usually at least one order of magnitude less than that of the associated electrical parts.

While stiffening the mechanics by “brute force” is feasible, but increases also system complexity, weight and cost, an increase of the mechanical bandwidth, proportional to the stiffness-to-mass ratio, it is a far tougher exercise. Neglecting non-optimised or wrong structures, which may show substantial improvement margins, the bandwidth improvement can be reached only by extensive use of relatively “exotic”, but surely more expensive, materials.

With direct drive, the active portions of the transducer are directly connected to the structure, eliminating the mechanical chain; with a clever architecture, this also enables to further reduce structural deformation by wrapping the generated force or torque over a large portion of the moved structure, increasing the equivalent stiffness of the drive “linkage”.

Ultra-fine positioning at extremely slow speed, possibly with zero speed and torque crossing, is typical of observing a star crossing a meridian.

Any mechanical chain implies a loss of **linearity** when speed crosses zero: for example, conventional gear trains have a little play, which cannot be neglected for fine positioning. Usually, gear preload is introduced or a friction drive is used, but both these techniques lead to a mechanical chain with a substantial stick-slip behaviour. Again, direct coupling of the force/torque generating member to the structure gets rid of these problems; lack of linearity at zero crossing is limited by the drive electronics and easily nullified.

Currently, the main drawback perceived in association with direct drive is **cost**; however, the total cost of a drive system must be considered, covering the integration to the moved structure, i.e., the design issues “driven by the drive system”, as well as the assembly and disassembly procedures. These hidden costs are often neglected, especially in the early program definition.

Many conventional drive systems cited before could require components individually less costly than a single direct drive; while guaranteeing a slight price advantage, they surely involve painful assembly and trimming procedures. In some of the most exotic designs, the machines took years to achieve marginal operation. Moreover, the easily attainable modularity of direct drive guarantees a “gentle” degradation of system performance during maintenance operation, further improving machine availability and productivity.

Substantial savings would be possible only by introducing large gear ratio, which must be ruled out from a performance standpoint. Low gear ratios do not guarantee a substantial reduction of the size of the active parts of the motors, i.e., of the cost of the system, while keeping the drawbacks of a “quasi-direct drive” solution.

Finally, it must be stressed that cost is one of the design parameters most influenced by design ingenuity and now it can actually become, even limiting to the component acquisition cost comparison, lower than that required by a conventional approach.

Early direct drives, especially employing linear motors, were plagued by heavy parasitic force/torque components due to **cogging**. This disturbance, resulting by the steel stack slots interacting with the permanent magnets, can be strongly reduced by design. Furthermore, these techniques are applicable to motors of any size and are non-recursive costs, i.e., do not imply expensive materials or production subtetlies.

3. VLT DRIVES DESIGN

Within this design framework, direct drive was chosen as the optimal drive solution from a performance standpoint.

The original VLT requirement for direct drive implied the design and realisation of unusually large torque motors, which, if manufactured with conventional techniques, would be made piece-wise and assembled on site. The simple **scaling** of a conventional torque motor design appeared inadequate. Infact, the adoption of a conventional design torque motor to the VLT drive would involve a linear scaling factor of 20 to 40 times from conventional technology motors. Linear scaling, however, is not correct, as the stiffness and bandwidth design targets are not scaled, while the structure flexibility and stray magnetic forces are and with different laws.

On a "normal" size torque motor, the radial stiffness of the rotor is adequate to bear the radial stresses due to the gap magnetic field, which are typically one order of magnitude greater than the tangential components. Dealing with diameters measured in meters, the radial deformation can grow to be comparable to the gap thickness. From another viewpoint, in conventional, radial air gap motors the motor torque cannot be generated without a parasitic modulation of the air gap perpendicular force. If this armature reaction modulation is allowed to deform the motor structure, a resonance mode can be excited in a full ring, symmetrical motor. This may impair the system controllability.

3. 1 Description of adopted solution

For all the reasons listed, a non conventional motor approach has been adopted. The direct drives consist of *segmented, dual axial air gap brushless motors* (see Fig. 1), similar to slightly curved linear drives. The Azimuth (AZ) drive rotates the whole structure around the vertical axis, while the Altitude (AL) drive rotates the mirrors assembly around the horizontal axis and is split in two parts, at the opposite ends of the rotating shaft.

The dual axial air gap brushless motors consist of:

- A disc shaped rotor part, realised in arc segments, with FeNdB type permanent magnets embedded in the disc and protected by a stainless steel structure. The disc does not provide a magnetic flux return path. The multi-pole field generated by the magnets is directed parallel to the rotor axis. The ring is stiffly mounted on what is conventionally termed the rotor, in practice the hydrostatic bearing track.
- A number of dual stator segments, each covering an arc of the rotor, which surround the disc on both sides and which are braced against each other to create an air gap on both sides of the disc. The stator segments are laminated in cylindrical layers and are slotted on the faces facing the rotor disc. The three phase windings are symmetrically located in the slots. The C-shaped stator sections locally balance the axial pressure due to the magnetic field: no action is transmitted to the main structure. All the sections are liquid cooled: the stacks are mounted on two cold plates, sporting integrated coolant lines. The two cold plates are connected to need just two, input and output, coolant lines per section.

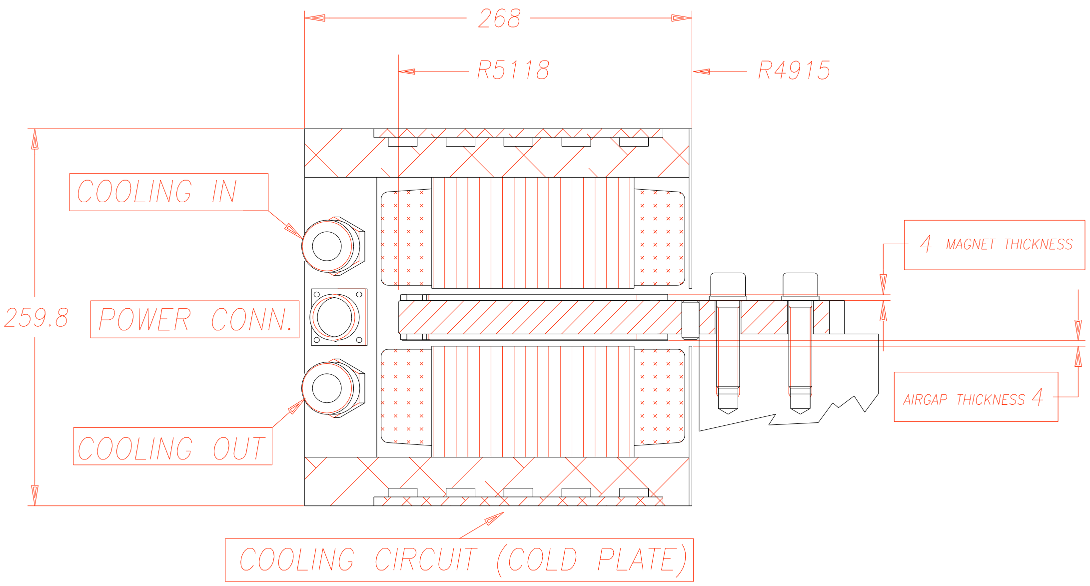


Figure 1: Section view of the Azimuth motor

- Within the same mechanical shape and dimensions of the motor stator section, two very high resolution tachometers are mounted, using the rotor magnet tiles as flux generators. These units also carry the Hall sensors board necessary for the motor initialisation procedure, which requires a short rotation before switching on to the high resolution sensors.

The design is characterised by a number of key advantages:

1) The non-torque producing magnetic forces, both primary and stray, are balanced out between each two symmetrical stator segments locally and are not applied to the rotor, which only experiences a pure tangential force; this not only simplifies manufacturing and assembly, but minimises motor deformation versus torque and increases the first resonance frequency;
2) The air gap is determined by the spacing of the two stators, i.e., with the present architecture, by a short chain of “small” mechanical pieces, and is easily adjusted segment by segment during on-site installation; the air gap is virtually temperature insensitive;
3) The addition or removal of any segment does not imbalance the machine and no magnetic force is applied between segments;
4) Any rotor segments can be removed easily by rotating the unit so that the desired segment is placed between two stators; disassembly is then carried out without need of specific high force tools;
5) From a piece wise manufacturing standpoint, a better air gap accuracy at a lower cost is achievable because the air gap is a flat instead of a cylinder;
6) Fluid cooling, necessary to satisfy the stringent thermal specifications, is also simplified as the stator segments exchange losses across a flat surface to a simple "cold plate";
7) The motor production is simplified and its cost greatly reduced, as the system is made by a lot of equal, easily manageable parts, independently mounted and tested.

3. 2 Electronic drive strategy

Owing to the absolute smoothness requirement of this application, three phase sinusoidal, current-fed drive is mandatory. The more traditional six-step drive with Hall sensors is deemed unsatisfactory because the sudden current switching between one winding configuration and the next would necessarily cause a torque "glitch", several milliseconds long, which is certain to disturb the most sensitive instruments.
The drive strategy adopted in the VLT attitude control is the following:

Altitude motors: there are two altitude motors on each side of the fork, and each of them is composed of two separate motor circuits. The four circuits are driven by four separate sinusoidal amplifiers which are current fed type and therefore operate as torque amplifiers. A single speed processor derives a speed signal from the tachometers and the high resolution position sensor and outputs an analogue torque reference for all of the drives. Operating all sections as torque amplifiers with the same reference minimises deformations and structural stress.

Azimuth motor: there is one azimuth motor composed of four separate motor circuits, interleaved across the periphery. The four circuits are driven by four separate sinusoidal amplifiers which are current-fed type and therefore operate as torque amplifiers. Also in this case, a single speed processor derives a speed signal from the tachometers and the high resolution position

Parameter	**Target**	**Achieved**	**Units**
Rated RMS cont. torque	125000	124820	Nm
Peak torque (25% duty)	250000	249630	Nm
Maximum speed	0.05	0.048	rad/s
Rated speed at nom. torque	0.0349	0.034	rad/s
Max. Cogging Torque	220	208	Nm
Torque Ripple	0.1	0.11	% rated, pk-pk
Current loop bandwidth	500	470	Hz
Loss at rated torque	3262	3320	W
Motor mean diameter	10000	-	mm
Motor Thickness, excluding cold plates	187	-	mm
Air gap, mechanical	4+4	-	mm
Rotor inertia	21536	-	kgm^2

Table 1: Azimuth motor data

sensor and outputs a torque reference for all of the drives.

The drive amplifier is a custom modification of a commercially available, fully digital brushless driver. It is based on 1200 V, 16 kHz IGBT technology and a 16-bit micro controller. The bandwidth of the current control loop is about 2 kHz. All of the 8 amplifier modules are equal except for software programming.

Each drive amplifier is fed separately and can be taken off the rack for service or maintenance without powering down the system. Considering the high operation time cost of the VLT, it is deemed that the highest availability should be sought by design.

The margin in driver available voltage provides a high torque slew rate, necessary to react to a rapidly changing torque demand, driven by wind gusts. In this configuration, the amplifiers can slew from 0 to 100% torque output in less than 5 ms.

For redundancy purpose, it is possible to operate the drives with half of the maximum continuous torque with only half of the drive, and even when a number of segments in the non operational part of the drive are removed for maintenance or upgrade. If an entire drive set is removed, the axis torque is limited to 3/4 of rated. If only one section is removed, the drive can be operated by replacing the section with a jumper connector. In this case, the loss of torque is 1/16 of rated for AZ and 1/12 of rated for AL.

4. COGGING AND TORQUE RIPPLE

As the telescopes are to be operated in a fine position loop at very low speed (down to one revolution per year), particular care was applied to minimise the cogging and torque ripple of the motor.

This parasite torque modulation can be generally divided in:

- cogging torque, due to the interaction between the permanent magnets and the stack edges and slots, i.e., between the magnets and the motor iron parts. This torque is solely dependant on rotor position and it is potentially the most disturbing for fine positioning.
- hysteresys torque, due to the hysteresis losses (mainly in the stack lamination), in which flows a variable magnetic field. Its contributions is minimal and pratically indistinguishable from the larger cogging component.
- equivalent “viscous” torque, due to the losses by Focault currents in the motor iron. This torque is proportional to rotational speed and it does not impair fine positioning as it does not generate stick slip.
- ripple torque, due to the incorrect matching of the modulated current to the actual motor e.m.f.. This term depends on the motor geometry as well as on the winding and drive current modulation, and results in a gain variation of the torque loop.

To minimise the cogging torque, the stack laminations and overall dimension were optimised by finite element analysis [Ref. 1]. The calculated cogging profile, periodical over 180 electrical degrees, was then used as input to the detailed study of the mechanical positions and electrical phase relationships between the stator sections: developing a harmonic distribution of the sections over the cogging periodicity results in eliminating the lower order, larger amplitude harmonics. This results in a total cogging torque on the Azimuth motor, delivering a peak torque of 250000 Nm, down to 210 Nm. It must be noted that, on a 5 m radius, this translates in 4 kgf tangential force; the telescope, supported by hydraulic bearings, can be, and actually is, moved by one man, single handed. It must also be stressed that, in these condition, motor cogging is virtually unmeasurable, as it is swamped by the hydraulic pads (extremely low) contribution to the friction torque.

Closely related to this issue, the bigger the motor, i.e., the more stator section are used, the higher the order of the cogging elimination and the lower the total torque ripple; the total cogging torque may even get lower than that expected on a single section.

The torque ripple, while already reduced by the motor geometry chosen to minimise cogging, can be further minimised by a suitable phasing of the four co-ordinated drivers feeding each motor; furthermore, the current modulation over 360 electrical degrees can be mapped to closely follow the actual e.m.f. This technique depend strongly on the quality of the position data input to the motor: the maximum efficiency (0.1% total torque ripple) results from using the high resolution (20-bit) position data from the laser encoder mounted on the telescope. 9 hall sensor signal distributed over 180 electrical degrees are also available for system start-up and emergency back-up

5. MOTOR TEST RESULTS

The first tests before the full production run were performed on a prototype Altitude section, the motor with the highest torque density. Two rotor plates were mounted on a large vertical mill turntable, while one stator section was bolted to a turntable chassis. The motor was braked by a tangential arm, i.e., a linear actuator made by integrating a brushless motor, a lead screw and a high resolution load cell; the position sensor was a wire linear encoder wrapped over the turntable circumference.

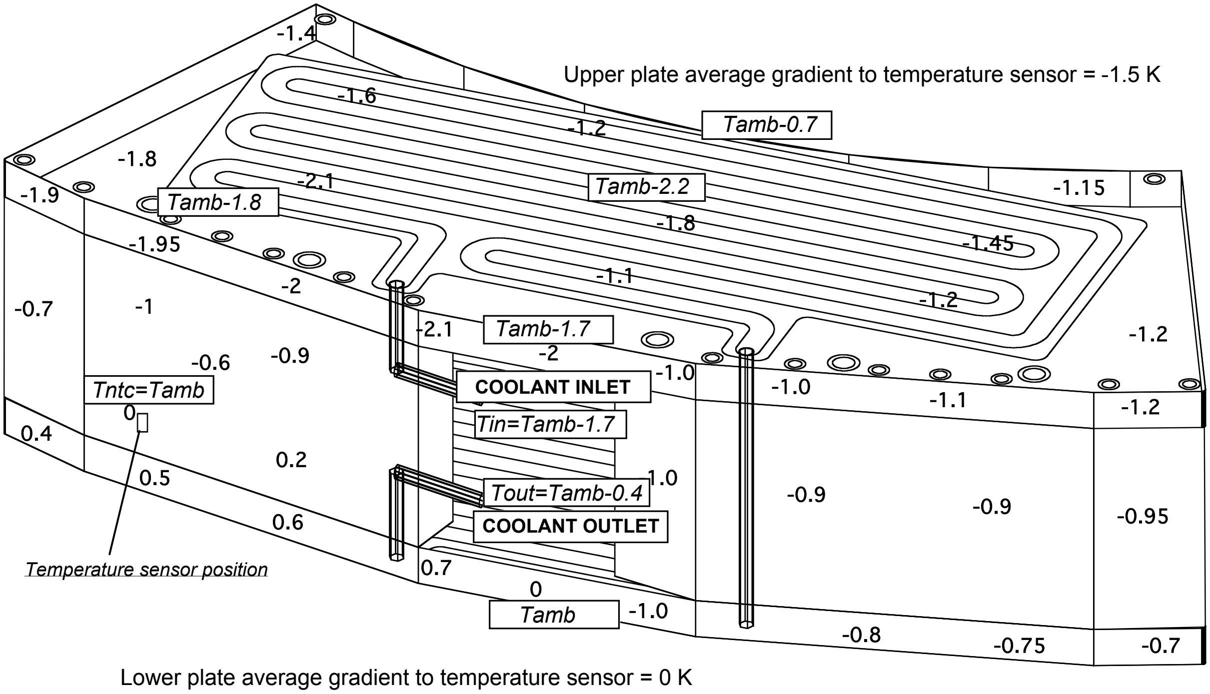
This configuration guarantees maximum stiffness, necessary to bear the large tangential forces expected: one single Altitude stator section delivers a nominal tangential force close to 6000 N. Furthermore, while the axial forces between the rotor and the stator are balanced (ideally, with a perfectly equal gap on both sides, the resultant is zero), the equilibrium is unstable: in first approximation, the magnetic attraction can be modelled by a negative spring. If the positive spring given by the stiffness of the motor supporting structure is not sufficient, the rotor plates will tend to lock on the stator.

The tests, while enabling to anticipate minor modification to the motor drawings, were in complete accordance to the calculations. The back e.m.f. and torque constant resulted equal to 99.85% of the design target. The total cogging torque on a single Altitude section was measured to 110 Nm peak. By harmonic elimination, the resulting cogging torque on the Altitude axis, made by 12 sections, is down to 5.5 Nm peak. In practice, the cogging on the 2.5 meter diameter axis is unmeasurable: the equivalent tangential force results less than 0.5 kgf.

The temperature distribution on the liquid cooled stator was also well within specifications: every point of the motor is within 2.2 K to room temperature while delivering the nominal torque. The maximum allowed temperature rise in the coolant is 4 K. Not to generate relatively hot air columns rising toward the mirrors, the exposed surfaces run at an average of 1.5 K less than room temperature. The temperature layout, together with a sketch of the cooling circuit, is given in Fig. 2.

The drive showed an exceptional linearity, without any measurable deviation while crossing the zero torque, as it is shown by Figure 3. The slight hysteresis is due to the testbench bearing friction and load cell offset.

Testing the tachometer prototype was equally impressive. Performing the integration of the e.m.f. over such a huge surface (8.15 dm^2) results in a sensor of exceptional resolution and repeatability. Filtering the "microphonic" noise due to the micro-seismic disturbances generated by speaking and traffic is not so easy on a sensor able to discriminate a 0.1 μm displacement: simply pressing the heavy stator hull with one hand resulted in a repeatable change in the integrated tachometer output lower digit. The tachometer has a measured e.m.f. of 2276 V/rad/s, with a 0.9% output ripple and a measurable torque output down to 0.01 arcsec/s!



Test conditions:	Nominal current
	Temperature measured at thermal balance (italics) compared to the results of thermal simulations
	Coolant flow: 5.5 lit/min Pressure drop: 0.44 bar

Figure 2: Thermal test on an Altitude stator section

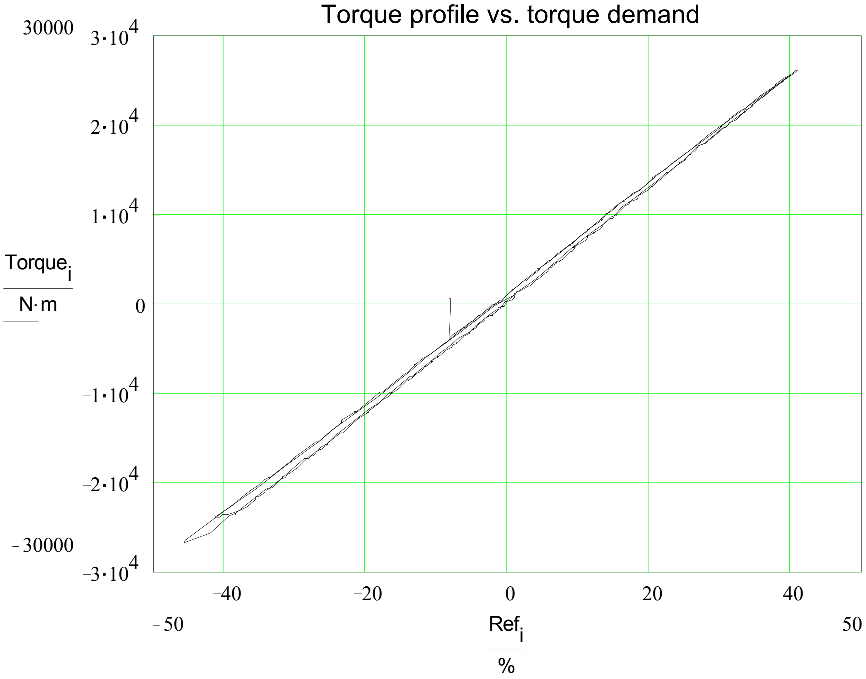


Figure 3: Drive linearity: torque output versus the percentage of torque demand, on Altitude Axis motor

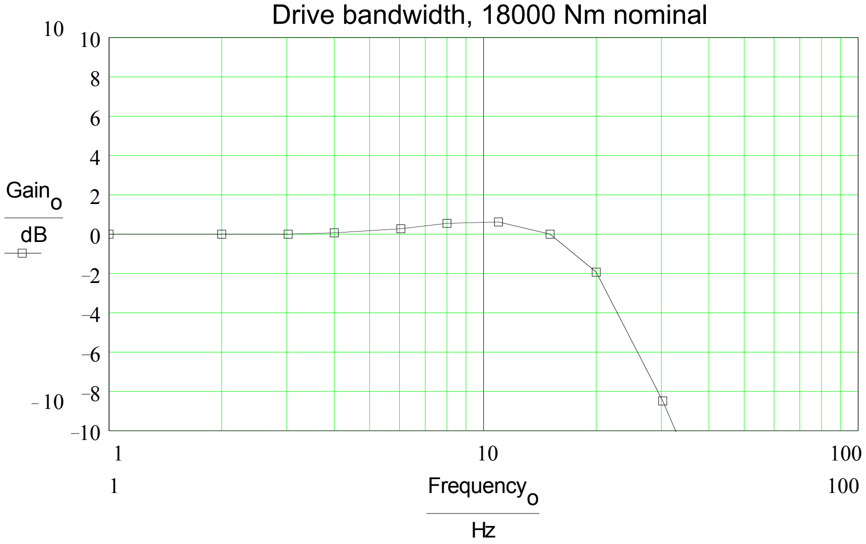


Figure 4: Bandwidth of the B/C axis drive system;
encoder resolution: 3600000 counts/turn

6. APPLICATION TO MACHINE TOOLS

Additional to telescope control, large direct drives are finding new application in the field of machine tools. A 2.5 m class, 60 kW, 18000 Nm, 100 rpm motor was developed for a unit capable of double operation as a controlled table for milling (B axis) and a spindle for turning (C axis).

During the telescope operation, the stringent thermal specification leads to a particularly low thermal torque. With complete commonality of parts with the Altitude motor, the B/C axis, two stator section drive sports winding and magnets adapted to the higher working currents and thermal loads allowable in a machine tools: the nominal current is increased 7 times, up to 100 Arms. The coolant temperature rise is 35 °C: the coolant runs considerably hotter than on the telescope, but the stator cold plates still shield the main structure from the motor's hot spots, nullifying any machine thermal deformation which would impair working precision.

The direct drive approach guarantees the low speed smoothness, high torque and stiffness necessary for milling while still delivering the large continuos power required by the turning operation. The first machine has now been operated daily for more than one year; various units are currently under production.

Figure 4 displays the measured Bode plot for this drive system, showing the high equivalent axis "stiffness" and disturbance rejection (bandwidth: 21 Hz). In practice, this results in reacting to a 6000 Nm step excitation, corresponding to a worst case milling operation, with a maximum 0.021° deflection angle. This parameter, on a 2.5 m radius, translates in a 0.5 μm deflection while sustaining a step load equal to 1/3 of the nominal torque. This performances enable the user to mill without braking the turntable mechanically; once more, the use of direct drive simplifies the system.

This simple architecture must be compared to the conventional approach, showing two separate motors for B and C axis and a mechanical brake. Direct drive leads to higher precision and operational speed, particularly in contouring, with an order of magnitude increase in produced parts quality and productivity. This application demonstrates the advantage of direct drive, which combines elegance, low cost and increased performance.

7. CONCLUSIONS

Direct drive is now coming of age, encompassing the entire spectrum of drive power and size. With ingenuous solutions to very large diameter motors specifications, exceptional performances are now available at a cost substantially lower than that of conventional drive systems. Direct drive, enabling simple and elegant machine architectures, is now reducing assembly, tuning and maintenance operations, with further reduction in operation cost and increase in overall productivity.

8. REFERENCES

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