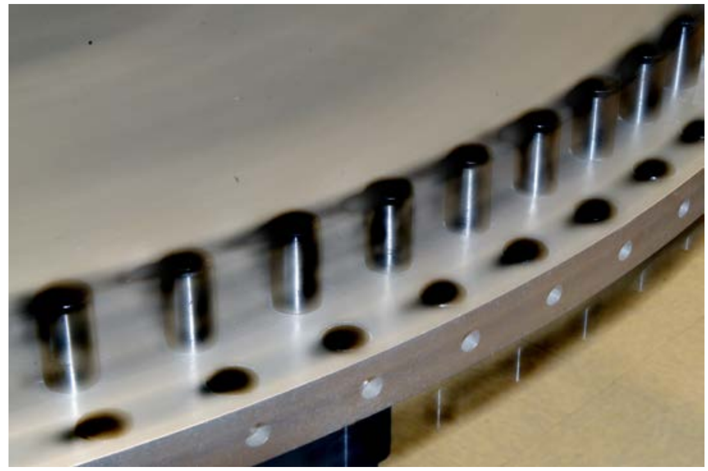

Power Savings through Energy Management using PMAC Direct Drive Servo Motor Technology

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White Paper

Direct Drive servo motor and drive technology not only reduces an axis' parts count, mechanical losses and often its objectionable noise; Direct-drive technology also increases a machine's efficiency, lowering operation cost for the user due to its inertia ratio, as compared to the more common mechanically advantaged multi-body axis designs. Reducing the mechanical transmission components such as gearboxes, timing belts, pulleys, cams, lead screws and so on, between the motor and its load is only part of the savings!

This article presents a determinate measure for managing energy utilization of a servo motor during a machine's design. This determinate measure of inertia ratio: J load / Jm, is presenting the Energy saving potential (Figure A) for dynamic applications as a function of an axis' inertia ratio, which is typically broadened in Direct Drive servo applications. However, with good mechatronic concepts during a machine's design, mechanically advantaged servo axes can also save significant energy cost.

Maximize Energy Savings[1] with a Determinate Measure

The potential energy savings of any dynamic servo axis can be determined by a comparison of its inertia ratio, where all acceleration & deceleration energy is transmitted to the load (*J_load / Jm* = ∞), against the maximum power transfer ratio: *J_load / Jm* = 1, where only half the acceleration & deceleration energy is transmitted to the load. Maximum energy savings is best achieved with a minimal *Jm* (theoretically: *J_load / Jm* = ∞; not a matched *J_load* to *Jm*).

The inertia ratio (also called moment of inertia ratio or inertia mismatch) for a rotary servo system can be divided into two main parts: (1) the total moment of inertia of the load (*J_load*), of all the axis' components (reflected back through the mechanism when applicable) summed together at the motor's shaft, and (2) the motor's moment of inertia (*Jm*).

The ideal inertia ratio is presented in many technical manuals to be 1 : 1 (where *J_load* = *Jm*). This ratio is the ideal inertia ratio limit for maximum power transfer (evenly splitting the acceleration & deceleration energy with the motor) to minimize potential control loop issues; however, it undesirably maximizes energy utilization in dynamic applications. Where the other ratio: *J_load / Jm* = ∞, presents maximum theoretical efficiency for any given axis under evaluation. When this best possible theoretical inertia ratio is compared against the maximum power transfer ratio, we have a determinate measure for energy management[2] (Figure A).

An axis' energy savings is maximized when as much electrical energy as possible is expended on the actual load. The lowest possible power requirements of an axis is achievable when the machine designer looks for the maximum acceleration/deceleration of the load inertia, while also considering the system's limitations and capabilities for the axis stability, controllability, performance, accuracy, repeatability and so on.

Even though most servo motion control axes that approach a 1 : 1 inertia ratio are less likely to have control-loop instabilities, an application's ideal moment of inertia ratio is much more fluid than a fixed number or range. That is, each axis' ideal inertia ratio depends on the actual process to be performed, its mechatronic solution, application, and components which include, but are not limited to, the specific axis' motion profile and dynamics, friction, stiction, external loading, backlash, compliance and stiffness, loads, mechanism inertia, feedback resolution, number of moving mechanical bodies between the load and motor, natural frequencies of the design, the motor's drive Pulse Width

[1] …Not including any increased machine efficiency due to component reduction, which can be significant.

[2] As discussed in the White Paper: **Energy Management of a Servomotor: Effects of Inertia Ratio**, a theoretical maximum savings potential of approximately 60% [1] exist as compared to a 1 : 1 (J_load : Jm) inertia ratio.

Modulation/Space Vector Modulation (PWM/SVM), and any applicable controller update rates. For closed-loop mechanisms all these design factors come into play when considering operation and stability. Paradoxically, owner's manuals and even articles on this subject of inertia ratio (J_load : Jm) do not fully discuss the above due to the technical and mathematical, complexity and difficulty of implementation.

Optimal Inertia Ratios Allow for Increased Energy Savings

These dynamic applications, whether indexing and/or providing constant high-speed correction, can achieve substantial energy savings using today's direct-drive servo technology's advanced digital drive capabilities with faster processor speeds, update rates, flexible filtering, and high feedback resolution capability (in excess of 2^21 bits [2,097,152 counts] to upwards of 2^27+ bits [134,217,728 counts] per motor revolution); together yielding high system bandwidth (BW) response times. These advanced drive capabilities coupled with the best mechatronic designs have presented noticeably higher control capability for the utilization of direct-drive servo technology, allowing the servo industry to have enough control over a typical dynamic application to assume the effects of the figure-of-merit (*J_load : Jm*) to be of minimal consequence. Unlike a typical mechanically advantaged system, the inertia ratio of the direct-drive servo is often limited to the compliance of the steel between the motor and load, the machine's frame stiffness, feedback resolution, and available system BW[3].

Direct-drive technologies have led to higher control-loop gains (which lead to higher BWs) greatly enhancing the servo system's capability to catch and control possible axis instabilities before they become unstable (or cause other machine instabilities [i.e. resonances]). These relatively new digital drive capabilities are allowing direct-drive servo motors with high-resolution feedback capabilities to take advantage of the available energy savings, in good mechatronic axis designs.

Dynamic Applications Create an Energy Savings Opportunity

Whether a direct-drive servo axis or a mechanically advantaged servo axis, the actual process times are often fixed and cannot be decreased under the existing process technology. Therefore the product or workpiece transfer times are the only decrease-able times within the subject-matter production-cycle. This is the base topology utilized for determining potential energy savings for dynamic servo applications as a function of an axis' inertia ratio. Thus, the process time is assumed fixed and held constant, forcing a reduced transfer time to make a specific move. The faster rate results in an increase of the specific axis' peak horsepower (HP) requirements during the acceleration and deceleration times, from its baseline production rate by the product of the increased ratio of both speed and torque.

This specific method allows for each calculated motion-profile, as a function of a fixed peak Torque, (X•Trms) to have a constant traverse RPM velocity (N) and a constant RMS equivalent velocity (N_rms), regardless of the inertia ratio; where the relative (*J_load / Jm = ∞* versus *J_load / Jm = 1*) available percent (%) energy savings, regardless of the value of X chosen [within system limits], approached a theoretical maximum of approximately 60%. Thus, enabling the industry to pinpoint an inertia ratio range for an axis' most efficient energy utilization for high-speed indexing type applications (with stability concerns set aside) while maintaining good risk management. Any manufacturing process, run at a faster rate for improved throughput, requires a machine with the capability to move and/or act on the product faster, and to respond to all commands and disturbances within the limit of the product and/or the process itself to maintain quality.

Individual servo axis systems that can best achieve the available energy savings are those that are continuously on the move, whether their motion profile commands are constantly changing due to indexing requirements or constantly changing due to dynamic load disturbances.

From this analysis the lowest power consumption for dynamic machine servo axes will come from the best mechatronic designs and not necessarily the machine with the most efficient motor. The knowledge and technologies are available to maximize energy delivery to a given servo motor's load for a Green machine.

[3] Stephens, Lee. (2010, August 12). The Significance of Load to Motor Inertia Mismatch. *www.kollmorgen.com.* Retrieved from www.kollmorgen.com/uploadedFiles/kollmorgencom/Service_and_Support/Knowledge_Center/White_Papers/KOL_MotorInertiaMismatch_Brief_08_12_10.pdf

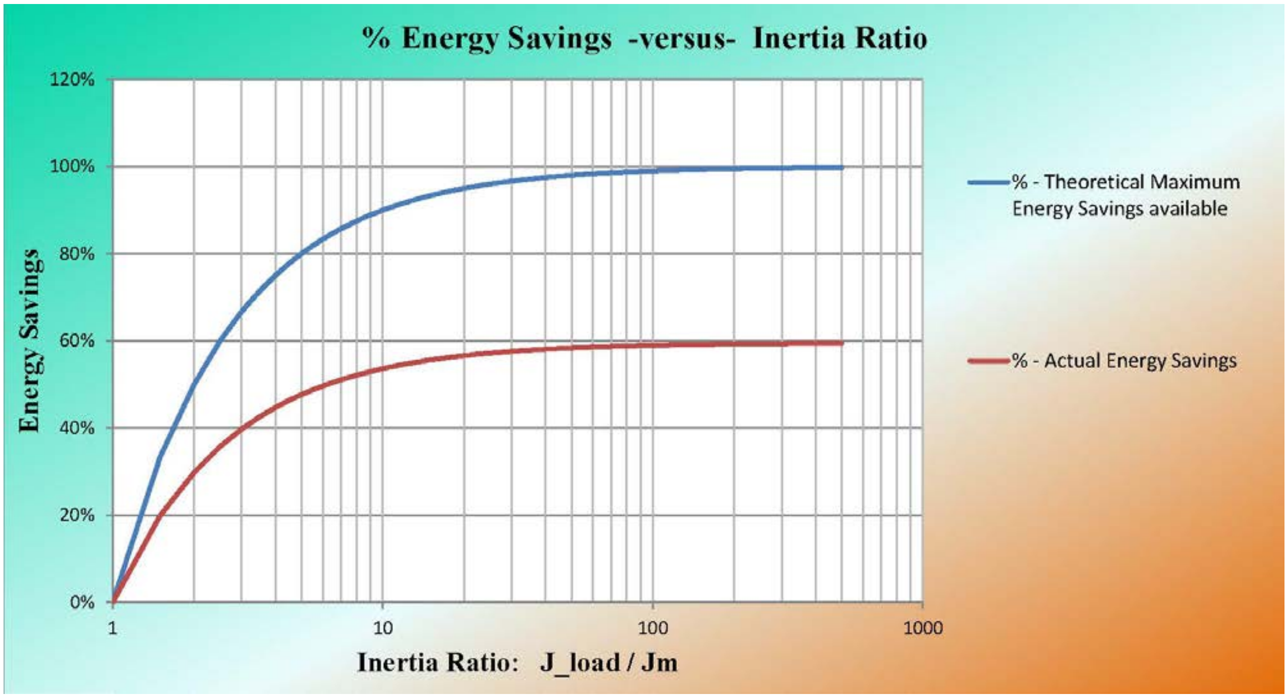

Figure A: *Energy saving potential as a function of inertia ratio: J load / Jm = ∞ verses J load/Jm = 1*

Mechanically Advantaged Axes: For an exceptional machine design, the mechatronic engineer must contend with backlash and/or compliance within the driven components, which still limits the inertia ratio range as a function of stability (the typical inertia ratio, where axis stability may still be achieved). The inertia ratios (*J_load* : *Jm*)**:** 8-20 : 1, yield ~87.5-95% of the available 60% energy savings as compared against the maximum power transfer ratio: 1 : 1. These energy savings ratios are achievable with high-resolution feedback and high BW drives when the mechanics of the system are designed with minimal compliance and backlash within the drive train and machine frame (and even ratios up to 30 : 1 are possible with some mechanically advantaged applications).

These inertia ratios of non-direct-drive systems require a good to top-notch mechatronic design to minimize compliance depending on the process/work to be performed. It is this overall increased system stiffness that allows for the higher inertia ratios with the lower risk of instability which makes the potential energy savings possible with high-resolution feedback and increased drive capability. Consequently, if an induction motor were replaced, on a typically designed axis for an induction motor, the controlled axis cannot be expected to perform as if originally designed for servo-motor utilization, whether there is a higher inertia mismatch or not.

Direct Driven Axes: To the contrary, the compliance of a directly driven axis is essentially limited to the driven components and frame. For direct-drive servo motor axes the inertia ratio[4] can easily exceed a 30 : 1 ratio yielding ~97% energy saving (of the theoretical maximum) so the typical direct-drive axis with a 200 : 1 to 300 : 1 inertia ratio approaches 100% achievement of the theoretically available ~60% energy savings (Figure A). Compliance still limits the inertia ratio range as a function of stability, but this compliance is now set by the driven material between the motor and load (typically steel) and the machine frame (steel, cast iron, etc.); thus the axis' lack of compliance (stiffness) allows for much higher direct-drive inertia ratios with little risk of stability issues, with high-resolution

[4] Stephens, Lee. (2010, August 12). The Significance of Load to Motor Inertia Mismatch. *www.kollmorgen.com.* Retrieved from www.kollmorgen.com/uploadedFiles/kollmorgencom/Service_and_Support/Knowledge_Center/White_Papers/KOL_MotorInertiaMismatch_Brief_08_12_10.pdf

feedback and high BW[5] drive capability. The required stiffness often demands larger shafts and bearings, and even the compliance of the machine fixture/stand holding the motor comes into play. Indexer style applications with inertia ratios of 1600 : 1 have been successful with a feedback resolution: 2^{24} [16,777,216], and greater.

In addition to achieving nearly 100% of the available energy savings gained from the inefficiencies of all mechanical transmission components that would otherwise be required to accomplish an equivalent process/work by a mechanically advantaged axis between the motor and load, even further cost reductions are realized by the lack of mechanical transmission components allowing for a cleaner mechanical assembly, lower parts count, and a more smooth and quiet operation. Additional benefits include: improvements in precision, throughput, reliability, Mean Time Between Failures (MTBF), and lower system maintenance.

Is Energy Savings Worth the Cost of Changing?

Whether using a direct-drive or mechanically advantaged, axis with the identified higher inertia ratios for best possible energy savings, it is up to the OEM/End User to decide if there are enough energy savings to consider the options for change. For example, the replacing of a fractional hp (Horsepower) servo motor will not have the energy savings impact (less possibly mobile or battery-operated) of a 30 hp servo, but a quantity of 50-100 axes will likely make a significant difference in energy utilization, even if each motor is less than 1hp (746 watts). Thus the actual savings will be more noticeable for larger servo motors, especially when there are multiple axes and/or multiple machines.

Direct Drive motors are now available in many form factors; for example, Kollmorgen offers Direct Drive Motors in either housed rotary (DDR), cartridge rotary (CDDR) or frameless (KBM high-voltage rotary, TBM low-voltage rotary or DDL linear motors).

Kollmorgen Housed Direct Drive Rotary (DDR) motors combine large diameter, short length and a high number of magnetic poles to provide outstanding torque density, while eliminating the need for gearboxes, timing belts and other transmission components.

The KBM™ series unique design allows the motor to be directly embedded in your machine, using the machine's own bearings to support the rotor. As a result, the total number of parts count is reduced while eliminating maintenance of gearboxes, belts or pulley.

Our exclusive Kollmorgen Cartridge DDR® servo motors combine the performance advantages of a frameless motor with the ease of installation of a full-frame motor.

Kollmorgen Ironcore and Ironless Linear Direct Drive technology designs enable linear motion to be directly embedded into a machine's design, reducing component count.

Conclusion
featured on Next Page

[5] Stephens, Lee. (2007, June 21). Get on the bandwagon with servo bandwidth. *Machine Design*. Retrieved from http://machinedesign.com/motorsdrives/get-bandwagon-servo-bandwidth

Conclusion

Dynamic applications, whether indexing and/or providing constant high-speed correction, can achieve substantial energy savings with their lower power consumption in a wide variety of direct-drive machine applications and solutions. Proper motor-drive-feedback selection of a servo-controlled axis is possibly the single most significant savings element a machine designer can make for reducing the user's operational cost. It is now clear that substantial energy savings can be achieved when machine designers utilize the latest knowledge and technologies available for their mechatronic solutions to maximize energy delivery to the load of each servo axis.

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ABOUT KOLLMORGEN

Kollmorgen is a leading provider of motion systems and components for machine builders around the globe, in business since 1916, with over 70 years of motion control design and application expertise.

Through world-class knowledge in motion, industry-leading quality and deep expertise in linking and integrating standard and custom products, Kollmorgen delivers breakthrough motion solutions unmatched in performance, reliability and ease-of-use, giving machine builders an irrefutable marketplace advantage.

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