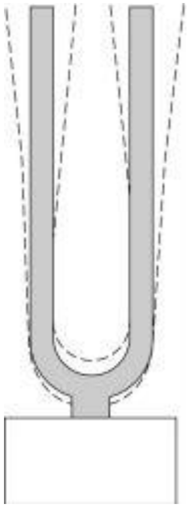
Bode Plot Interpretation and Use

Definitions

- System: In the context of this document, system refers to anything that effects performance as a control. PLC, interface between the Controller and the drive (serial, step-n-direction, analog, etc), drive, cable (yes, cable), motor, feedback, coupling, screw, nut, attachment of nut to load, load, linear bearings, even the table the assembly is sitting on.
- Bandwidth: Bandwidth is the measurement of a control system's performance. The industry standard units are "Hz". We use this to describe the capability of the system and the actual performance. Ex: You want to improve the performance of a robotic arm. You need a unit of measurement to compare the existing application to improvements or other applications. The best way is to measure the number of cycles, your system can perform, in a fixed period of time. Then you can report the performance of your system in "cycles/sec" or "Hz".

Definitions

- Resonance: This is when an object will osculate, in phase with it's excitation, without much excitation input. Ex: A tuning fork will ring, at it's resonance frequency, for an extended period of time without much energy input. All it takes is a little tap or a noise to start it off. It moves in the same direction as the excitation energy.



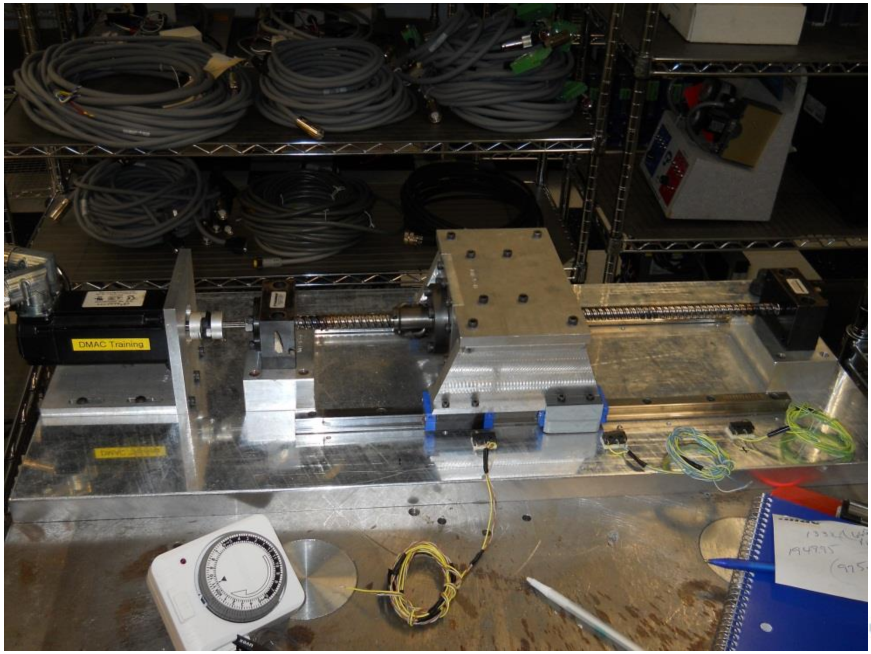
- Anti-resonance: This is when an object will osculate, 180 degree out of phase with it's excitation, without much excitation input. Ex: Paddle ball. The ball moves in the opposite direction of the paddle. There is a specific Hz or paddles/sec that it doesn't take much energy to keep the ball moving. Trying to speed up or down requires more energy input.

Types of bode plots

- **Plant:** Measurement of the mechanical system with as little influence from the drive, control, etc as possible. The drive will be in Torque or Force mode if linear. It's purpose is to show the mechanical resonance and possible mechanical bandwidth by looking at the resonances.
- **Open Loop:** Measurement of the mechanical and control filters without feedback correction for velocity. The gains; IL.KP, VL.KP, VL.KI will effect the result and the filters are enabled. It's purpose is to show what the bandwidth can be and what resonances are apparent. It is used also to measure your stability or how far away from an unstable condition you are in both phase and gain.
- **ClosedLoop:** Measurement of the total system with velocity correction. The crossover of the open loop and the bandwidth of the closed loop will be close to each other.
- **Controller:** Measurement of the drive only. I think this is the difference between the "plant" and the "closed loop".

My test bed

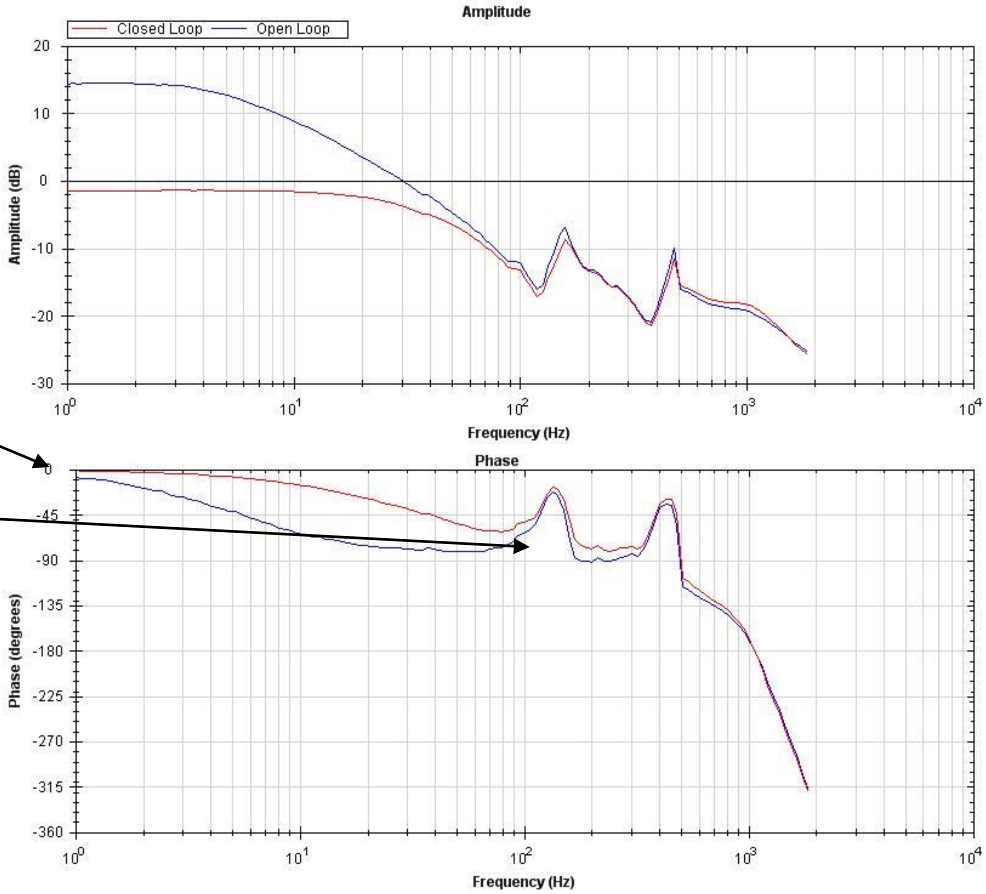
- Before I start to talk about bode plots, I need to list the test bed that I used. I have an AKM23D motor w SFD feedback. AKM MV03 with 120VAC supply. It is coupled to a Thomson “rolled” ballscrew. The ballnut is attached to a slide supported by Thomson 500 series bearings. Between the ballscrew backlash, the axial play in the ballscrew radial support bearings, and the motor coupling; the motor can move a few degrees without moving the load.



Good Bode vs bad bode

Before we talk about what we can learn from a bode plot, we need to talk about how to recognize a successful measurement. There are three things to look for

- The phase starts between 0 to 90° on the Open Loop plot.
- The anti-resonance and resonance points are clearly visible
- The load made a lot of noise. With sine excitation, you can hear audible amplitude changes as the frequency increases.

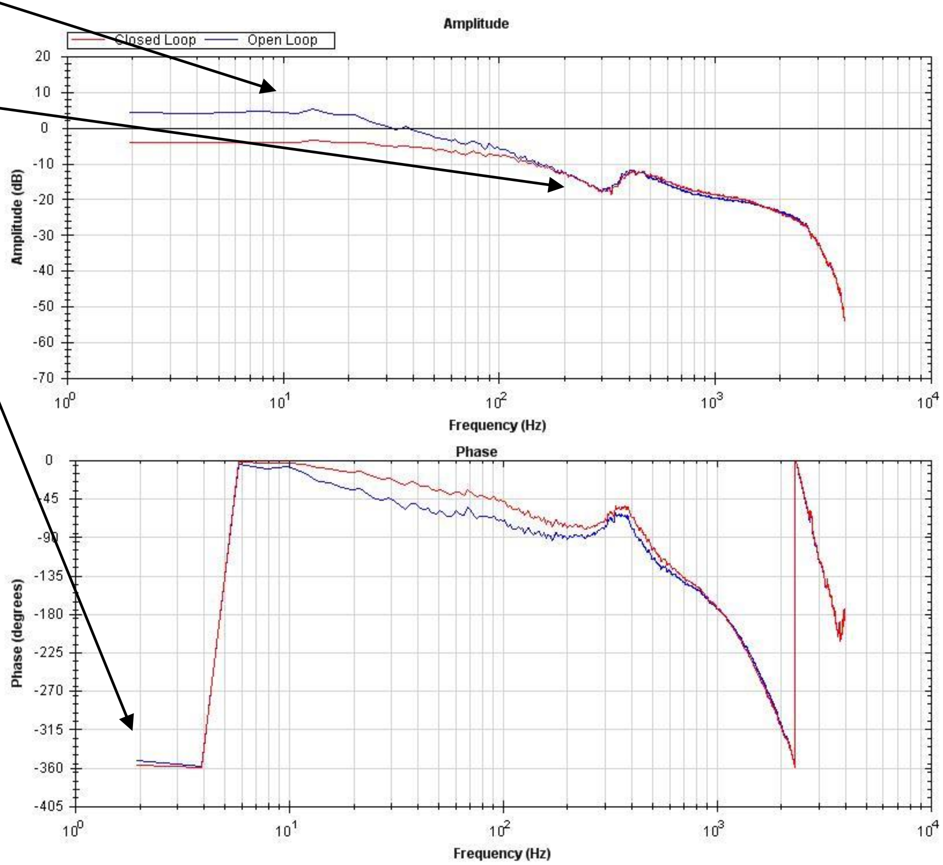


Good Bode vs bad bode

An unsuccessful bode plot can be detected by:

- The open loop is not very smooth
- You get poor resolution on the resonance and anti-resonance points.
- The phase starts at a unexpected point.

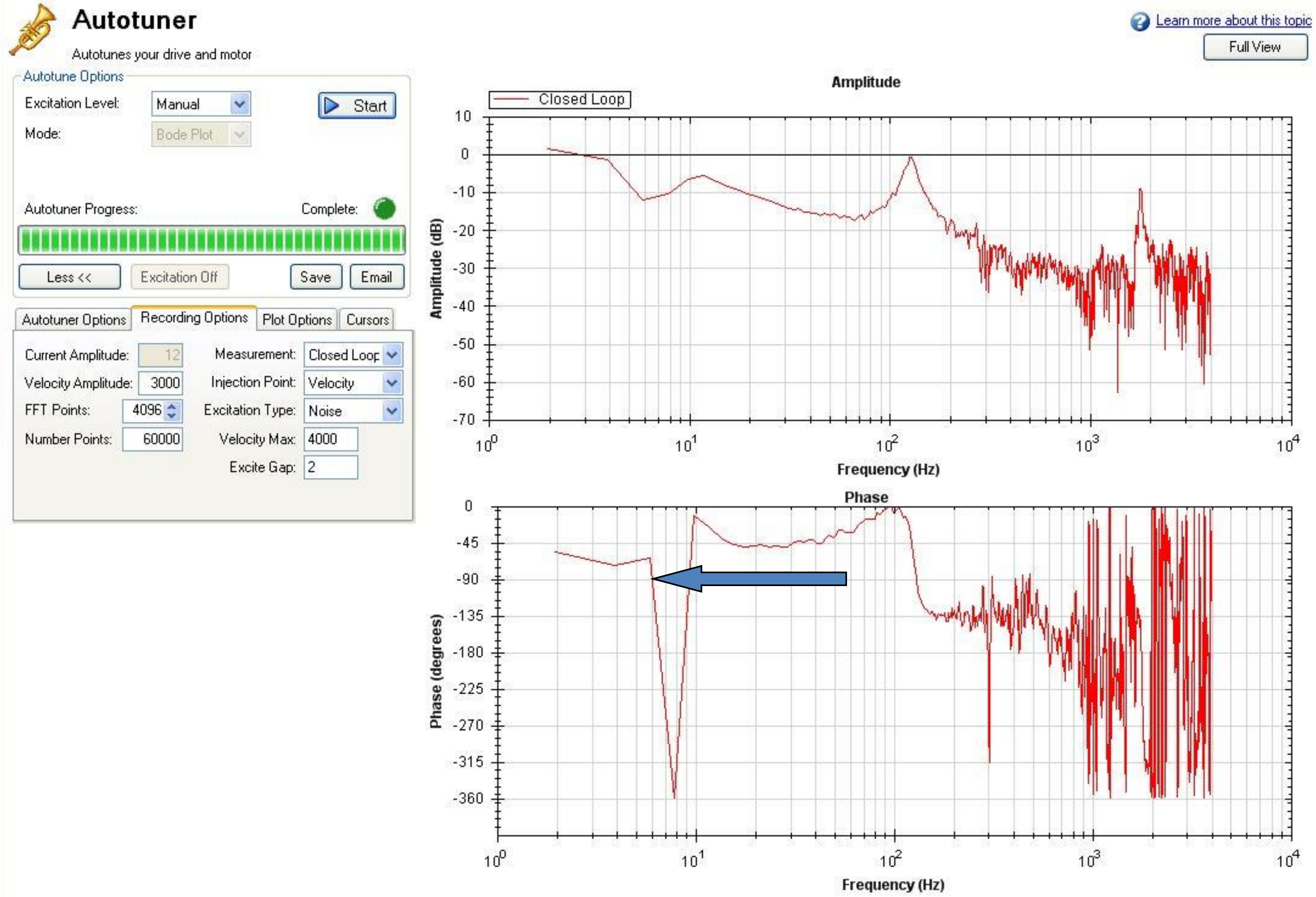
The reason this bode plot is bad is because the excitation was not high enough to overcome the backlash. The only way I was able to get a good bode plot was to use sine excitation, velocity or current injection, and excitation amplitude very high.



Friction

- One of the tell–tale signs that friction is affecting your measurement is the phase of the system in the low frequencies (<10 Hz). If the sign of the phase is questionable and the gain is low, you probably are not getting reliable data in the low range. This is evident in the following plot of a very large system.
- Since we are injecting current and reading velocity, that is one integration away from the source. Integrators start their phase at -90º

Frictional Affects



Autotuner

Autotunes your drive and motor

Autotune Options

Excitation Level: Manual

Mode: Bode Plot

Autotuner Progress:

Complete:

Current Amplitude: 12

Velocity Amplitude: 3000

FFT Points: 4096

Number Points: 60000

Measurement: Closed Loop

Injection Point: Velocity

Excitation Type: Noise

Velocity Max: 4000

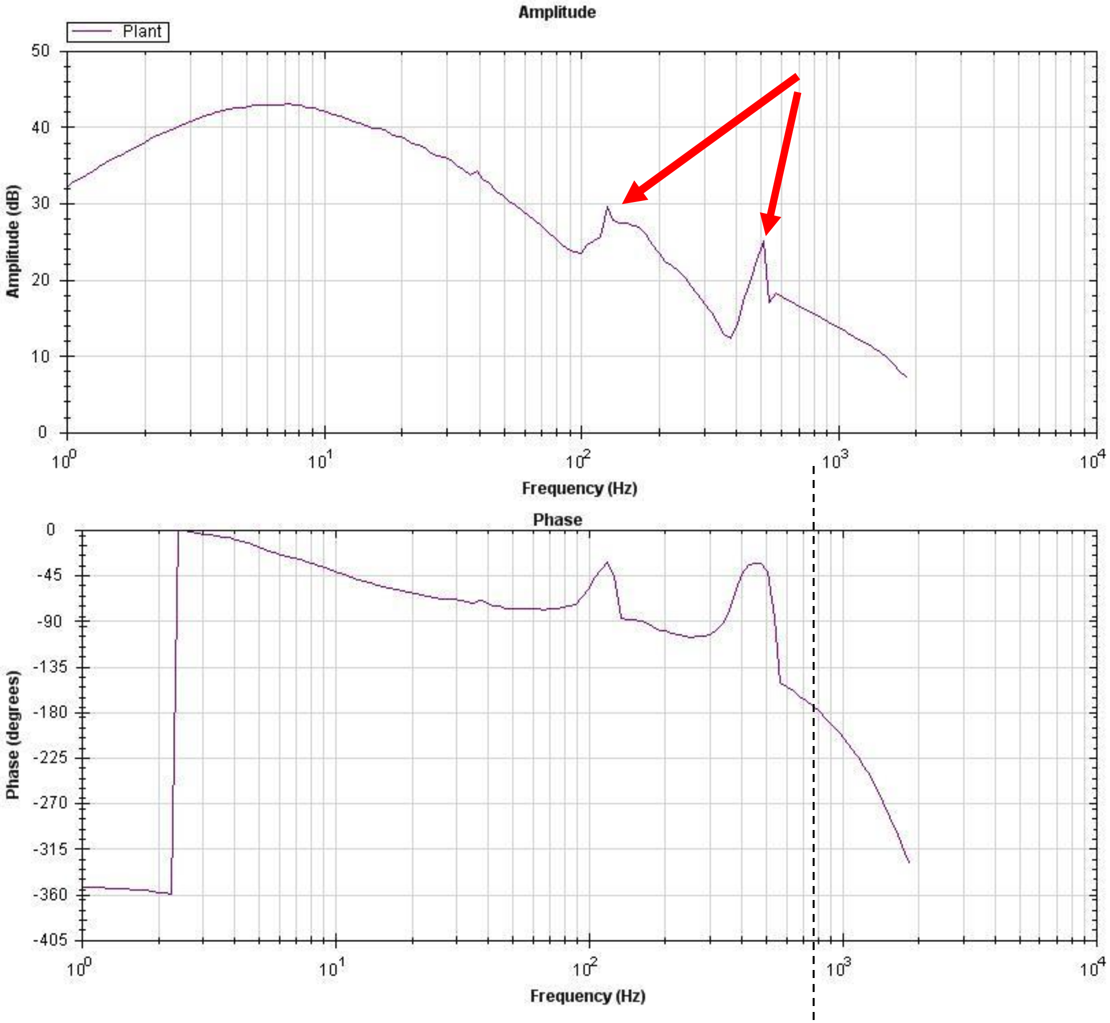
Excite Gap: 2

First, lets see what limits the mechanical system will put on our bandwidth.

This system has two distinct resonant characteristics. These will be necessary to compensate later.

The frequencies of interest will be 200 Hz and 600 Hz.

That seems a little high to me but again, this is mechanical limits and not the system limits.

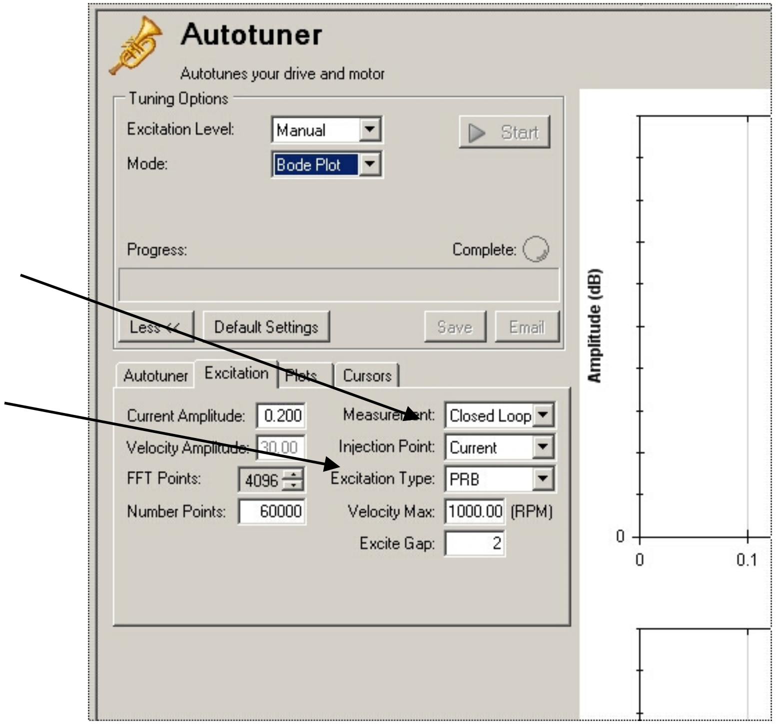


What we learn from bode plots

Now Lets setup a test for open loop and closed loop

Set measurement to “closed loop”

Again, I used sine as my Excitation type



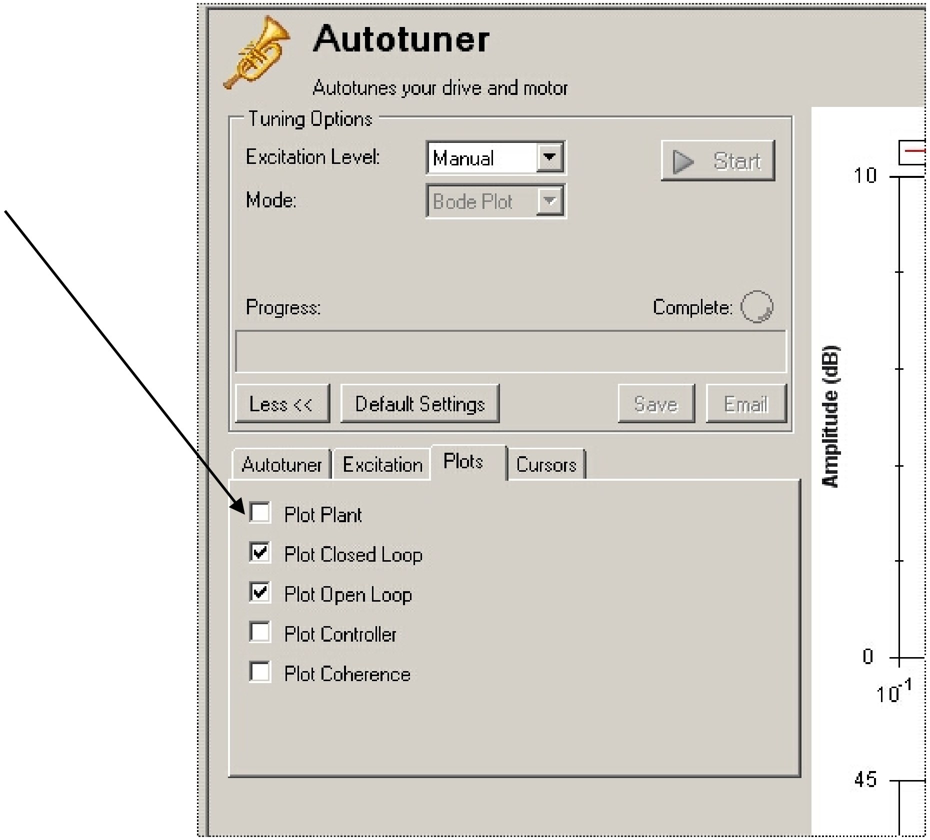
Excitation Level: Manual
Mode: Bode Plot
Progress:
Complete:
Current Amplitude: 0.200
Velocity Amplitude: 30.00
FFT Points: 4096
Number Points: 60000
Measurement: Closed Loop
Injection Point: Current
Excitation Type: PRB
Velocity Max: 1000.00 (RPM)
Excite Gap: 2

What we learn from bode plots

Last step is to pick the plots you will want to see.

For tuning, pick Open and Closed

Now, run the test



Autotuner

Autotunes your drive and motor

Tuning Options

Excitation Level: Manual

Mode: Bode Plot

Progress:

Complete:

☐ Plot Plant

☑ Plot Closed Loop

☑ Plot Open Loop

☐ Plot Controller

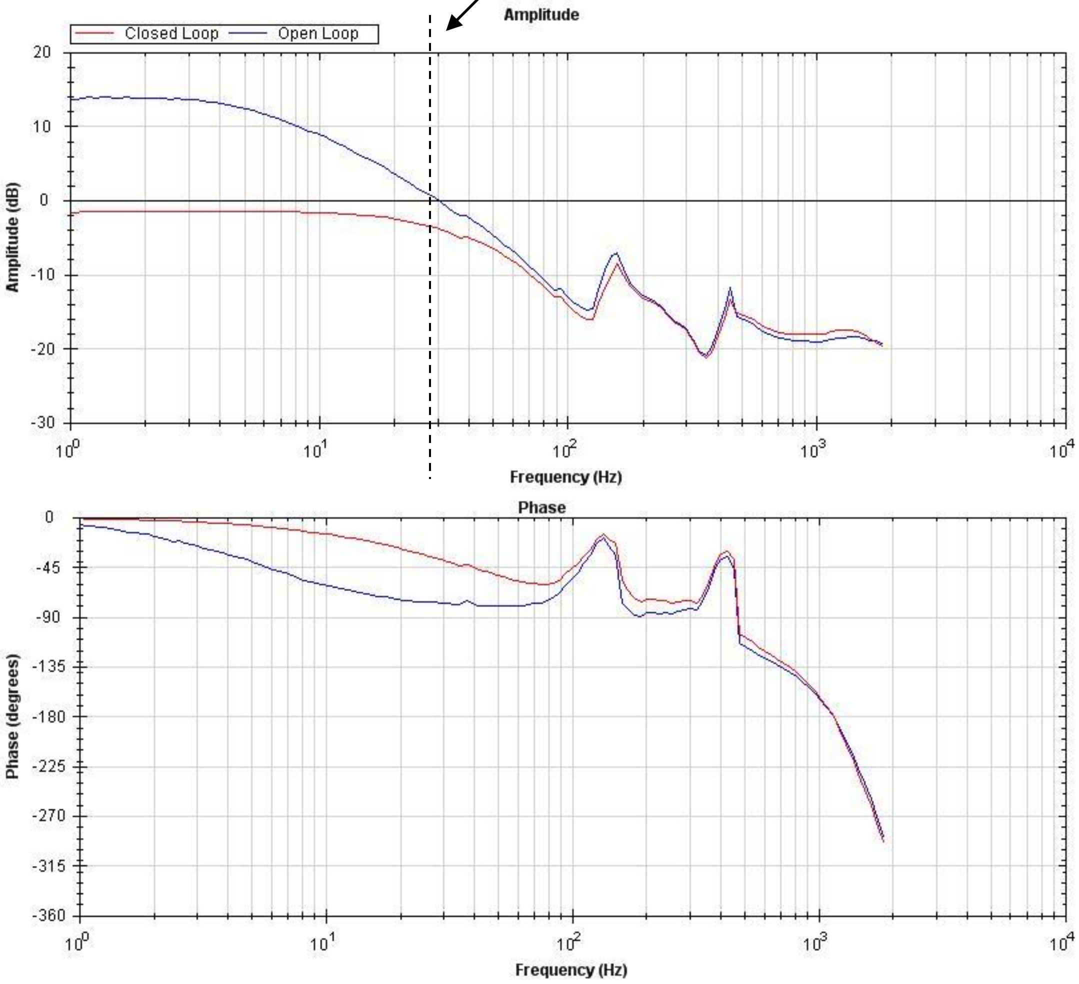
☐ Plot Coherence

What we learn from bode plots

From the Open loop plot, pick the point where the line crosses 0dB in the amplitude screen

This result is your system bandwidth in Hz.

In this case, the bandwidth will be approximately 28Hz



0dB crossing

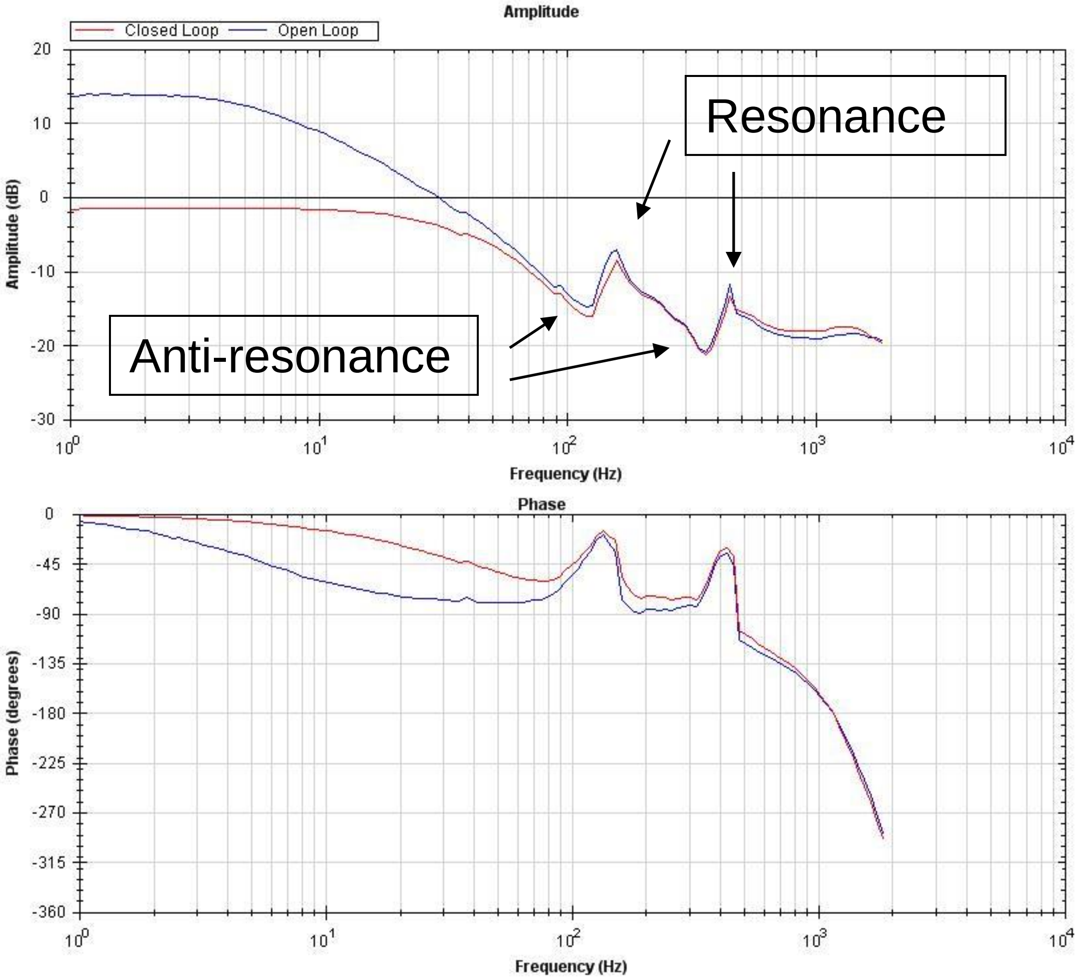
What we learn from bode plots

You can also learn the anti-resonance and resonance frequency

You will want to know this so you know where to apply the filters.

You can also calculate the system stiffness

In this test bed case, there are two points of “decoupling”. One is the motor coupling and one is the ballscrew itself. You could have more decoupling points. The one at the lower Hz has the most effect on your tuning.



Resonance

Anti-resonance

You will need to know the inertia

To calculate the system gains, you will need to know the total system inertia.

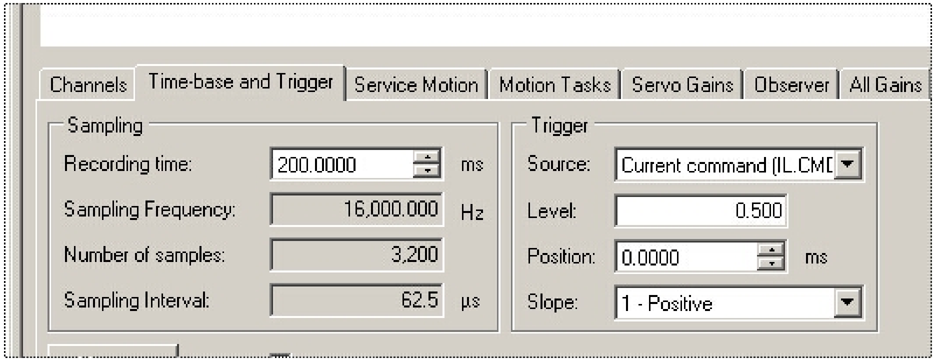
There is a simple test, you can use, to calculate the load inertia. You can put the drive in torque mode and use the service motion to do a "pulse" of current. You then plot the acceleration rate of the system with the known current pulse. The inertia can be calculated by:

$$\text{Torque(NM)} = \text{Inertia(KgM}^2\text{)} \times \text{Acceleration(Radians/s}^2\text{)}$$

Or

$$\text{Inertia(KgM}^2\text{)} = \text{Torque(NM)} / \text{Acceleration(Radians/s}^2\text{)}$$

Example of scope setup



Sampling

Recording time: 200.0000 ms

Sampling Frequency: 16,000.000 Hz

Number of samples: 3,200

Sampling Interval: 62.5 µs

Trigger

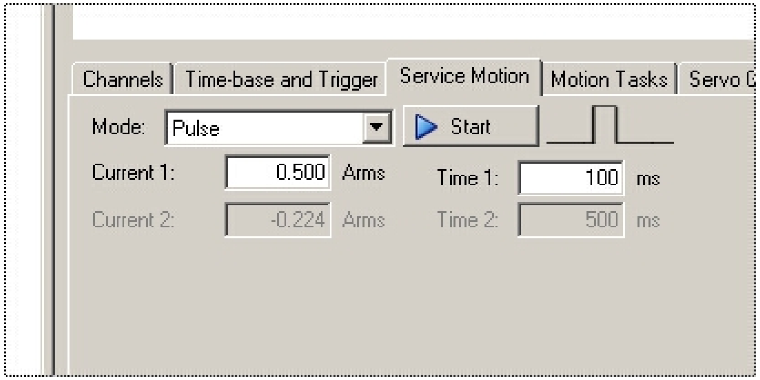
Source: Current command (IL.CMD

Level: 0.500

Position: 0.0000 ms

Slope: 1 - Positive

Example of service motion setup



Mode: Pulse

Current 1: 0.500 Arms

Time 1: 100 ms

Current 2: -0.224 Arms

Time 2: 500 ms

You will need to know the inertia

From the scope plot of my move, I get:

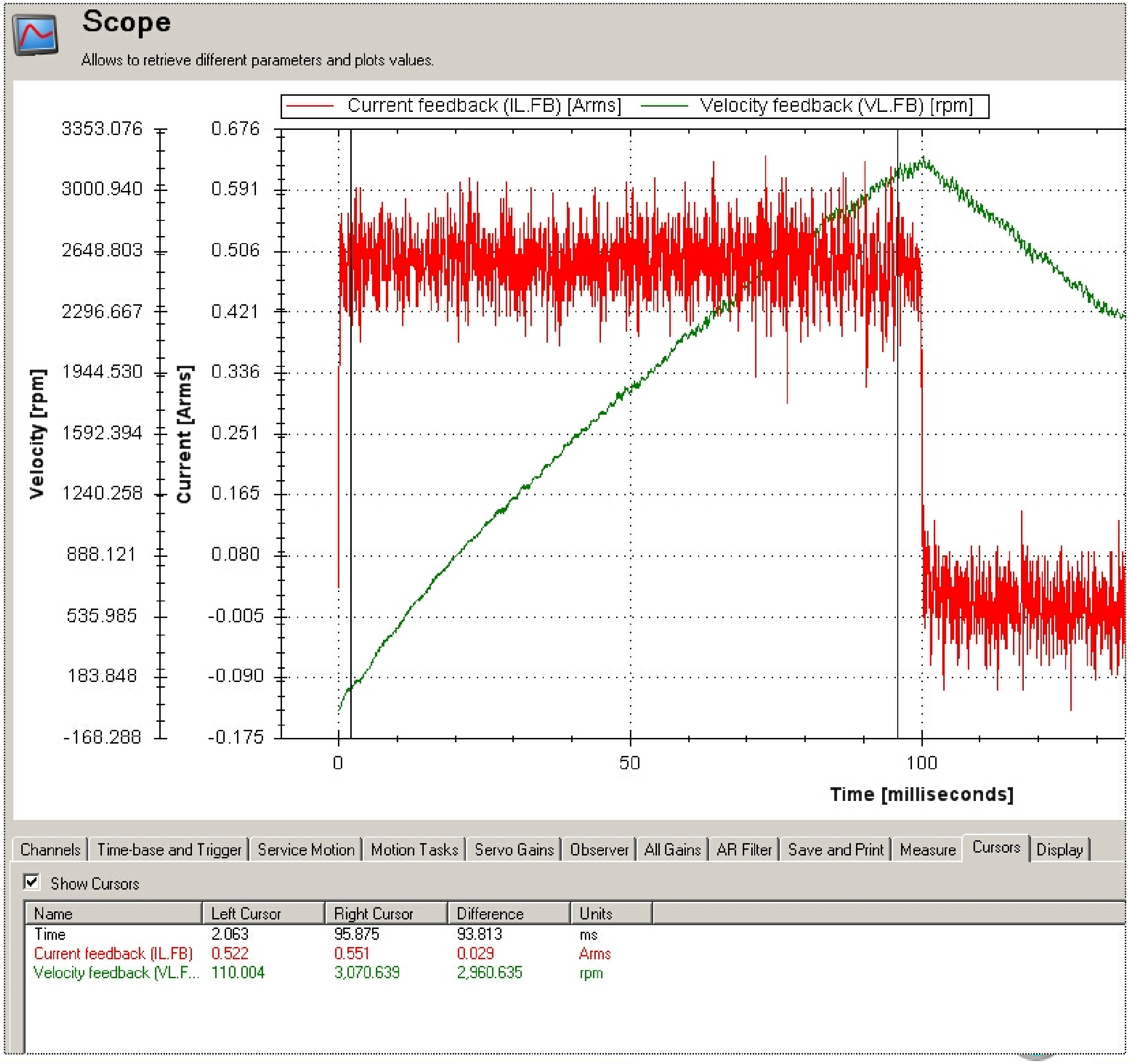
Current = 0.5A (my input)

Delta speed = 2960.635 RPM

Delta time = 93.813mS

Motor Kt = 0.52NM/A (from catalog)

Current for friction losses = 0.1 (we got this from earlier test)



Scope

Allows to retrieve different parameters and plots values.

☑ Show Cursors

Name	Left Cursor	Right Cursor	Difference	Units
Time	2.063	95.875	93.813	ms
Current feedback (IL.FB)	0.522	0.551	0.029	Arms
Velocity feedback (VL.F...	110.004	3,070.639	2,960.635	rpm

You will need to know the inertia

So the original formula is:

Inertia(KgM^2) = Torque(NM)/ Acceleration(Radians/s^2)

Calculate acceleration rate:

Acc = 2960.635 RPM/.09381s = 31559.9 RPM/s = 3304.95 Rad/s^2

Calculate motor torque:

torque = 0.52NM/A * (0.5A – 0.1A) = 0.208NM

Plug it all in and you get:

Total Inertia (at the motor shaft) = 0.208NM / 3304.95 Rad/s^2 = .000062936KgM^2

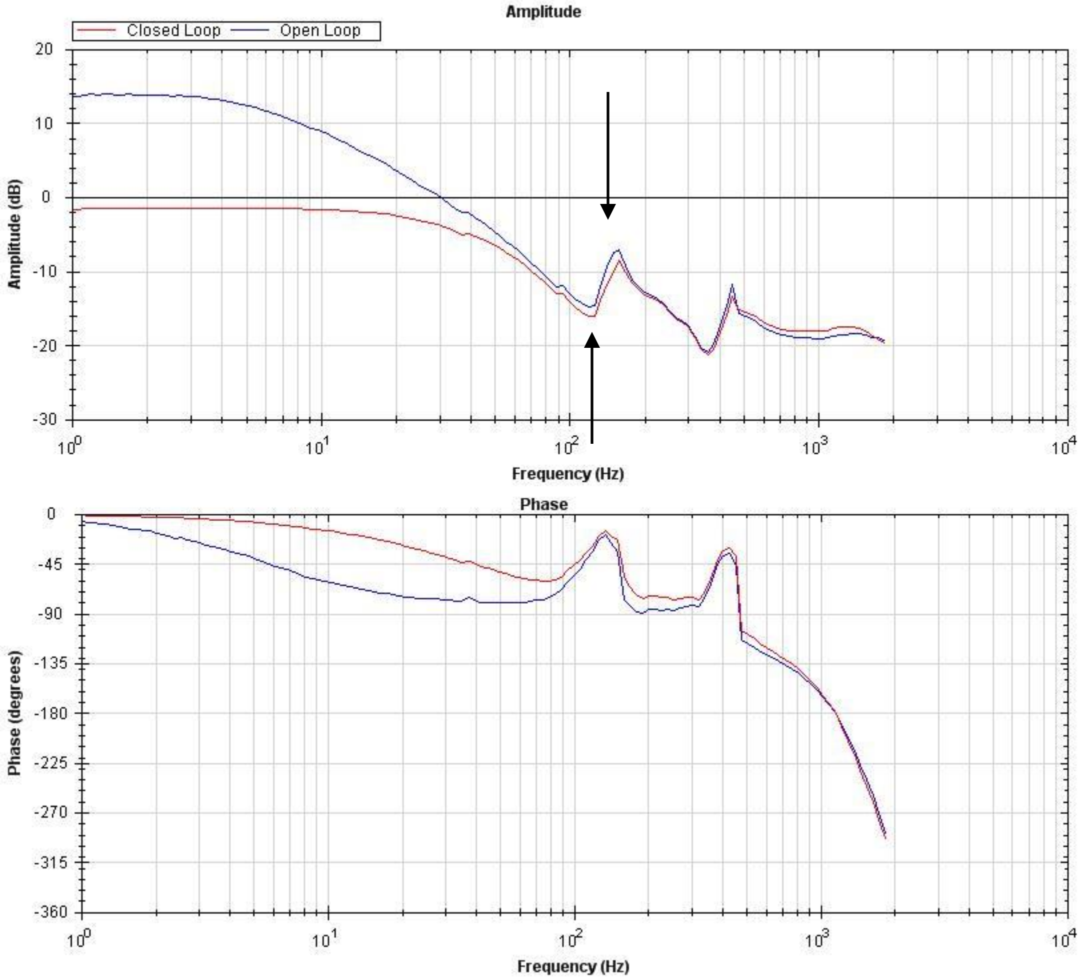
The load inertia will be this number subtracted from the rotor inertia of the motor. Now the system will be known.

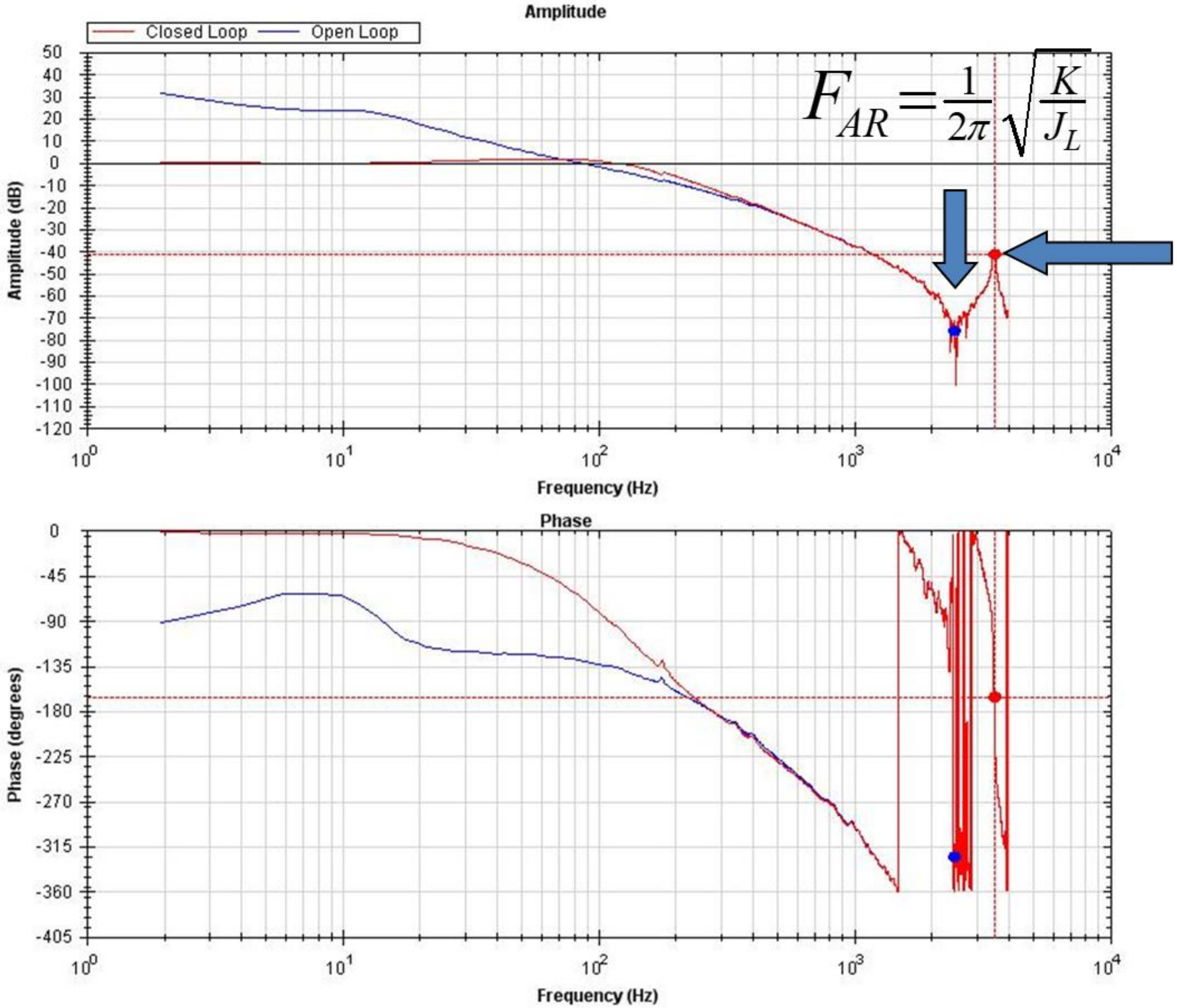
Calculate Stiffness

Stiffness and reflected inertia ratio work can be used to decide the chance of success with a system. To understand this, we need to know how to calculate the "stiffness" of the system. This can be calculated from the resonance and/or anti-resonance peak.

Anti-resonance peak = 125Hz

Resonance = 165Hz





$$F_{AR} = \frac{1}{2\pi}\sqrt{\frac{K}{J_L}}$$

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

Calculate Stiffness

The formula to calculate the stiffness from the Anti-resonance and resonance is done with simultaneous equations and solve for stiffness in Nm/rad, called K in the equation:

Knowing the Anti-resonant point the equation is:

$$F_{AR} = \frac{1}{2\pi}\sqrt{\frac{K}{J_L}}$$

The resonant frequency also has a formula using load information but includes the parallel combination of load and motor.

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

Algebraic Equations

Resonant Node

$$\omega_r := \left[\left[K_p \cdot \left(\frac{1}{J_m} + \frac{1}{J_{L2}}\right)\right]\right]^{.5}$$

$$\omega_r = 703.012$$

$$f_r := \frac{\omega_r}{2 \cdot \pi}$$

Calculated Frequency $f_r = 111.888$

Anti-Resonant Node

$$\omega_{ar} := \left(K_p \cdot \frac{1}{J_{L2}}\right)^{.5}$$

$$\omega_{ar} = 36.995$$

$$f_{ar} := \frac{\omega_{ar}}{2 \cdot \pi}$$

Calculated Frequency $f_{ar} = 5.888$

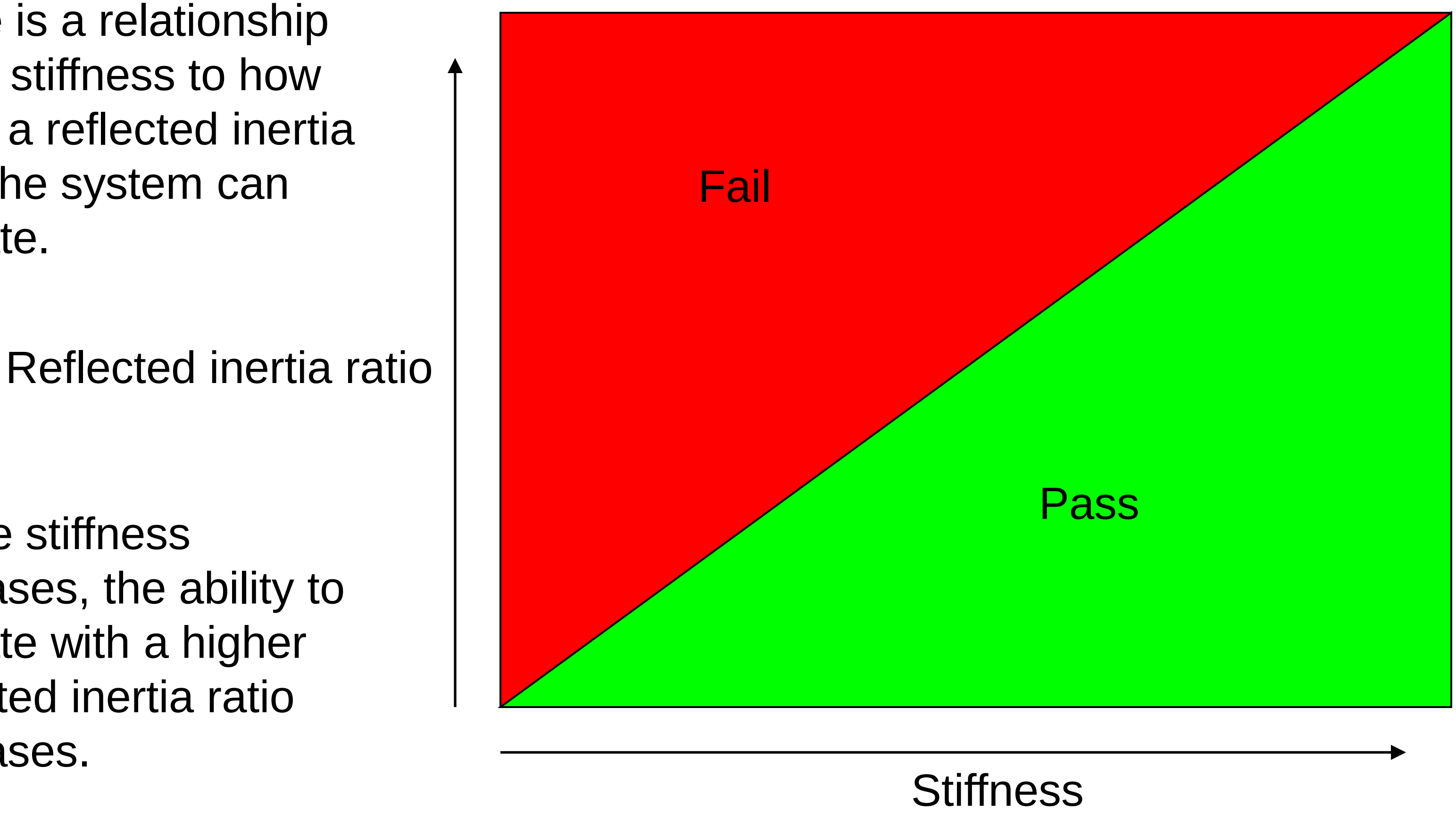
Calculating the Forward Loop Gain of the Load $G2(s) := s \cdot \theta_L(s)$

Stiffness continued

- What should become apparent is that the Anti-resonant node is affected by the load and stiffness, but the motor will not change it.
- The second takeaway is that the resonant frequency is affected by the parallel combination of the motor and load and will be affected by it.
- Solving for K will result in your Nm/rad units and increasing K will result in both the Anti-resonance and Resonant Frequencies to increase.

So…what do we learn from stiffness?

There is a relationship of the stiffness to how big of a reflected inertia ratio the system can operate.



As the stiffness increases, the ability to operate with a higher reflected inertia ratio increases.

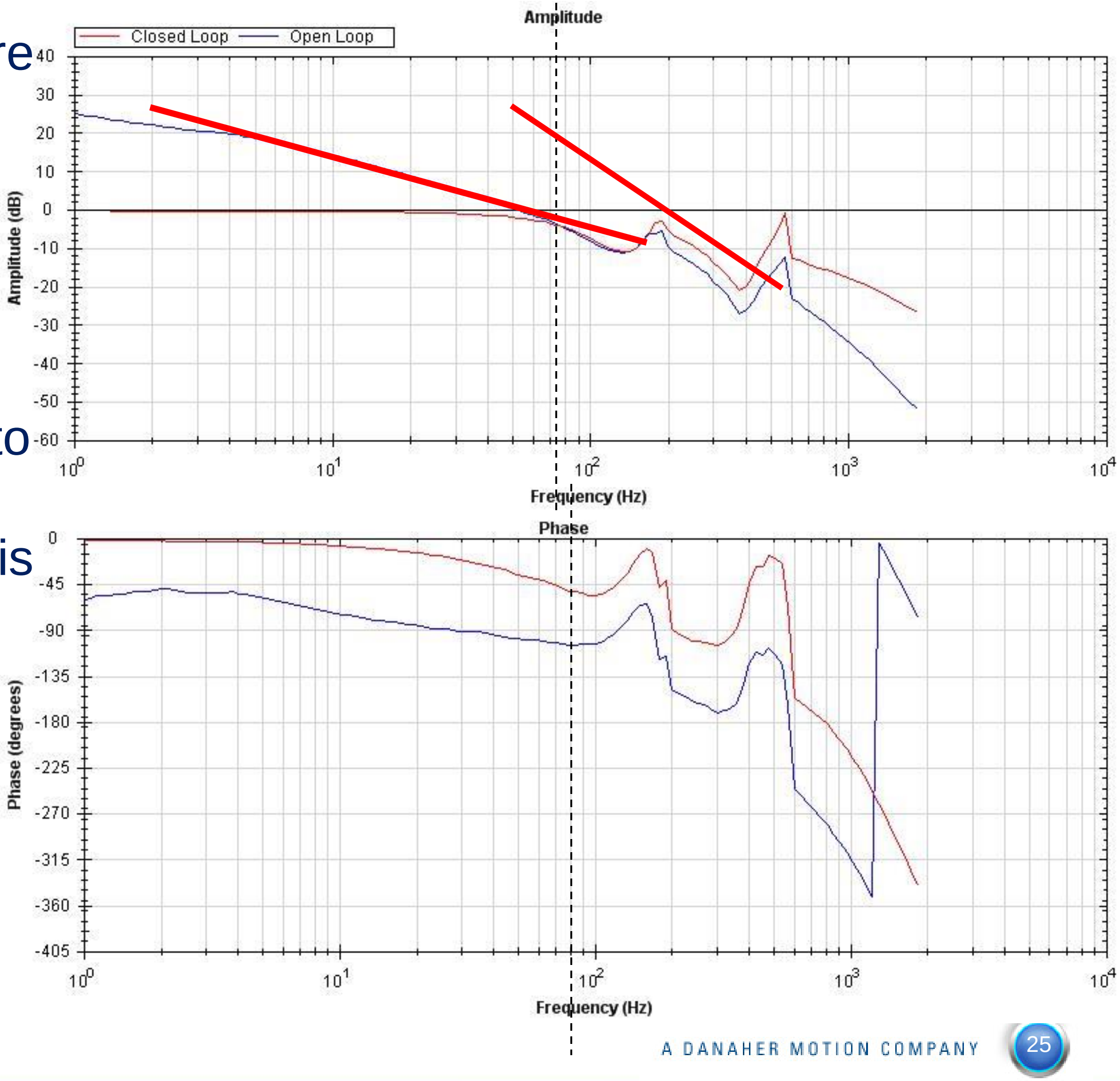
Stiffness

- Unfortunately stiffness is not one of those things where “if more is better, than too much is just right” quantities. Resonances take on an energy parameter and that is referred to as Q. As the Q of the resonance increases, the energy increases in amplitude and narrowness on the bode plot. The more narrow, the more sinusoidal and the more amplitude, the more energy. Too much energy and a sympathetic resonance to your control could result in an oscillation growing until something lets loose, usually the mechanics.

Other Notable Pieces of Information

- In the bode plot, there are some information areas.

- The two lines represent two different slopes. The first order slope to the left is 20dB per decade. The second is -40 dB per decade. What that means is that it is first order to the left and second order effect to the right. Two bodies are involved here.



Lets talk about Filters

Low Pass: This is a basic filter that is good to remove high frequency noise. The problem is it adds "lag" to the system and will reduce performance.

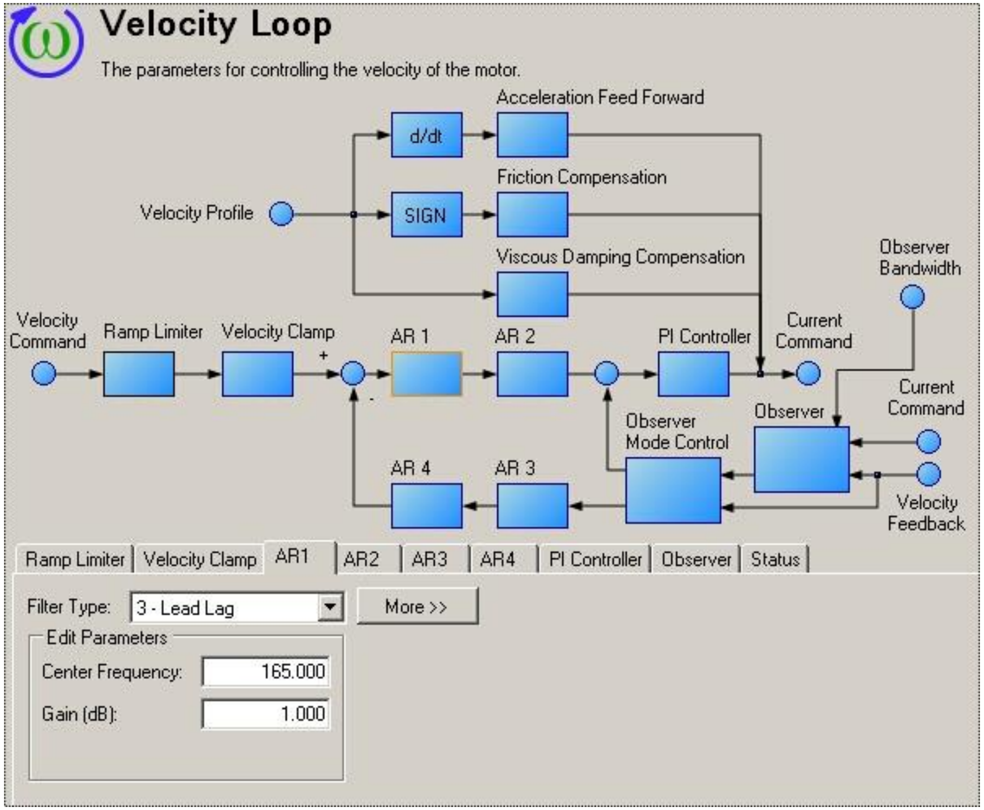
Notch: This is a very specific filter. It lowers the gain in a narrow bu specific frequency area. It is not very forgiving. It will need adjustment if anything in the system changes. Ex: belt tension, load or friction.

Lead-Lag: This is the most popular filter because it's easy to set and can allow higher bandwidth. By utilizing the phase lead, you get a little boost to allow you to get the low pass portion of the system steep without losing phase at lower frequencies.

BiQuid: This is the math that we use to create all the filters above. It's very flexible. The GUI sets it, depending on what type filter we choose from the pull down menu. Some experts need to be able to set it different from the above filter types. That is why we also have it as an option.

Adding a filter

Lets add our filter as a Lead-lag filter and see what improvements it makes. I choose filter AR1 because the open loop and closed loop amplitude, in the region of the resonance, is almost the same. Our anti-resonance & resonance was between 140Hz and 190Hz and the amplitude looks to be 5dB. We will set the center frequency to 165Hz and the gain to 1dB (a test).



Velocity Loop

The parameters for controlling the velocity of the motor.

Filter Type: 3 - Lead Lag

Edit Parameters

Center Frequency: 165.000

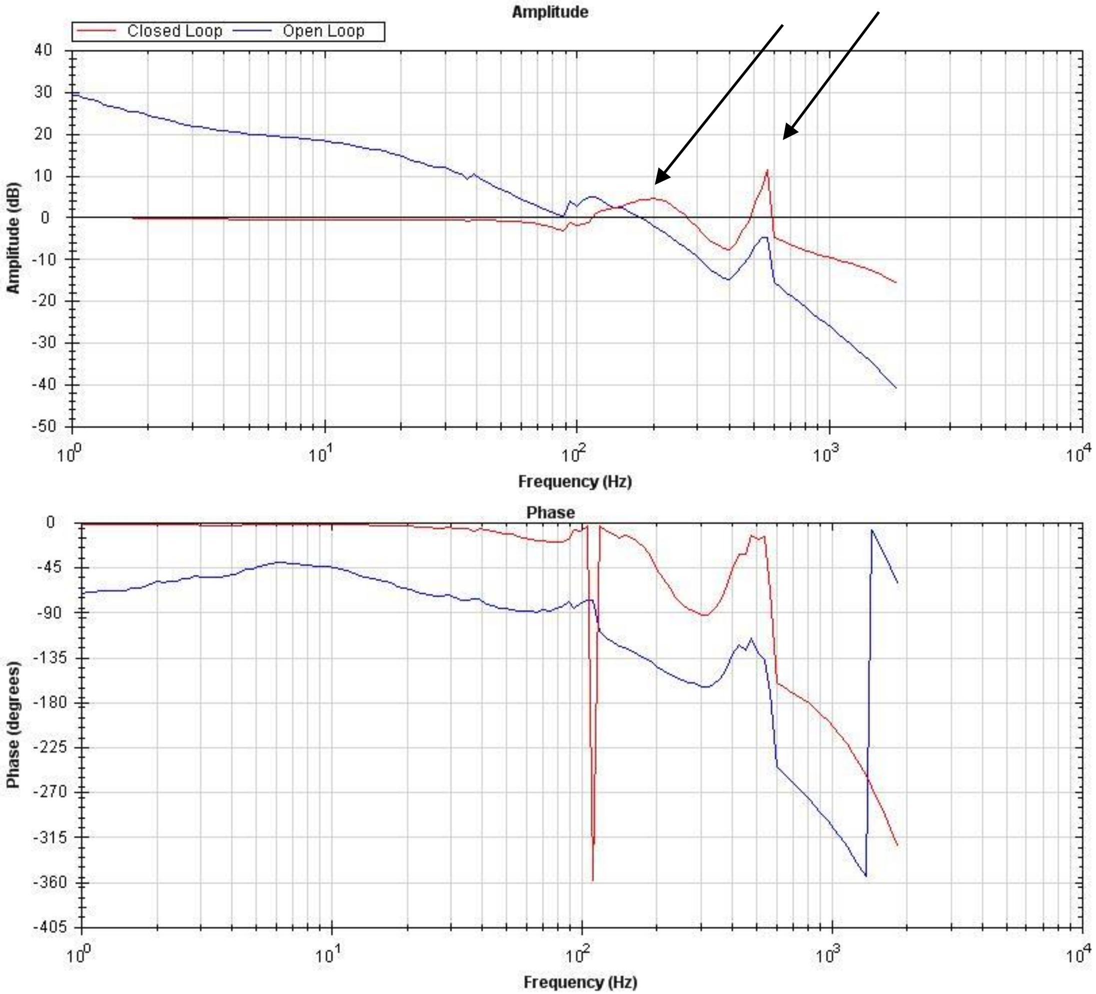
Gain (dB): 1.000

Note: Because of the design of a biquad filter, pushing the gain too high will have the opposite effect of reducing the resonance. It can even push the resonance to a different frequency.

Test again

OK, it looks better but we are starting to see the resonance pop up else where. Maybe we are done?

It does look like the new bandwidth is +90Hz. Maybe we could push the gains up a little more?



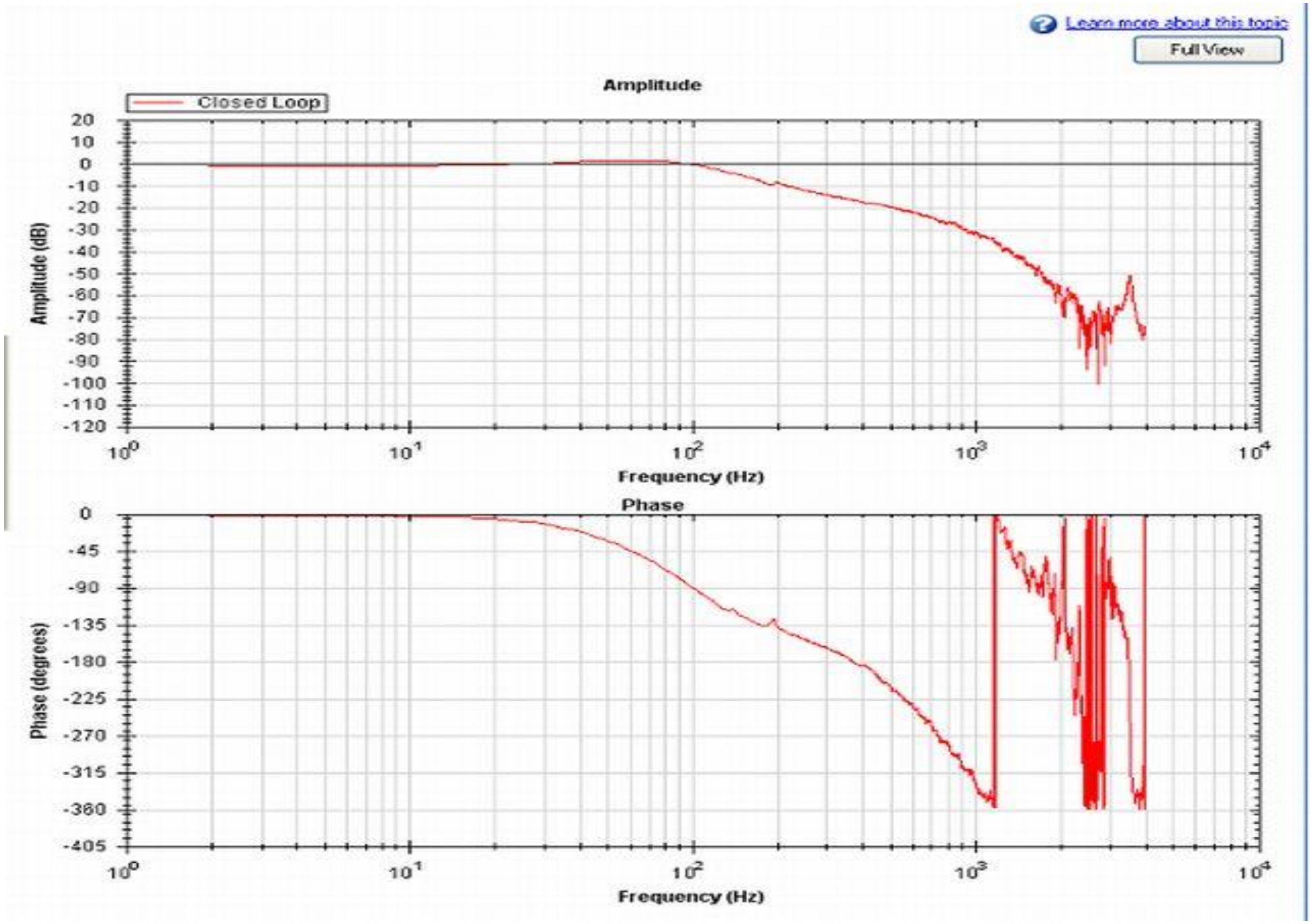
The path to Success

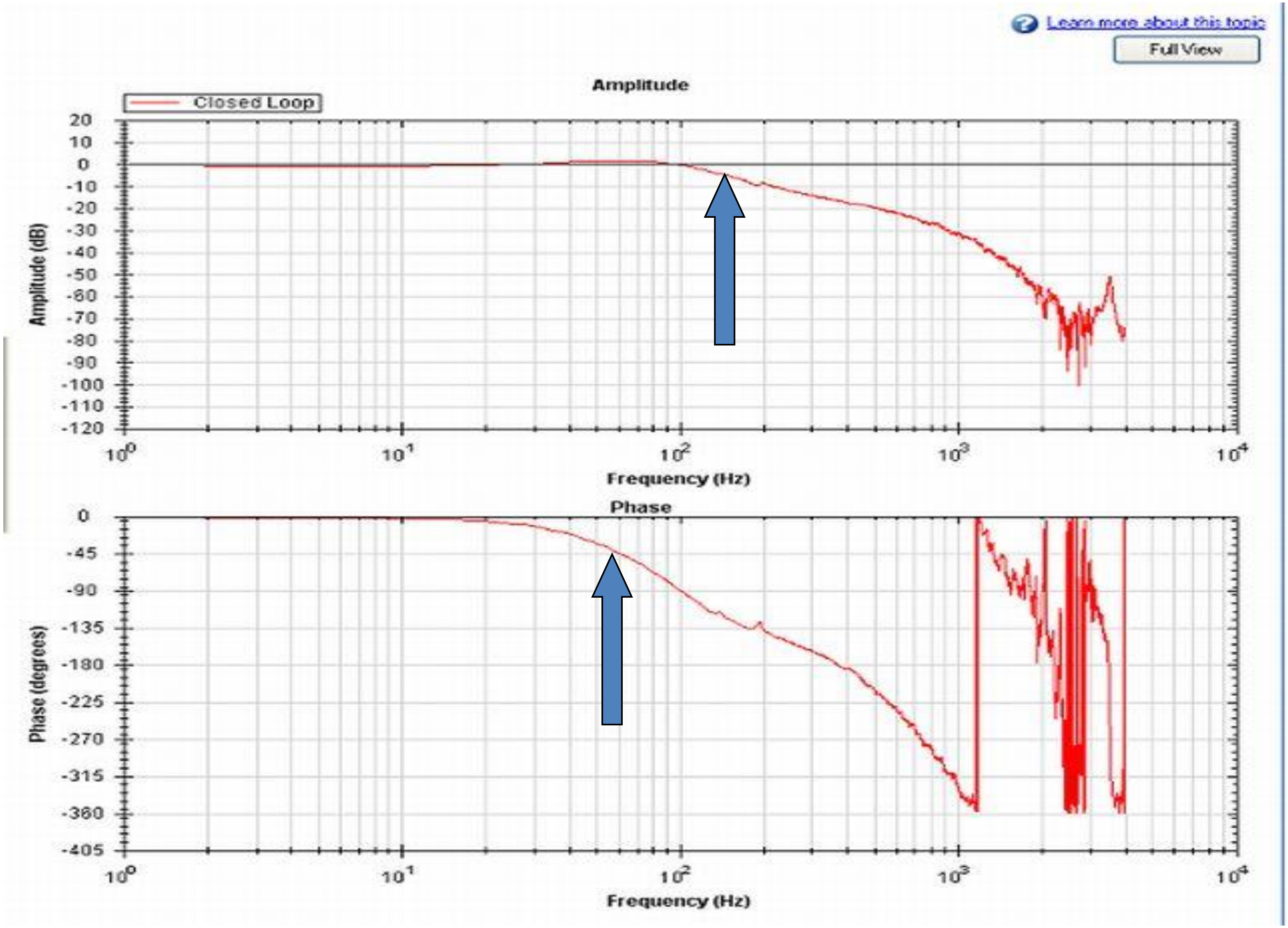
- Do the upfront math.
- Motioneering Models
- Analyze the bode plot
- Know the Requirements of the system.

- Remember, it does no good to try to get 50 Hz bandwidth from a system that is not capable. Recognize the limitations.

Bandwidth

- In the closed loop domain, the point where the gain is –3dB and/or the phase is –45°.




Learn more about this topic
Full View
Amplitude
Closed Loop
Amplitude (dB)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
10^0
10^1
10^2
10^3
10^4
Frequency (Hz)
Phase
Phase (degrees)
0
-45
-90
-135
-180
-225
-270
-315
-360
-405
10^0
10^1
10^2
10^3
10^4
Frequency (Hz)

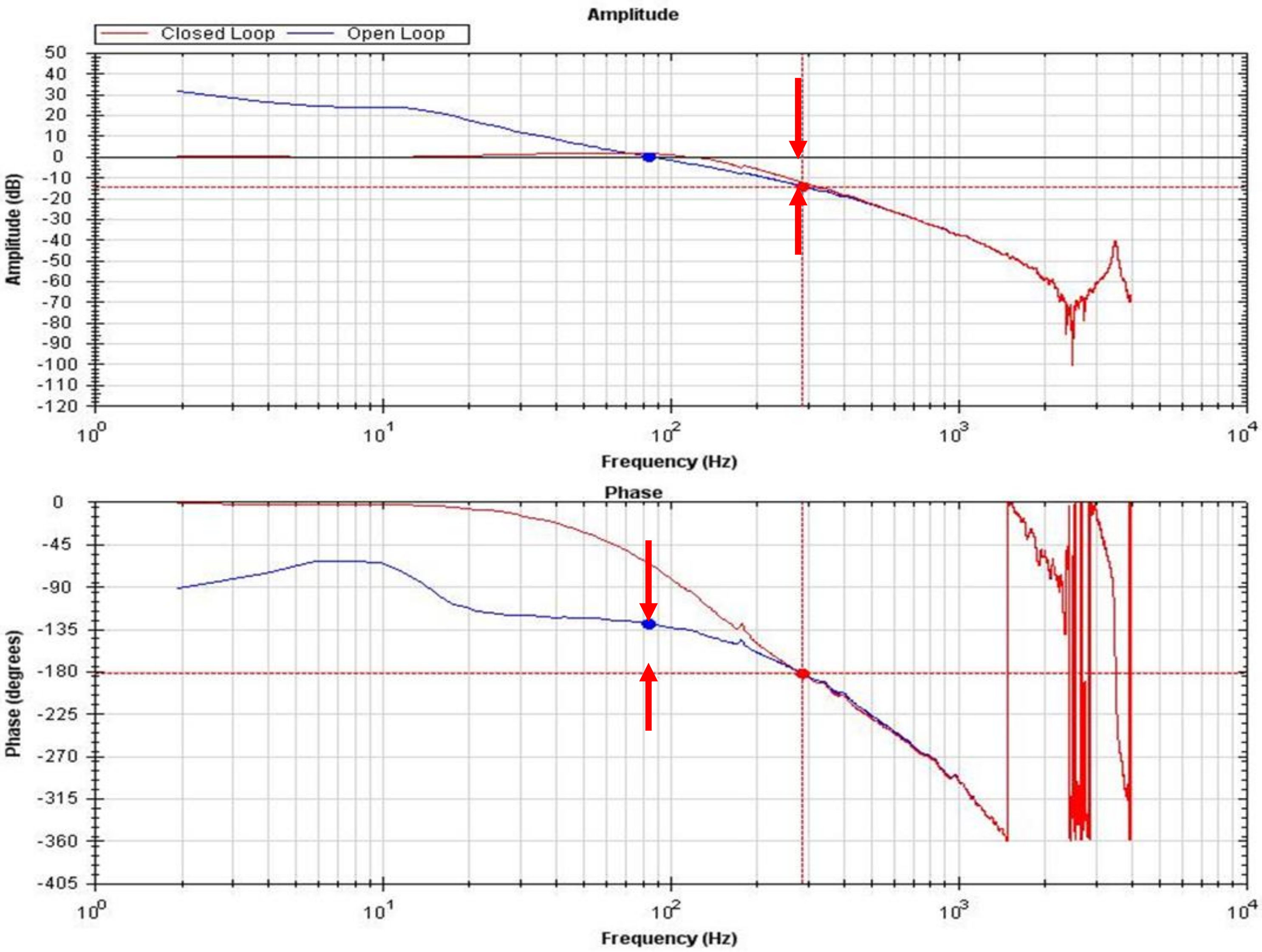
Phase/Gain Margin

- Using the open loop gain and phase plots from the AKD, determine what the phase is at 0 dB. In most cases, where is starts from –90, if the moving to the right at the highest frequency where the gain is still on 0-dB, record the phase. The distance from –180 degrees is then the phase margin of a system.
- Gain Margin is defined as the distance away from 0-dB when the phase of the open loop is –180 degrees.
- **Why is this important?**
- Do not depend on the bandwidth and think that you are fine. You have no idea if you are conditionally stable, in other words, how close you are to breaking out of control.

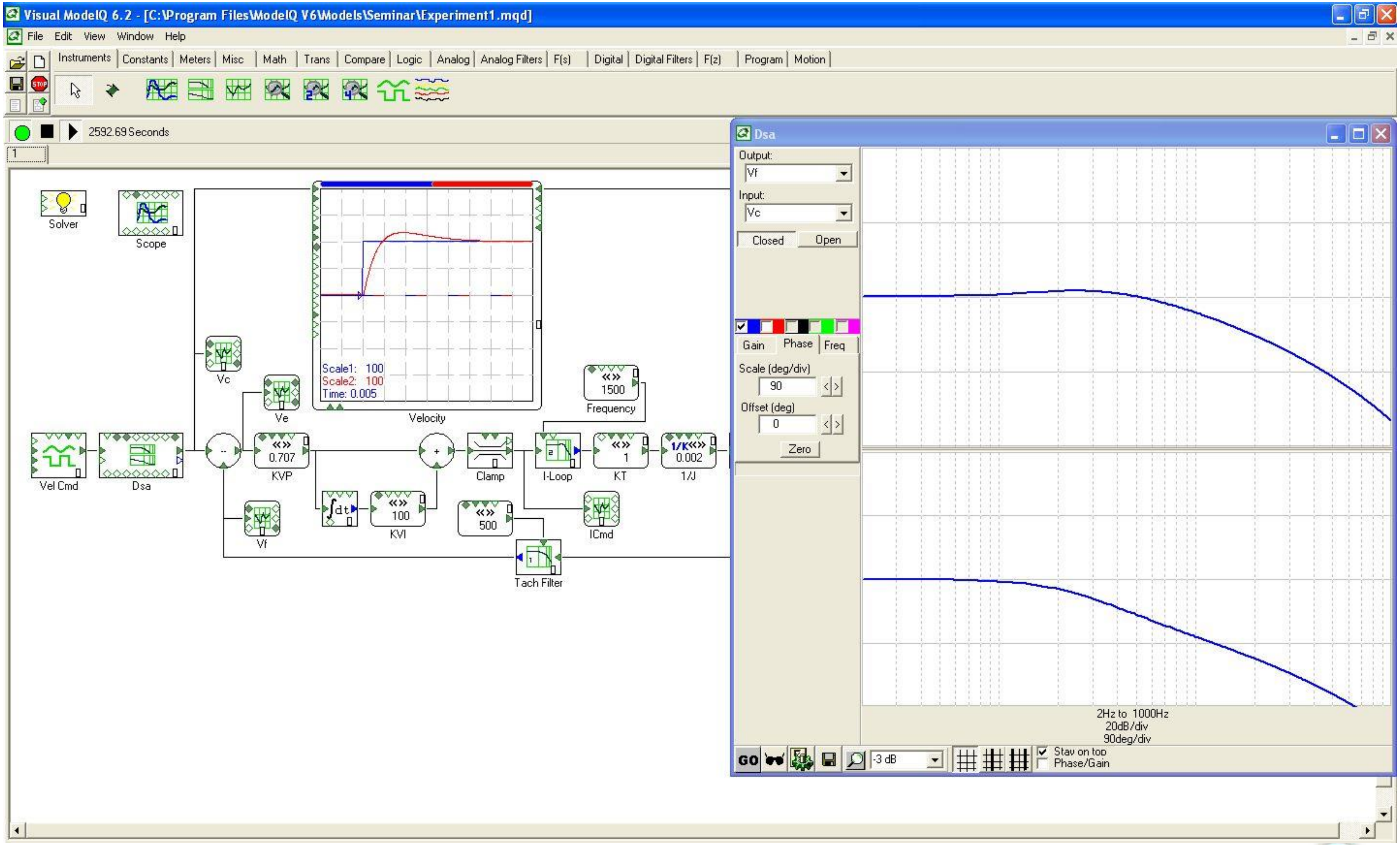
Measuring the Phase/Gain

What is the phase at the zero cross of the open loop plot. This gives you the margin of error. Remember that you are already -90 degrees. A stable system is one that allows you enough margin to be away from any resonance. A good defined system will be hard to say. Books often quote 45 or 60 degrees and 12 dB of margin but that would be a very low bandwidth system and not stiff. Most customers require phase gain margins of 35 degrees and 8 dB. You will see that there are settings for the Autotuner to decide this for you. How is it measured?

55 Degrees and 12dB Phase/Gain Margin



Model Q Evaluations (Gain)



Visual ModelQ 6.2 - [C:\Program Files\ModelQ V6\Models\Seminar\Experiment1.mqd]

2592.69 Seconds

Scale1: 100
Scale2: 100
Time: 0.005

Output: Vf
Input: Vc

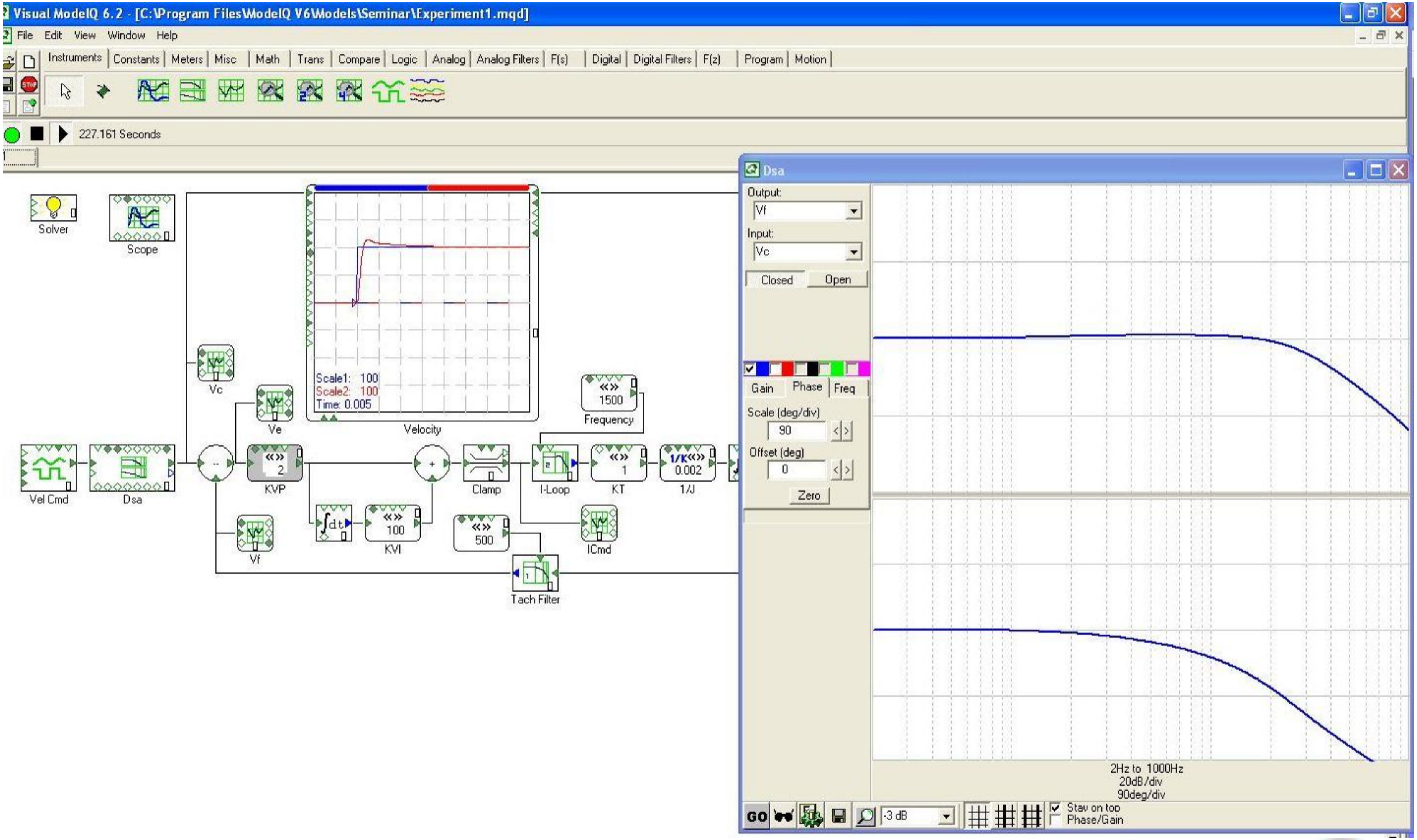
Scale (deg/div): 90
Offset (deg): 0

2Hz to 1000Hz
20dB/div
90deg/div

-3 dB

☑ Stay on top
☐ Phase/Gain

Model Q Evaluations (Increased Gain)



Visual ModelQ 6.2 - [C:\Program Files\ModelQ V6\Models\Seminar\Experiment1.mqd]

227.161 Seconds

Scale1: 100
Scale2: 100
Time: 0.005

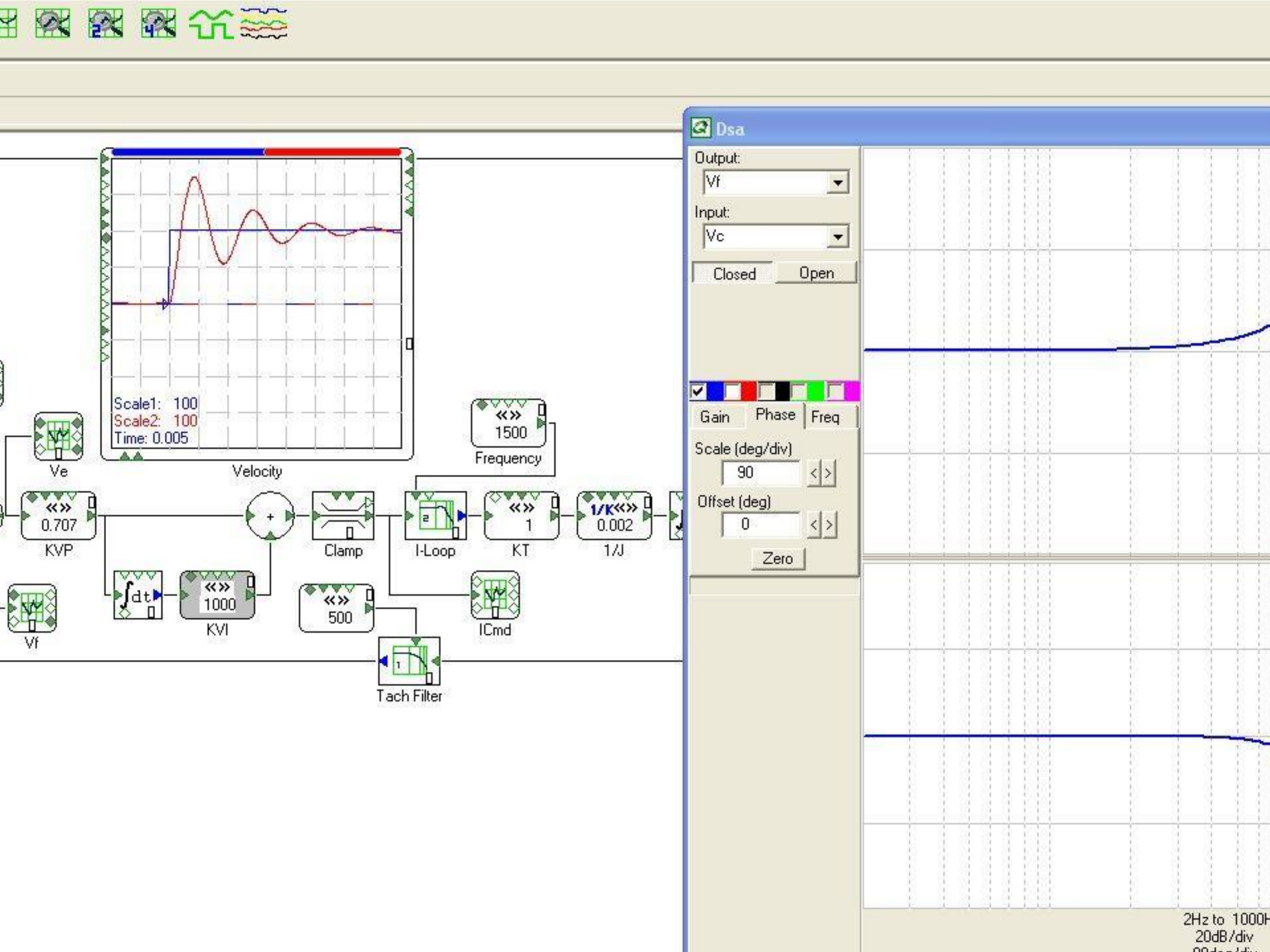
Output: Vf
Input: Vc

Scale (deg/div) 90
Offset (deg) 0

2Hz to 1000Hz
20dB/div
90deg/div

-3 dB

☑ Stay on top
☐ Phase/Gain



Output: Vf

Input: Vc

Scale (deg/div): 90

Offset (deg): 0

Scale1: 100

Scale2: 100

Time: 0.005