Holding brakes for Space Mechanisms with minimum Power Requirement

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Abstract

In space applications the rotational axes of mechanisms, which are driven with electric motors, need to be secured, not only during launch but very often during most of their operational life or cycle. Holding brakes are therefore required, which are mostly engaged in the un-energized condition. Such brakes should, however, require a minimum of electrical power during release, as energy is at a premium in space. It is also important to avoid or to minimize thermal losses.

In this paper various alternative holding brake technologies are presented with their characteristic advantages and disadvantages.

Introduction

One preferred motor type for space use is the hybrid stepper as this electric motor type has good torque-density. It can further operate without angular position feedback and exhibits a high intrinsic detent torque at many holding positions per revolution (typically 200). However there also many applications, which require servo- or torque-motors, which do not or should not exhibit any natural salient holding-torque positions. In this case or when a stepper motor is used for the design of a specific mechanism but its detent torque is insufficient, a brake must be implemented, which must also fulfil a major secondary requirement – low or better zero power consumption in the holding condition. We consider four interesting brake implementations, which can meet this requirement:

- Locking and release mechanisms
- Friction holding brakes
- Reluctance brakes, passive
- Reluctance brakes, active

Locking and release mechanisms - electromagnetic, pyrotechnical (when only one-time operation is required) etc. – are common in space applications but are not described here further.

Friction holding brakes, usually with spring operation and electromagnetic release, are frequently used in industry. Two suitable configurations for space use are presented below. This type of brake has the advantage of allowing the motor shaft to be held in any position but it has the significant disadvantages of mechanical interference and wear; it also requires a mechanical separation movement of two brake plates. It is often a major challenge to ensure safe movement of the brake plates over the wide and demanding environmental conditions of space application.

The passive reluctance brake is also employed in space. It has a symmetrical geometry using highly salient poles on stator and rotor, which cause the brake to relax automatically to preferred positions with a high detent torque, thereby holding the shaft in one of these positions.

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The fourth option, the “active reluctance brake”, we believe to be unique. This has been developed to meet the requirement of zero or minimum torque or damping, when excited. Like the passive reluctance brake it also has no wearing or mechanically interfering parts and consumes no power when active.

Friction Holding Brakes

We have developed a disk type of friction brake for a rotating antenna drive application on a drone, not directly for space but for stratospheric used. It has therefore been qualified to environmental conditions, very similar to space – low air pressure (100mBar) and low temperatures (-60°C).

In order to achieve high torque the design makes use of the large diameter of the torque motor, which is to be secured by the brake when the motor is stationary or inactive. A thin stainless steel ring is mounted around the rotational axis, attached to the rotor of the motor. This ring has high torsional stiffness but is flexible in the axial direction, to allow for some freedom of motion of the mechanism in the shaft axis.

Two brake calipers with pinching brake pads are mounted around the disk. These calipers are operated by mechanical springs to apply braking friction force to the disk and thereby braking torque to the motor. Electric solenoid actuators release the pads and reduce the brake torque to zero.

Figure 1 - 10 Nm Friction Disk Brake (MACCON)

This brake also fulfills another demanding requirement. Due to the sensitivity of the application, it was specified that a specified maximum level of reaction torque on the supporting structure may not be exceeded, if the brake is operated, while the motor is rotating. The brake described requires 36W to release but only 7W to maintain the released condition. Due to the springs incorporated in the calipers this brake is fail-safe.

Now we describe another type of friction brake, which can achieve high braking torque values in a much smaller diameter, thanks to the large torque multiplication factor of a gearbox. Figure 2 shows a high torque brushless DC actuator with an integral gearbox and friction disk brake. This actuator is used in a robotic arm application where power-off holding of a large moment is required. While the peak torque of the brushless actuator is 22 Nm, the unpowered holding torque of the brake is 8 Nm, reflected to the output shaft. With the mechanical advantage of the gearbox, a small friction disk brake provides significant power-off holding torque provision for a minimum of mass and volume.

A disadvantage of both friction disk brakes is the relative high power needed to pull-in or activate the free-running condition of the actuator. For instance, the brake design in the actuator in Figure 2 draws 7W power at 28 volts DC, the rated voltage. The voltage and power to maintain free-running actuation is however significantly lower, as it takes less than one watt holding power to maintain the brake in the disengaged condition.

There are several methods to minimize the sustained power draw of both friction brake designs described above. Since the “drop-out” or engagement voltage is significantly less than the pull-in voltage, the control system may simply reduce the excitation voltage after the free-running condition has occurred. The activation happens quickly, in about 10mS. As it may not be desireable to regulate the voltage, it is simpler to have two separate coils in the brake bobbin assembly. This is also an option for redundancy. The second “low power” or “sustaining” winding may be used to allow deactivation of the first “high power” or “activation” winding after the free-running has been achieved. The “sustaining” coil winding may have significantly higher resistance to minimize power draw, compared to the “activation” coil winding. This schematic is represented in Figure 3.

Figure 2 - 22 Nm Actuator with Integral Friction Disk Brake (Avior)

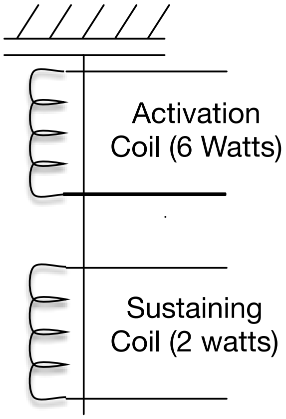

Figure 3 - Dual Coil Brake Schematic (Avior)

A method to easily remove the power from the “activation” coil is to add a “blocking” capacitor in series with the winding. As the DC excitation is applied to the “activation” coil winding, the current flows through the winding, as the inductance allows. Once activated the current levels off and the blocking capacitor drains the current down to zero. This is a simple method that does not require additional logic or switches to disable the “activation” coil.

Passive Reluctance Brakes

Passive reluctance brakes (or detent brakes) are always active, which in turn means that the motor needs sufficient starting torque to overcome the brake detent torque in addition to any stall load torque. However once the shaft is rotating, the additional power needed to run the motor drops, as the reluctance torque equally assists as well as resists motion; the effect of this pulsing load torque drops with increasing speed. Typically this type of brake only offers a limited number of holding positions per revolution (4,6, 8.12 etc…).

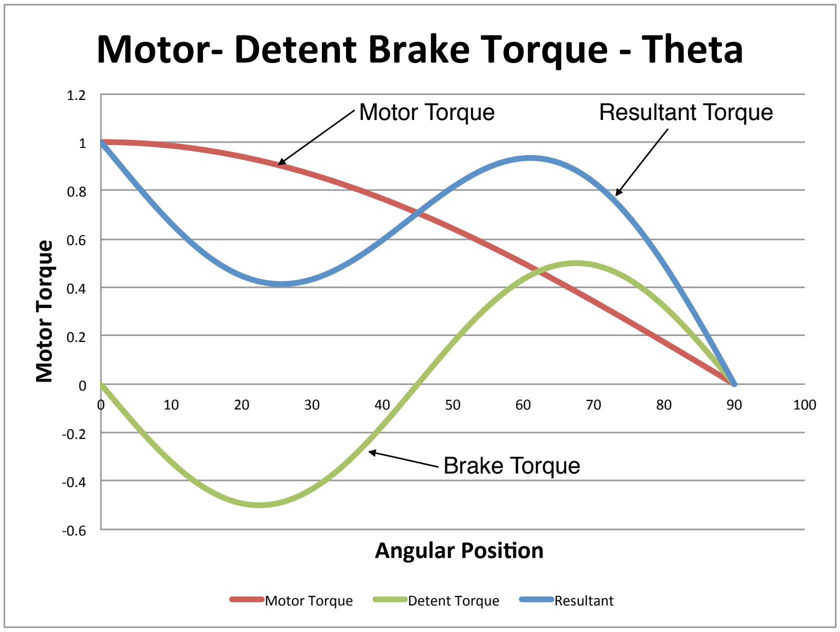

Figure 4 - Stepper Motor and Reluctance Brake Torque vs. Position Plot (Avior)

Figure 4 shows a Motor Detent Brake Torque versus position (or Torque-Theta) plot of a stepper motor combined with a passive reluctance brake. In this configuration, the motor steps and stable brake detent positions coincide. At each step of the stepper motor, the torque drops off from the peak torque to zero in a cosine function (for sinusoidal back EMF). The detent brake repels against the motor torque for the first half of the step, and assists in the second half of the step. While the area under the curve integrates out, it is over-simplistic to state that the detent brake does not have an impact on dynamic performance. In fact, the detent brake may have a positive affect on performance. Since it can add torque as the stepper motor is approaching the stable step position, the rotor accelerates faster through zero and creates more overshoot at cardinal stepping frequencies.

As described in [1], overshoot in a stepper motor creates cardinal maxima and minima torque variations at various points along the torque-speed curve. The addition of the detent brake inherently attenuates the pull-in torque of stepper motor actuator at low pulse-rates. The actuator pull-in torque curve in Figure 5 shows performance with and without a 19 mm passive detent brake that produces 1.0 Nm torque at the output. As you see at low velocities, the whole torque of the detent brake reduces the available pull in torque. As the step rates increase, there are varying affects of the detent brake. The pull-in torque attenuates or increases at varying step rates. At high velocities, above the mechanical time constant, the detent brake has virtually no affect on the actuator performance.

The advantages of the passive brake configuration are zero energizing power and no control circuit requirement.

Using this brake directly on the servomotor shaft before a high-ratio reduction gearbox allows its dimensions to remain small and minimizes servocontrol problems, which result from the motor having to operate against the high ripple torque of the reluctance brake. Positioning is intentionally limited to the preferential positions of low reluctance to which the brake is naturally biased. It is interesting to note that the pull-out torque is much less affected by the detent brake. In other words, the pull-out torque performance of an actuator with a detent brake closely matches the pull-out performance of the same actuator without a detent brake. We strongly recommend full characterization with simulated load inertia of actuators incorporating passive detent brakes.

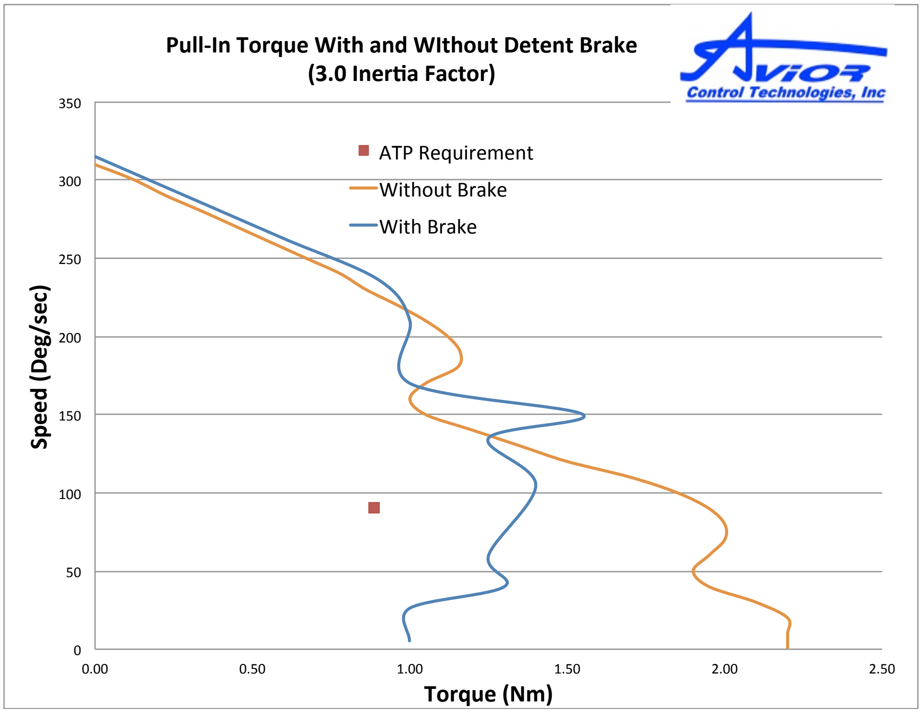

Figure 5 - Pull-In Torque Performance

Active Reluctance Brakes

This active reluctance type of brake will be used in a valve actuator of a space vehicle launcher application. The solution chosen has a special stator/rotor geometry with many positions of minimum reluctance per revolution. Permanent magnets fitted in the stator cause this brake to have 200 holding positions with a closely defined holding torque value. The permanent magnet field can however be neutralized by passing current through a single winding within the stator, thus allowing the mechanism to rotate with minimum magnetic drag.

The first application we have realized is illustrated in Figure 6. It has an outer diameter of 120mm and length 30mm and a holding torque of 3.3Nm.

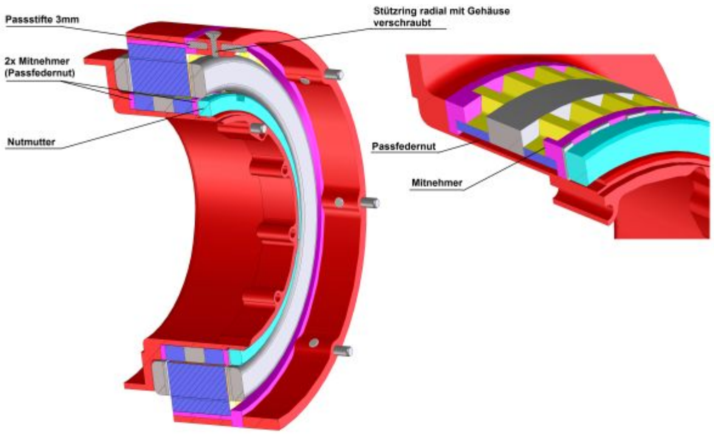

Figure 6 - Active Reluctance Brake (MACCON)

The torque characteristic of the active reluctance brake over one pitch is shown in Figure 7 and the flux distribution in both operating conditions in Figure 8.

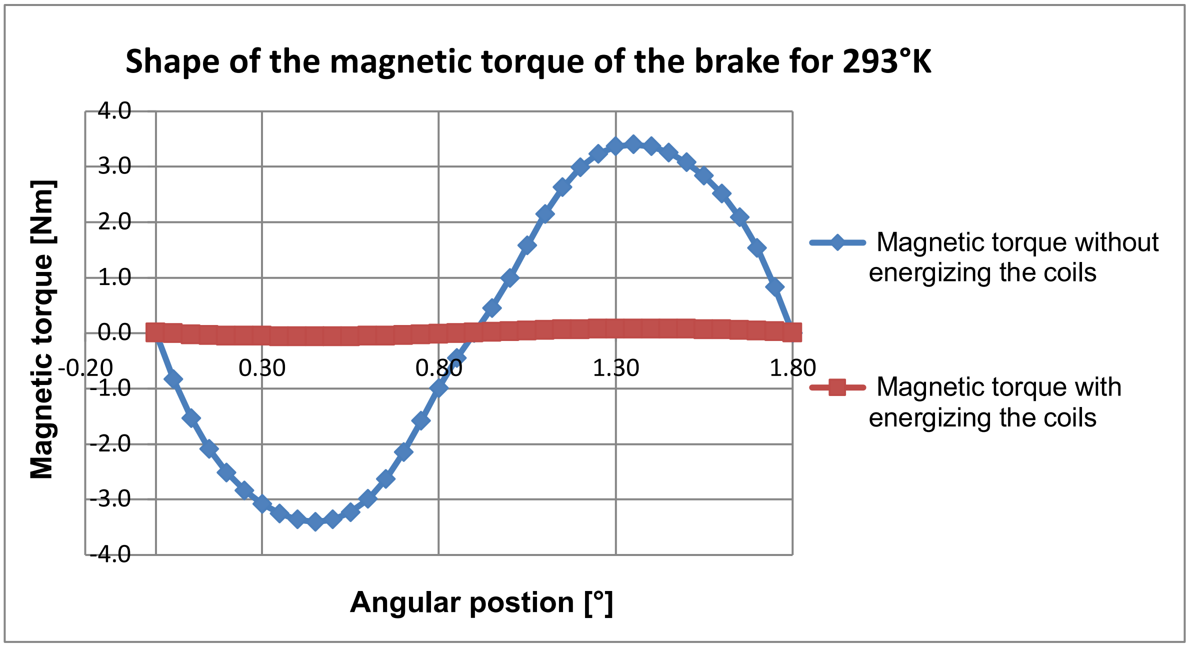

Figure 7 - Holding torque of Active Reluctance Brake (MACCON)

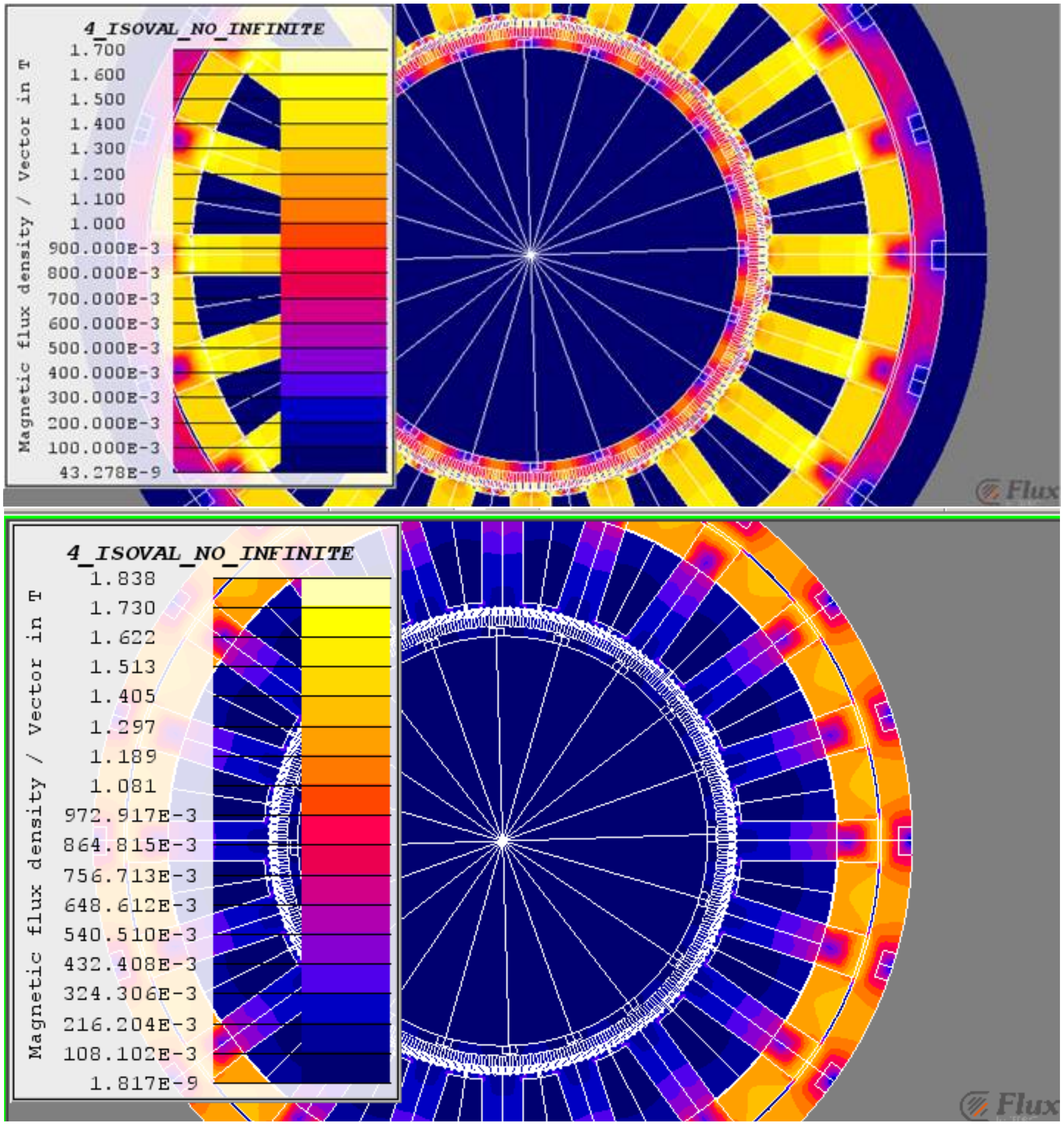

Figure 8 - Magnetic Flux distribution in active releuctance Brake with stator coils energized and not-energized (MACCON)

The clear advantage of this brake design is the high number of preferred braking positions per revolution, 200, without the need to energize the brake. There is also a good geometrical match between the brake and its matching motor design dimensions. On the negative side it does require high excitation power to release, i.e. for the neutralization of its holding torque (58W) . In applications, where release is only needed for a short periods this energy dissipation can be accepted.

Conclusions

The four holding brake configurations described in this paper have been especially designed for demanding hi-rel und space applications. As they offer very differing mechanical configurations and braking characteristics, it is probable that one of these configurations will serve any new electro-mechanical drive or actuator application.

All brake designs discussed share the essential properties of requiring zero energy, when braking torque is required and of being fail-safe. If the energy supply fails, the holding condition is guaranteed. Passive-reluctance brakes offer the advantage of no power excitation, but detailed characterization of performance with simulated load inertia is recommended, due to induced operational pull-in torque variations due to increased step-response overshoot. Additionally, passive reluctance brakes are not recommended for servo-systems, because the control system may always be fighting against the brake torque.

Lastly, all the active brake configurations can easily be made electrically redundant, with the simple implementation of a second excitation or release coil [2]. Friction disk brakes designs may use unbalanced power configuration with a two-coil option, to minimize quiessent power draw with a higher resistance sustaining coil.

References

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