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Changes for the Better

WHITE PAPER
by Mitsubishi Electric

Autotuning Servos Optimize Machine Performance Effortlessly

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An ideal autotuning servo drive features proactive autotuning capabilities to prevent command sequences from exciting resonances and reactive autotuning to eliminate any additional error that crops up over the lifetime of the machine.

Takeaways:

- Autotuning speeds the commissioning of servo axes.
- Continuous reactive online autotuning adjusts drive parameters over the actual motion sequence.
- Proactive online autotuning analyzes and adjusts the drive signal to avoid exciting resonances.
- The MR-J4 autotuning servo drive with One-Touch software makes it easy to continuously optimize machine performance.
- Continuous autotuning adds value to both OEM and end user.

Introduction

On paper, designing a machine that performs to specifications is straightforward. When the machine is up and running with a load, though, things don't look so straightforward any more. In the real world, vibrations crop up in the load and the machine base from load inertia mismatch, compliance in the mechanism, and mechanical issues like improperly tensioned belts and loose couplings. Throw those vibrations into your feedback loop and you get ringing, overshoot, and cycle times that stretch into tomorrow. The solution is to tune each axis to suppress the effects of vibration but that is a process that can take hours, if not days, to perform manually. Meanwhile, your customer is on the phone wondering when they can expect delivery.

Servo drives with autotuning capabilities provide a solution, but not all autotuning drives are created equal. Only real-time autotuning acting on the actual machine command sequence can truly identify and mitigate the negative effects of resonances. Drives with reactive online autotuning identify and compensate for positioning and speed errors introduced during each move. Proactive online autotuning analyzes the machine over a few cycles to determine elements of the command sequence that excite vibrations. It then filters the signal to eliminate those vibration frequencies, allowing the servo to move the load smoothly and quickly.

Resonances and Error

A truly effective autotuning drive, like the Mitsubishi Electric MR-J4, leverages both approaches to deliver the load where and when commanded over the lifetime of the machine.

At the most basic level, a motion system consists of a controller, a servo amplifier or drive, and a motor coupled to the load. The controller does the path planning, sending commands to the servo drive. The servo drive converts the command sequence to an electrical signal and uses that to command the motor, causing the shaft to turn to the target position at the commanded speed.

In a perfect system, the axis would move the load to the commanded position or speed with no overshoot or ringing. Unfortunately, that's not the way the real world works. Every machine has one or more characteristic resonances introduced by the properties of the frame, the load inertia, torsional stiffness, the weight of the various motion components, etc. Making the machine frame and tooling stiffer is not a solution — it will simply change the resonant frequency while adding mass.

In the old days of purely mechanical designs, the solution was to build the machine, run it, and damp vibration modes by reinforcing the frame or adding weights. With the introduction of servo motors, OEMs had a somewhat easier solution. Now, they could run the axes

MR-J4 autotuning drives free OEMs and end-users to focus on design aspects that truly differentiate their product.

as they were building the machine, determine the error, and compensate for it by turning the potentiometer screws (pots) on the drive using the proportional-integrator-derivative (PID) loop approach.

The basic equation for PID error is:

PID error $(t) = K_p E(t) + K_i \int E(t)dt + K_d \frac{d}{dt} E(t)$

Equation 1

where the first term represents the proportional gain (adjusting system response), the second term represents the integral gain (correcting any accumulated error over time), and the third term represents derivative gain (compensating for small variations in the positioning error as a function of time).

In manual tuning, servo axes need to be tuned one at a time, first unloaded then under load. Equation 1 essentially describes a parametric model in which adjusting one coefficient affects the others, which may have to be adjusted themselves. As a result, the process is as much an art as it is a science and optimizing a single axis can take from hours to days.

That's why Mitsubishi Electric developed high-performance autotuning drives. Our MR-J4 drives adjust themselves to optimize performance, and keep tuning over the lifetime of the product. The technology frees OEMs and end-users from grunt work, allowing them to use their time for more important things like focusing on the characteristics that truly differentiate their product

There are three general approaches to autotuning:

- Off-line autotuning: The drive moves the load through some factory-defined command sequence, then configures the PID gains and possibly filters.
- Reactive continuous autotuning: The drive continuously compares system performance to that of an ideal observer system to correct errors by filtering out resonances and using an automated version of PID loop tuning.
- Proactive online autotuning: The drive analyzes the machine performance using the actual user program to identify and remove any aspects of the drive signal that might excite resonances, eliminating vibration before it ever arises

Off-line autotuning represented a major advance when it was introduced. Off-line autotuning drives exercise the axis with a predefined motion sequence, analyzing the feedback and applying PID loop tuning automatically to drive the error toward zero. The devices can save hours, even days, but they have one major drawback — that canned command sequence may bear no resemblance to the actual operation of the machine. As a result, these drives can only tune to a first approximation. Getting to optimal performance still requires significant time and expertise, which means autotuning is typically only run at installation.

The problem is that while the primary resonant frequency of the machine base and the load inertia may remain relatively static, machine condition changes over time. Belts stretch, bearings wear, grease breaks down, operating temperatures rise or fall. These effects may be gradual enough that nobody actively monitors the effects, although they may notice that the machine jams more frequently, that the top speed is no longer as high, or that it makes more noise. Off-line autotuning can help compensate, but only to a point, and only if the user thinks to invoke it.

Reactive autotuning provides a better solution. Based on actual machine operation rather than an arbitrary set of commands, it does a much more effective job of tuning the drive for the application. Conventional online autotuning drives analyze machine performance over a short segment of the command sequence, and only when invoked by the user, however. In the case of complex tasks, a short segment may not fully exercise the capabilities of the drive and thus may not fully reveal all issues. Another problem is that the tuning function must be initiated by the user. As we've already discussed, this

The MR-J4 corrects any error before the operator realizes that there is an error to correct.

can be a problem simply because sometimes the changes are so gradual that the overall performance degradation creeps up on users.

State-of-the-art autotuning drives like the MR-J4 take the user out of the loop by performing autotuning continuously over the life of the machine without any participation by a human being. The MR-J4 applies a combination of filters to screen out any unwanted vibration and PID loop tuning to minimize errors

Even the best continuous autotuning drive has one key flaw — it is based on an inherently reactive approach. Equation 1 defines an error, which means that it can only be applied once that error exists. The obvious solution is to use a proactive approach. Instead of identifying resonances and tuning or filtering to remove them, proactive autotuning tackles the error at the source — the command sequence that excites vibration to begin with. Proactive online autotuning drives monitor machine performance over a few cycles, then filter the command sequence so that it no longer excites any resonances.

Reactive Autotuning Basics

In terms of actual implementation, the MR-J4 uses an observer — a virtual servo axis that calculates the response to the control program as delivered by an ideal system. As the actual system goes through its command sequence, the observer follows along, calculating the perfect motion profile to properly position the load and comparing it to the performance of the physical system. The difference between motion of the virtual and real servo is used to identify load inertia ratio, resonance frequencies, and oscillation. The drive then configures the loop gains to optimize the performance of the real servo motor. Additionally, if oscillation is detected, the drive can automatically adjust the filters to damp oscillation and resonance. See Figure 1.

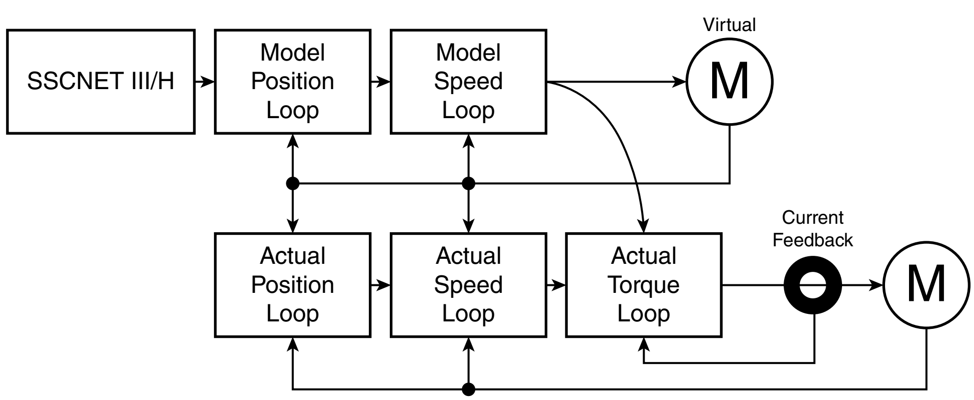


Figure 1: The MR-J4 servo drive applies the command sequence to an internal virtual servo motor (the observer) simultaneous with the real physical system, using any deviation detected in closing the speed or position loop to drive errors zero.

Although the process takes place automatically, the Vibration Tough Drive function sends a message to the HMI to notify the end-user any time it makes a change. This last feature is essential. Frequency shifts or the emergence of new frequencies can indicate a possible problem — maybe a bearing is beginning to wear or a belt has stretched. If the situation persists, it could cause problems down the line. Although continuous autotuning can allow the machine to maintain performance, alerting maintenance allows them to investigate and schedule repairs as necessary.

Reactive Filters

Most autotuning servo drives offer the ability to suppress resonant vibration modes with

> Autotuning filters address load inertia; resonances induced by mechanical components such as couplings, ballscrews, belts, and drive shafts; and problems inherent to the machine frame.

online tuning. The MR-J4 goes further with a comprehensive array of filter options that can not only address common resonant modes but deliver specialized capabilities such as Shaft Resonance Suppression, Vibration Suppression Control, and Command Notch Filtering. (see Figure 2).

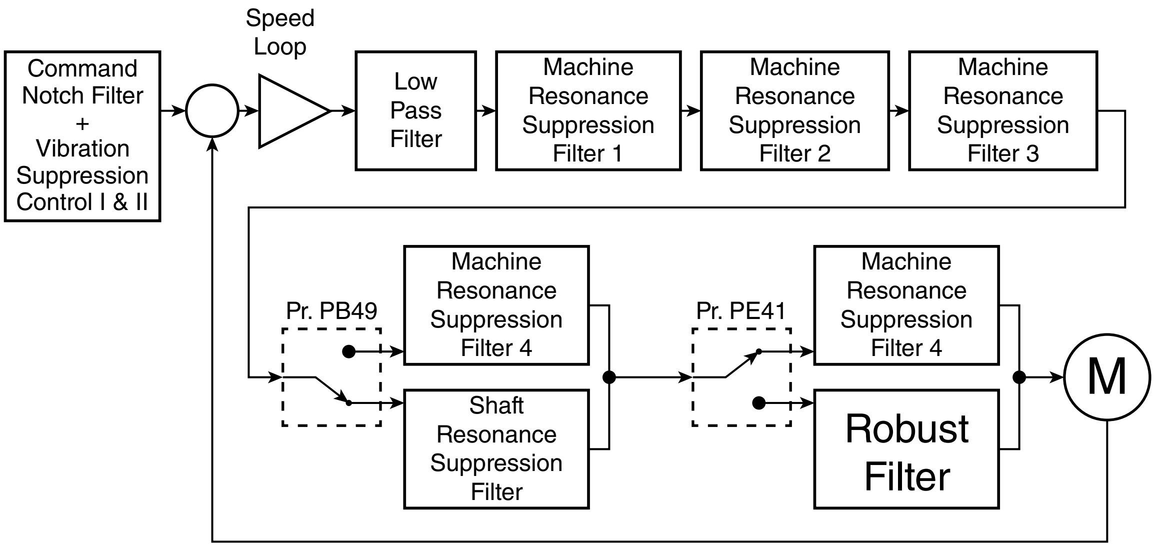


Figure 2: With a variety of filters designed to automatically suppress various types of vibration, the MR-J4 optimizes machine performance

Low-pass Filter

The drive also includes a low-pass filter with a passband of 100 to 18,000 rad/s. It is useful for filtering out high-frequency "singing" that can be caused by turning up the gain too high on the drive. Although the MR-J4 tunes automatically, it also supports some manual configuration. The system is set for a default gain, but the user can reset that through the software interface, as we'll discuss in the software section. At certain levels, the gain may deliver just the motion the application needs, but accompanied by a nasty high-pitched screech. The low-pass filter is designed to remove the screech without altering the performance of the machine at frequencies below that level.

Machine Resonance Suppression Filters

The filters we have been discussing up until now address problems that are inherent to the machine frame and any static load inertia. The next set of filters is designed to compensate for resonances induced by mechanical components such as couplings, ballscrews, belts, and drive shafts, as well as dynamic load inertia. The MR-J4 features five different Machine Resonance Suppression filters to optimize its ability to address these issues and maintain performance.

Machine Resonance Suppression filters 1, 2, and 3 operate independently to target individual problem frequency bands with the following parameters:

- Frequency: 10 to 4500 Hz
- Notch depth: -40 to -4 dB

The MR-J4 includes a feature known as the Vibration Tough Drive, which allows the machine to automatically suppress resonances caused by the types of changes we just discussed. When it detects a resonance, it configures Machine Resonance Suppression filters 1 and 2 to drive vibration toward zero.

As an example, imagine a machine for packaging ice cream sandwiches that is originally built in a nice, warm shop. It's sent to a food and beverage customer, who promptly installs it in a refrigerated room. The belts contract, the lubricants become more viscous. Now the resonances have changed from the way they manifested when

Suppressing resonances also helps ensure the long-term health of the machine by eliminating vibration that would otherwise cause premature wear.

the OEM ran the autotuning routine. The Vibration Tough Drive detects the problem and reconfigures the filters while flagging the user that changes have been made. The result is that the machine performs as advertised, the OEM prevents an accusatory phone call from a frustrated customer, and the end-user avoids an expensive service call from the OEM. Suppressing the vibration also helps ensure long-term health of the machine by eliminating vibration that would otherwise cause premature wear.

In theory, Machine Resonance Suppression filters 3 through 5 can also be configured to address resonant spikes. More commonly, filters 4 and 5 are used as preconfigured tools to address both resonances and inertia mismatch, as we will discuss below.

Shaft Resonance Suppression Filter

Using the hardware and software for Machine Resonance Suppression filter 4, the Shaft Resonance Suppression filter is preconfigured to address oscillations generated by the torsional flexing of the motor shaft. No motor shaft is perfectly stiff. Depending on factors like load inertia, speed, frequency of reversals, shaft material, etc., the shaft will display a certain amount of flex that will introduce very high-frequency resonances. The Shaft Resonance Suppression Filter corrects this issue automatically across the frequency band from 290 Hz to 4500 Hz.

Robust Filter

Using the hardware and software for Machine Resonance Suppression filter 5, the Robust Filter improves performance in low stiffness, high-inertia systems. At high gains, these types of motion systems introduce resonances that get added into the feedback loop and can send the axis into oscillation. The robust filter addresses this problem by introducing a very small phase offset in the command signal. That delay helps prevent the resonances from affecting the feedback loop. Eliminating that instability allows you to turn up the gain without creating a problem.

The robust filter can improve performance but it doesn't address the fundamental problem. Typically, a high inertia mismatch is caused by using the motor that is too small for the load. In that case, the obvious solution is to select a more appropriately sized motor using Mitsubishi's Msize tool. If motor sizing is not the source of the problem, it may be a mechanical issue. Check your couplings and belt tensioning.

Engineering is a matter of trade-offs. In certain applications, an OEM might knowingly design an axis with a high inertia mismatch because it satisfies other design criteria. In these types of cases, the robust filter acts not as a fix for a design flaw but as a tool to allow them to eke out every bit of performance from their machine.

Proactive Autotuning Basics

The Hand Clap

To understand proactive autotuning on a conceptual level, think about what the propagation of sound — for example, an impulse function like a hand clap — can tell you about your environment. Does it contain hard surfaces or soft surfaces? Is it a large space or a small space? The information you receive from that impulse function can help you understand whether you're in a closet or a gymnasium, so that you can adjust your voice accordingly.

Large spaces like the gymnasium exhibit resonance and the hard surfaces create echos. When trying to communicate with someone on the other side of the room, the words that you speak (your input signal) are probably highly distorted by the time they arrive at the listener. Now imagine that you could evaluate the acoustic effects of the space using that hand clap. By comparing the test and output waveforms, we can come up with what is essentially the transfer function of the room. If we can create a filter that corrects for the effect of that transfer function, then we should be able to come up with an acoustic input signal that will yield the desired output. It may sound garbled at the source but by the time it propagates to the target on the other side of the room, it will sound exactly as we intend.

The Vibration Suppression Control filters operate on a “set it and forget it” basis to dramatically decrease settling time.

This is essentially the operating principle of the proactive MR-J4 autotuning servo drive. It starts by exercising the axis with a segment of the command sequence (the equivalent of our handclap). It uses encoder feedback to determine the actual position or speed of the load which deviates from the commanded version as a result of resonances introduced by the machine frame, the load inertia, mechanical problems, etc. The autotuning function uses that information to determine the transfer function and then calculates a filter that will compensate for it (see figure 3). The drive applies the filter to any future command it receives for that axis. The command interacts with the mechanical system to attenuate vibration and ensure that the load arrives at the desired position at the desired time.

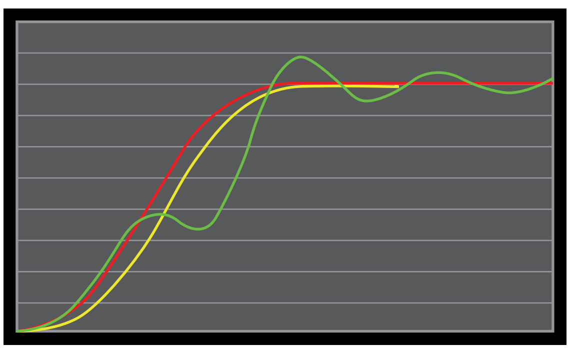


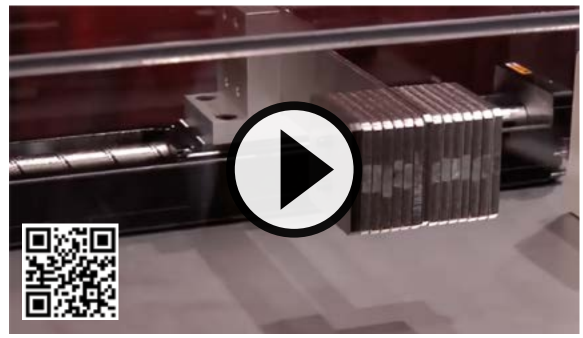
Figure 3: In the most basic form of autotuning, the system runs a command sequence, calculates the deviation (green) from the ideal profile (red), and develops a filter to eliminate the error and achieve proper motion (yellow).

Vibration Suppression Control Filters

The filter sequence starts with the Vibration Suppression Control I and II filters. These filters are designed to remove static vibration introduced by inherent resonances of the machine base and by a static load inertia. They’re basically part of the online autotuning function, so they operate on a “set it and forget it” basis. These filters offer three modes of operation:

- Standard
- 3-inertia
- Low-response operation for high payloads
- Automatically configured frequency: 1 to 100 Hz
- Manual configuration: 1 to 300 Hz

The Vibration Suppression Control filters can decrease settling time dramatically, as shown in the video below. These filters tend to be static, changing only periodically to address major events like commissioning and product changeovers that can cause changes to vibration modes.



Video: http://meau.biz/ZRbr

Command Notch Filter

To add flexibility, the MR-J4 offers users an additional option known as the Command Notch Filter, which for practical purposes acts almost like a third Vibration Suppression Control filter. Based on the following parameters, it can be configured in the software, as we’ll discuss in the section below.

- Frequency: 4.5 Hz to 225 Hz
- Notch depth: -40 dB to -0.6 dB

Still, it’s designed only to suppress static resonances introduced by machine construction. It makes a major improvement but it can’t respond to changes in machine performance over time.

Neither the proactive or reactive approach is perfect on its own. Although the proactive approach can be quite effective, it primarily works for slowly varying effects like resonances from the machine base. It can help minimize those errors but it can’t suppress them entirely. That’s why the MR-J4 applies both types of autotuning. Based on an ASIC designed and fabricated in house, the drive starts with proactive autotuning

The MR-J4 is the single best way to add value for your customers and differentiate yourself in the marketplace.

to minimize error. It then applies reactive autotuning to correct any residual issues, continuing the exercise in real time to maintain performance quality over the lifetime of the machine.

Software Makes It Easy

At this point, you might be thinking that improved performance is great but that all of these filters sound complicated. Isn't autotuning supposed to be easy? With the MR-J4, it is. All you have to do is:

1. Launch the drive software.
2. Start your machine normally.
3. Choose a response mode to match your machine condition (high-performance, basic, or low rigidity).
4. Select the One Touch autotuning button.

One Touch autotuning is by far the easiest way to invoke the appropriate filters and tune the servo with a mix of proactive and reactive autotuning. Your machine will go through its typical cycle, including overshoot and ringing. The MR-J4 will analyze the motion, determining the characteristics and showing a graphical presentation of the resonance and anti-resonance points. Then it will configure the filters to optimize system performance. The negative effects will magically disappear, the servos will quiet, cycle times will decrease, the machine will operate at peak performance, and you will be the hero.

To get the best return out of capital equipment investment over the long haul, you need to make sure that each servo axis operates at optimal performance all the time. Proactive autotuning can simplify the process of removing static vibration caused by machine resonances, but it's not enough. The MR-J4 features both proactive and reactive autotuning capabilities to keep your machine operating at peak performance, not just at commissioning but years down the road. It's the single best way to add value for your customers and differentiate yourself in the marketplace.

For more information on the MR-J4, please visit: **http://meau.biz/ZRbs**

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