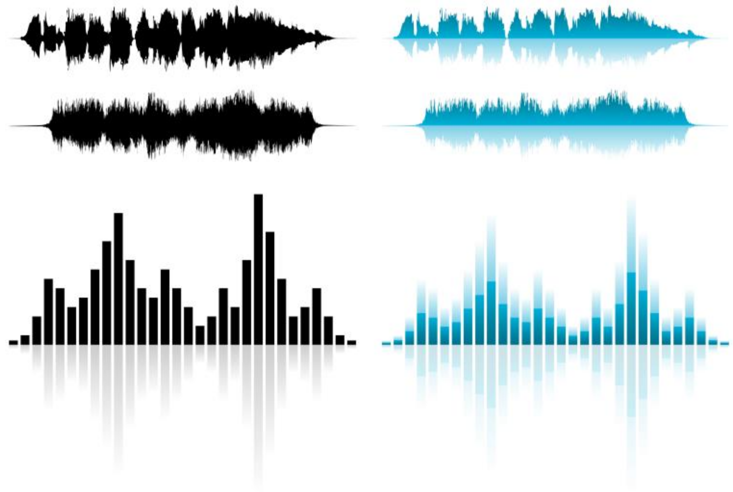

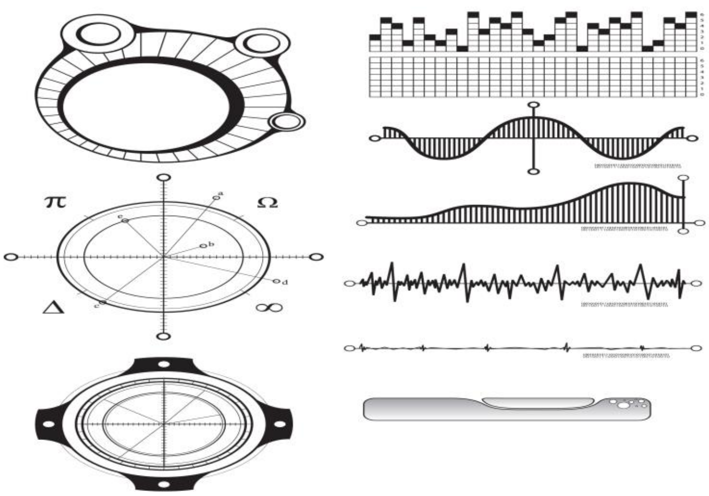

Using Bode Plots to Troubleshoot and Improve the Performance of a Servo System

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Because Motion Matters™

White Paper

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Motion controlled servo drives are typically used in machines where performance is critical and the response time, positional accuracy and smoothness of the servo have a major impact. Servo drive performance is most easily investigated as a function of frequency and servo drive tuning is typically evaluated in the frequency domain.

Bode plots are typically the tool of choice to describe the system frequency response because they provide a comprehensive picture of servo system performance. Some new generation of servo drives have built-in digital signal analyzers that can generate and use the data internally for tuning.

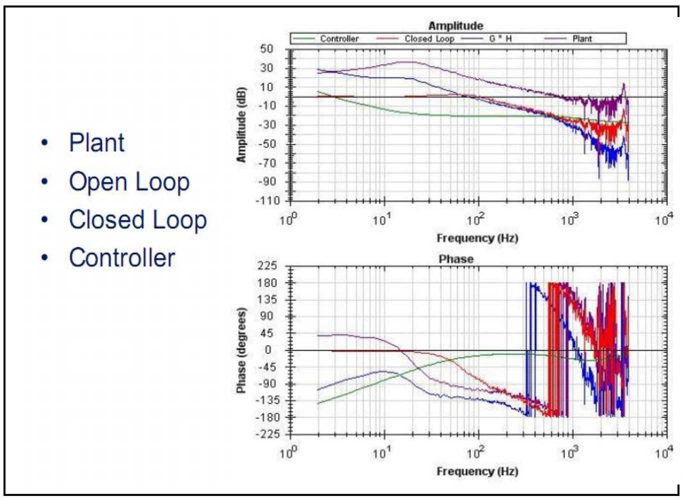

Figure 1: Bode plot examples

A Bode plot is a frequency domain analysis of a control system using a graphical technique from LaPlace transforms that can be used to determine gain and phase relationships from the input to the output as the frequency changes. A Bode plot is produced by exciting the control system with swept sine excitation at every frequency of interest. The frequency response of the system determines the amplitude and phase of the system response. There are two types of Bode plots: amplitude versus frequency and phase versus frequency. The Bode amplitude plot shows the amplitude ratio, the amplitude of the output sinusoidal curve divided by the amplitude of the input sinusoidal curve, as a function of frequency. The Bode phase plot shows the ratio between the output and input phase shift as a function of frequency. The phase shift is measured across a range of frequencies and each value is plotted as a function of frequency. The latest generation of servo drives like Kollmorgen's AKD® has dynamic signal analyzers (DSAs) built in so that engineers can easily view frequency domain signals.

Types of Bode Plots

Several different types of frequency domain measurements can be performed on a servo drive and expressed as a Bode plot. A plant measurement is an open loop type measurement used to discover the load information. Plant measurements are performed by applying a signal directly to the load and measuring its response. The open loop transfer function will yield gain and phase margin information, anti-resonance and resonance data for interpreting stability by separating the forward and feedback loops. Open loop measurements are performed by disconnecting the feedback loop and measuring the response from the command to the output of the feedback device. Closed loop measurements show the bandwidth as well as the resonance effects. Closed loop measurements are performed by connecting the feedback loop and measuring the response from the command to the output of the feedback device. Controller measurements are performed by injecting the signal into the command node and measuring the control block output.

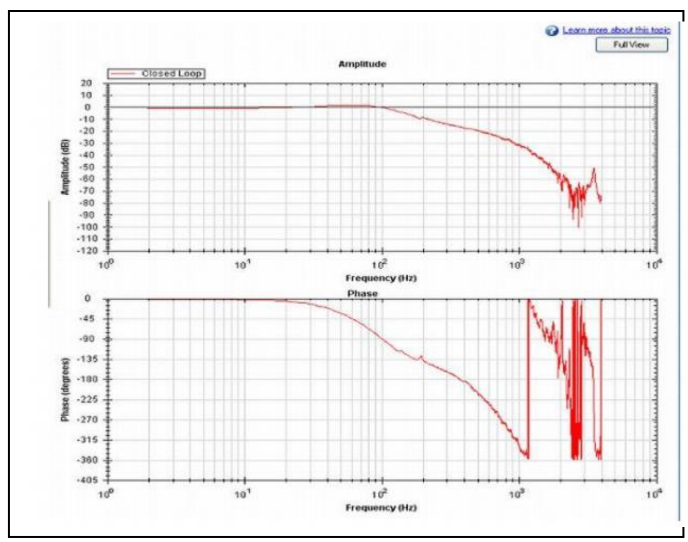

Figure 2: Bandwidth is the frequency at which the closed-loop magnitude response is equal to -3 dB and/or the phase is shifted by -45°

Bandwidth

Bode plots can be used to determine the bandwidth of a servo system. Bandwidth is defined as the frequency at which the closed-loop magnitude response is equal to -3 dB and/or the phase is shifted by -45^{o}. The significance of the bandwidth frequency is that sinusoidal inputs below the bandwidth frequency are tracked reasonably well by the servo system, however, higher frequency inputs are significantly attenuated in amplitude and are also shifted in phase by substantial degree. *These effects can be seen in Figure 2 where the bandwidth frequency is just above 100 Hz.*

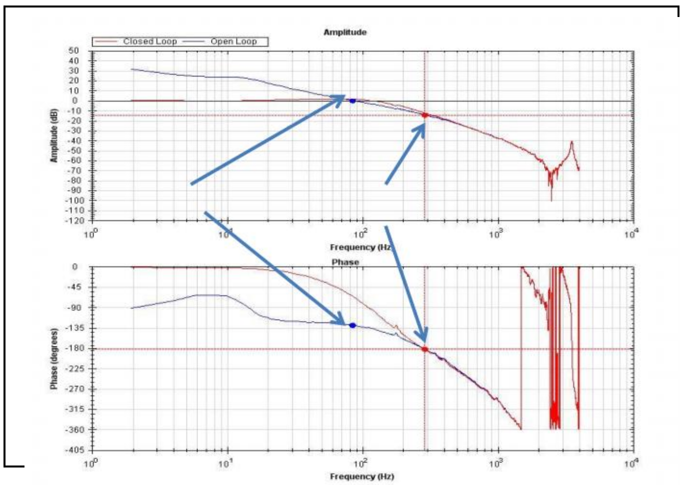

Figure 3: Determining phase margin and gain margin

Gain Margin and Phase Margin

The open loop gain and phase plots from the servo drive can be used to determine the gain margin and phase margin of the servo system. The phase margin is the difference in phase between the phase curve and -180^{o} at the point corresponding to a frequency that generates a gain of 0 dB, the gain crossover frequency. The easiest way to determine phase margin is to identify the highest frequency on the Bode plot where the gain is 0 dB. The difference between this frequency and 180^{o} is the phase margin of the system. Phase margin determines the amount of phase lag that can occur before instability occurs. At least 45^{o} of phase margin is recommended. The gain margin is the difference between the amplitude curve and 0 dB at the point corresponding to a frequency that generates a phase of -180^{o}, the phase crossover frequency. Gain margin defines the amount of gain change that can occur before instability occurs.

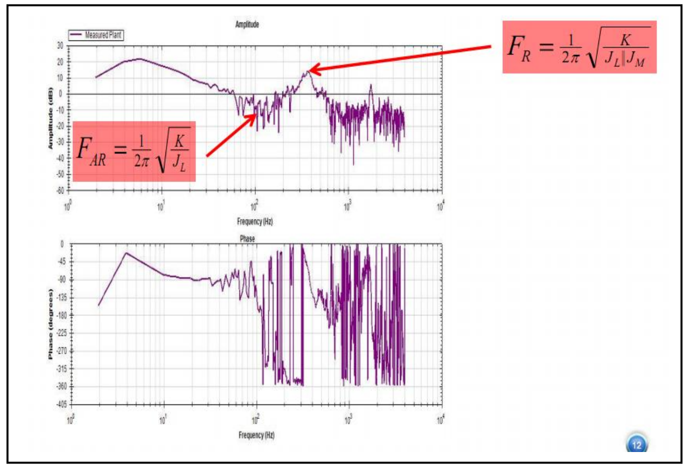

Figure 4: Determining resonance and anti-resonance

Resonance and Anti-Resonance

A two body system will have on frequency of anti-resonance F_{AR} and one frequency of resonance F_R. The anti-resonance frequency is defined as

$$F_R = \frac{1}{2\pi}\sqrt{\frac{K}{J_L}}.$$

In the frequency range below the anti-resonance frequency the plant acts as a scaled low frequency inertia. The resonance frequency is defined as

$$F_R = \frac{1}{2\pi}\sqrt{\frac{K}{\frac{J_L J_M}{J_L + J_M}}}.$$

In the frequency range above the resonant frequency the plant acts like a scaled inertia with the value of the motor inertia. The inertia ratio, spring constant and system damping define the plot in the transition area between the resonant frequencies.

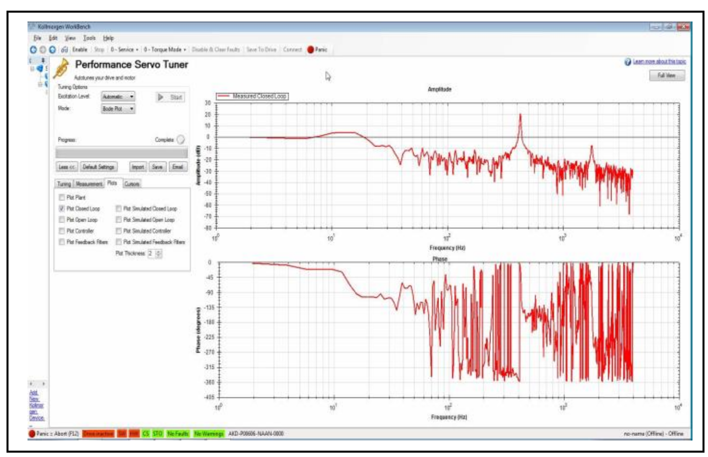

Figure 5: Bode plot of a servo drive that was not well coupled to the load because the belt was experiencing excessive friction

Tuning a Control System

Bode plots can play a valuable role in tuning a control system. Normally, 60^{o} of phase margin and 18 dB of gain margin should indicate a stable system. However, using these numbers as an absolute may result in the design of system that is too conservative. We have seen systems with 35^{o} of phase margin and 8 dB gain margin deliver excellent performance over long periods of time. The key proviso is that to operate with a relatively low gain and phase margin the machine must be very repeatable. For example, a system with a direct drive from the motor to the load tends to be quite repeatable. On the other hand, a belt drive is less repeatable because of the potential for the belt to become looser or tighter with a resulting change in friction. Machines that are not so repeatable need more phase and gain margin.

Stiffness

Stiffness plays an important role in evaluating a servo system. Stiffness of the system K can be algebraically determined based on the resonance, anti-resonance and the motor inertia. The stiffness of a servo system is analogous to the stiffness of a mechanical system – the amount of deflection produced by a force – and is typically expressed in meters per Newton. The stiffness can be thought of as the reciprocal of the spring constant which is expressed in units of Newton-meters (Nm). A servo system behaves somewhat like a spring – if you apply a force to the output it will deflect. Stiffness of the system is highly frequency dependent, which is why disturbance measurements are usually taken across a range of frequencies.

To determine stiffness, start by disconnecting the load and measuring the current required to accelerate the rotor – this is the rotor inertia. Then measure the current required to run at a constant velocity – this is the static friction. Then measure the current needed to accelerate the load and subtract the static friction and rotor inertia to determine the load inertia. The load inertia can be used in the formulas provided earlier for the resonance and anti-resonance frequencies to calculate the stiffness K. If the stiffness of a system, for example, is determined to be 1 mm per Newton then it can handle disturbances up to 1 Newton without deflecting by more than 1 mm.

RULE OF THUMB: A section of a Bode plot with increasing amplitude should be associated with increasing phase and a section with falling amplitude should be associated with a reduction in phase as shown in Figure 7.

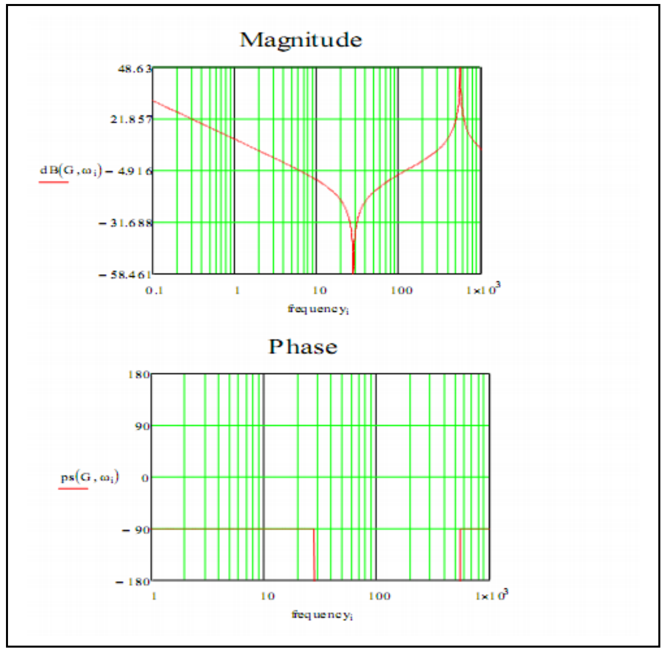

Figure 6: The open loop phase margin should start at -90^{o}

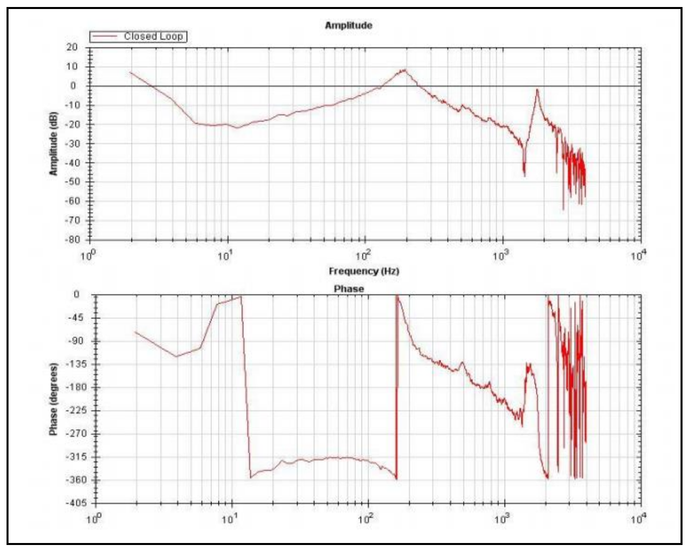

Figure 7: Closed loop Bode plot of a computerized tomography scanning system with 213 kilograms per meter of inertia

Starting Point

A motor is an integrator in that it converts torque into velocity. Integration shifts the phase by -90^{o} so open loop Bode plot should start at the phase of 90^{o}. If the source input is torque and the output is position then two integrations are needed and the open loop Bode plot should start at -180^{o}. If the starting point of the Bode plot does not make sense, the chances are that the plot may be bad due to insufficient excitation, backlash or frictional component issues.

Conclusion

The performance of the servo system is critical to the overall performance of many different types of machines. Bode plots can help understand the interaction of the servomotors, feedback sensor, servo drives and mechanical transmission to improve machine performance. This article delves into the different types of Bode plots and how they can be used to determine bandwidth, gain margin, phase margin, resonance, anti-resonance and stiffness of a servo system. In turn, the article explains how these different measurements can be used to diagnose problems and improve servo system performance. The net result will be a machine that delivers high quality, higher throughput and a higher level of reliability.

ABOUT KOLLMORGEN

Kollmorgen is a leading provider of motion systems and components for machine builders around the globe, 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 solutions unmatched in performance, reliability and ease-of-use, giving machine builders an irrefutable marketplace advantage.

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