Servo Controls Deliver Performance Benefits for Medical Imaging Systems

Lee Stephens, Senior Motion Control Engineer
Kollmorgen
540-633-3545
contactus@kollmorgen.com
www.kollmorgen.com

Medical imaging technology has rapidly advanced in recent years, increasing the speed and resolution of the images it produces. These advances have shifted the limiting factor on the time required to complete a scan and the quality of the resulting image from the imaging technology to the motion control system. As a result, medical imaging original equipment manufacturers (OEMs) have begun looking for alternatives to the AC induction motors traditionally used to position imaging gantries.

Advances in servo technology provide much faster and more accurate positioning than induction-based motion systems. The result for medical imaging original equipment manufacturers (OEMs) are faster scans and higher image quality.

Servomotors offer much faster and more accurate positioning than induction motors, but the high inertial loads provided by medical gantries have historically made it difficult for servos to work in such applications. More recently, however, a new generation of drives with digital biquadratic filters is enabling servo motors to be successfully applied to imaging gantry applications with inertial load mismatches of up to 1000 to 1 and their associated resonance challenges. The results are more accurate motion profiles and faster acceleration and deceleration, resulting in higher throughput and clearer images.

Induction motors vs. servomotors

Servosystems with biquadratic filters deliver more accurate motion profiles with faster acceleration and deceleration, resulting in higher throughput and clearer images compared with induction-based motion.

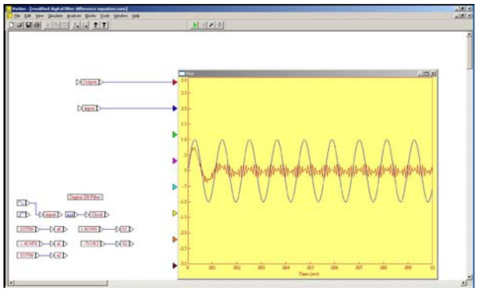
Open-loop and closed-loop AC induction motors have come to dominate the market for positioning gantries in imaging equipment such as computed tomography (CT), positron emission tomography-computed tomography (PET-CT) scanning and x-ray machines. The high inertia of AC induction motors reduces the mismatch between the motor and the load. However, as medical device manufacturers attempt to improve the throughput and image quality provided by their machines, they are often faced with the inherent performance limitations of these motors.

In many applications that require fast and accurate positioning, induction motors have been replaced by permanent magnet servo motors that provide very high peak and continuous torques resulting in high acceleration and deceleration rates for substantial performance improvements in precision positioning systems. A key advantage of these motors is that torque is directly proportional to input current while speed is linked to input voltage.

Low inertia construction is an inherent design of many permanent magnet servomotors. As a result, large mismatches between the high inertial loads of imaging gantries and the low loads of the motor need to be accounted for. Servomotor control systems can be tuned to handle inertia mismatches, but once tuned, they may respond poorly as the inertia of the load is either increased or decreased. For most medical applications the load rarely changes; however, the belt drives normally used in these devices cause compliance or lost motion between the motor and the load which in turns changes the reflective inertia.

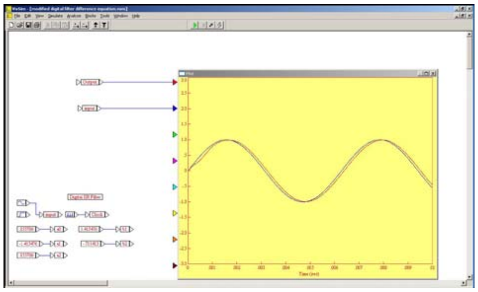
Optimizing the control system

For servo systems to operate effectively, servo amplifiers need to be tuned to optimize the response of the system. Increasing the response of the system often involves increasing gains. But adding too much gain will lead to instability and sometimes uncontrollable oscillations. The goal is to tune the system for maximum responsiveness with minimal instability. Instability can result in overshoot with respect to the speed for which the motor has been given a command.



With specific coefficients that create a notch function at 900 Hz, the frequencies around 900 Hz can be cut significantly. This plot illustrates input of 900 Hz entering the filter, with filter output that is significantly lower in amplitude due to the notch filter functionality.

For example, increasing the inertia relative to the value for which the control system was tuned may result in the motor overshooting the command. The frequency of instability is low and requires longer and longer settling times as the inertia increases. On the other hand, as inertia is increased relative to a given tuning, the motor tends to become unstable at a relatively high frequency. To overcome these oscillations, the system must be de-tuned. When tuning is reduced the oscillations will stop but this will reduce the performance of the system.

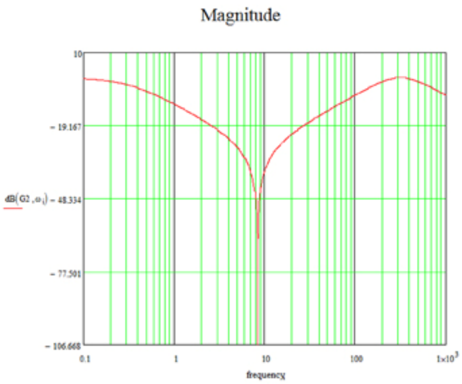


Now with a lower frequency entering filter there is very little disturbance outside of the 900 Hz point; and this lowering of gains is adjustable for width, depth of cut and general shape. Additionally, the variance doesn't require any cascading of more filters - just different coefficients. The biquadratic filter can also automatically accommodate for any high frequency resonance that could otherwise potentially disturb the system.

A control system is out of control when the gain is -3dB or less or the output phase is -45 degrees or less from the control signal, or -135 degrees relative to a reference from the motor. The open-loop transfer function is well known to predict stability problems using two measures: phase margin (PM) and gain margin (GM). PM is the difference of –180 degrees and the phase of the open loop at the frequency where the gain is 0 dB. GM is the negative of the gain of the open loop at the frequency where the phase crosses through –180 degrees. The greater the unpredictability of the load, the higher that GM and PM need to be to ensure the stability of the control system.

For example, when the resonant frequency is well below the first phase crossover (270 Hz) the effect of the compliant load is to reduce the GM. If the inertia mismatch is 5 the reduction of GM will be 6, or about 16 dB. Assuming no other remedy were available, the gain of the compliantly coupled system would have to be reduced by 16 dB, compared to the rigid system, assuming both would maintain the same GM. Such a large reduction in gain would translate to a system with much poorer command and disturbance response.

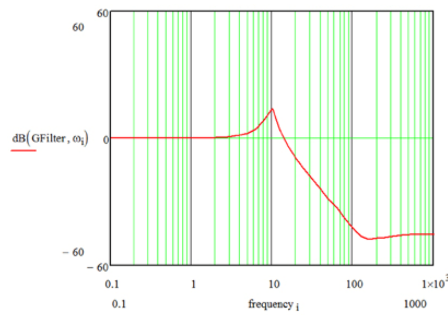
Filters enable servo controls to manage compliance



This graphic illustrates the transfer function of a system handling a large load. The system is peaking at approximately 135 Hz, and at this frequency attempting to increase gain would result in instability and oscillation. However, using a simple biquadratic filter provides superior gain margin by simultaneously boosting the lower frequencies while cutting the higher frequencies. So boosting the 10 Hz range and reducing the 135 Hz range is accomplished via the coefficients of the digital filter.

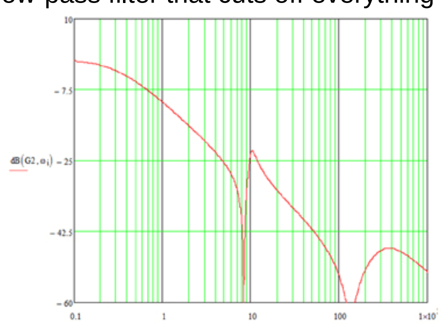
Recently, servo control system manufacturers have substantially improved the ability to compensate for inertial mismatches and compliant loads. These efforts are based on the fact that compliant mechanical systems typically have a few resonant points that are prone to oscillations, while performance is much better at other frequencies. The traditional approach is to use low-pass, band-pass and high-pass filters to eliminate the unwanted frequencies. The problem with this approach is that the multiple filters that are required to eliminate all the resonances introduce calculation delays and phase shifts that have a tendency to throw the system out of control.

Recently, substantial improvements in performance have been achieved with the use of biquadratic filters. The biquadratic filter consists of two quadratic equations with five coefficients so it can emulate nearly any combination of simpler filters without introducing significant delays. By tuning out problematic frequencies, the biquadratic filter makes it possible to increase the PM and GM to optimize servo system performance. For example, if the mechanical system has a 200 Hz resonance, the biquadratic filter can be configured to remove 200 Hz while keeping the gain at the much lower control frequencies high.



With a biquadratic filter employed, this graphic illustrates what the transfer function might look like.

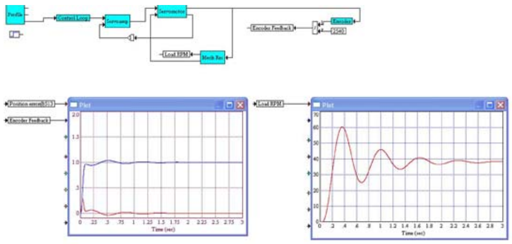
It's important to note that large belt-driven gantries have a strong physical roll-off that makes them act as a low-pass filter that cuts off everything above approximately 10 Hz. By cutting the gain at 10 Hz while passing the velocity loop between 30 Hz and 40 Hz, the biquadratic filter makes it possible to substantially increase the gain at the critical control frequencies around 2 to 4 Hz.



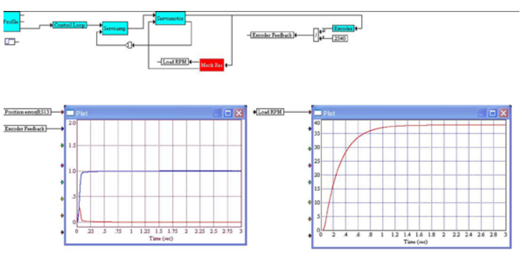
When a biquadratic filter is incorporated into the transfer function of a resonant system, high frequencies are cut and obtaining a flat response is possible with much higher gain. In this example, the resonant peak is reduced by more than 40 dB, or equivalent gain of 100. Thus the proportional gain could be increased, which equates to higher frequency response and stiffer systems.

Velocity feedback in combination with the biquadratic filter provides dramatic improvement for systems suffering from low-frequency resonance. Compared to the traditional solution of a single-pole low-pass filter, the combination of the biquadratic filter and gains allows the settling time to be cut by a factor of three and the bandwidth to be raised by that same factor. At the same time, feedback maintains the stability margin with acceleration and jerk forces substantially reduced.

As a result, the latest generation of servo controls can be configured to provide the GM and PM needed to compensate for the high inertial loads and compliance involved in imaging applications. This makes it possible and desirable for manufacturers of medical imaging systems to take advantage of the higher acceleration and velocity provided by servomotors to deliver systems that substantially improve their customers' throughput. As an additional benefit, leading manufacturers of servo systems have implemented manufacturing efficiency improvements that have reduced the cost of servo technology to the same level as AC induction motors.



This VisSim (Visual Solutions) model of a mechanically compliant system was used to analyze what happens in controls. The graph on the right shows that the load is oscillating while the control is correcting for the position loop; this is what happens in a gantry using a belt drive and with high inertial mismatch. The load is moving significantly more than the control system recognizes, and the reflections cause oscillation.



With the load to motor inertia ratio reduced from 50:1 to 10:1 and the stiffness increased, there is a crisp position and velocity profile showing no oscillation. Acceleration time is reduced, actual velocity tracks more closely to the command, and settling time is brought to a minimum.

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

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