PWM Filter
for
Active Magnetic Bearings

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PWM Filter for Active Magnetic Bearings

Issues with PWM amplifiers without an output filter:

1. Ground noise caused by high dV/dt
2. Radiated noise due to
    a) Ripple currents
    b) Resonant currents in output LC-loops formed around parasitic capacitances
3. Reduced life of the magnet wire and power electronics
4. Increased eddy-current and hysteresis losses in actuator lamination stacks
5. Difficulties of working with long cables (often it is impossible)

Reasoning behind the filter selection:

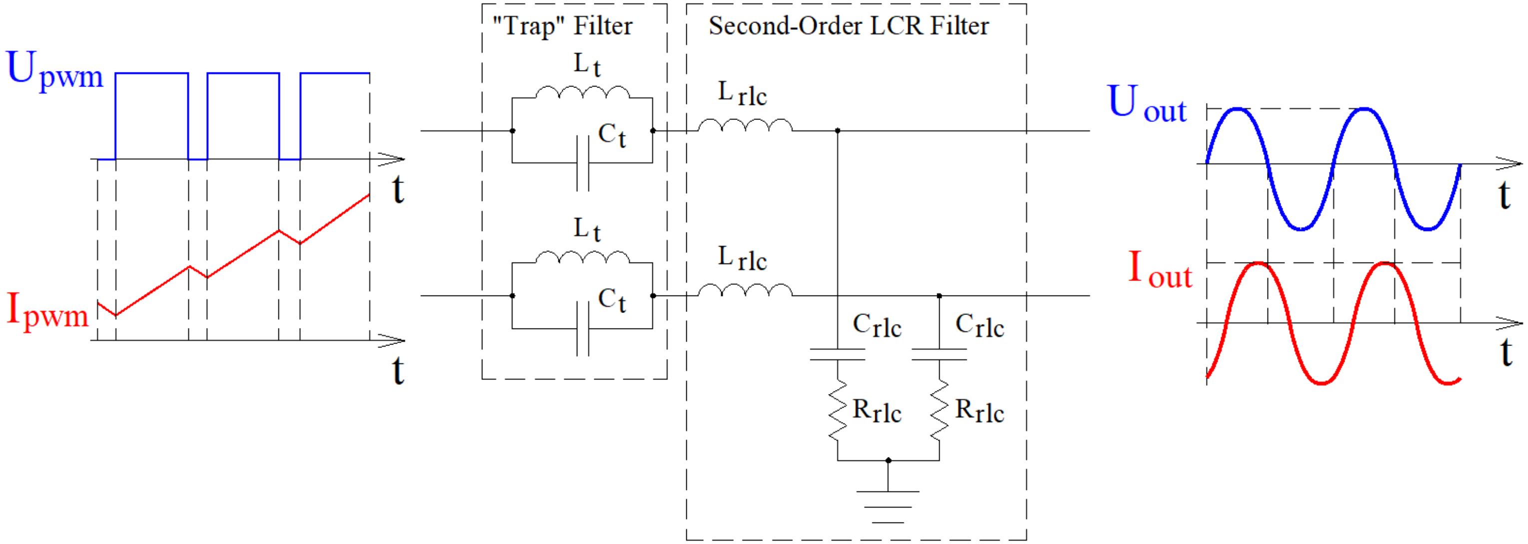
1. The filter has to provide a sufficient attenuation of the PWM frequency and its harmonics without affecting much the signal gain and the phase within the AMB control bandwidth.

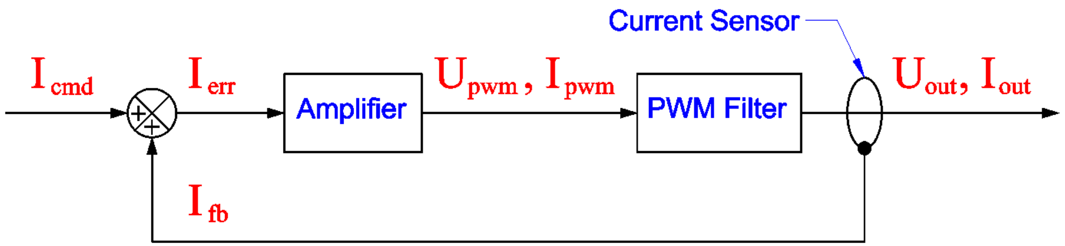
2. A second order LCR filter is typically used, but this choice provides limited attenuation of the PWM switching frequency it is close to the upper limit of the control bandwidth.

3. Combination “Trap Filter + 2nd Order LCR” filter is selected for further investigation, which was first proposed around year 2000 for motor applications.

PWM Filter for Active Magnetic Bearings

PWM filter topology: “Trap” filter + 2nd order LCR filter

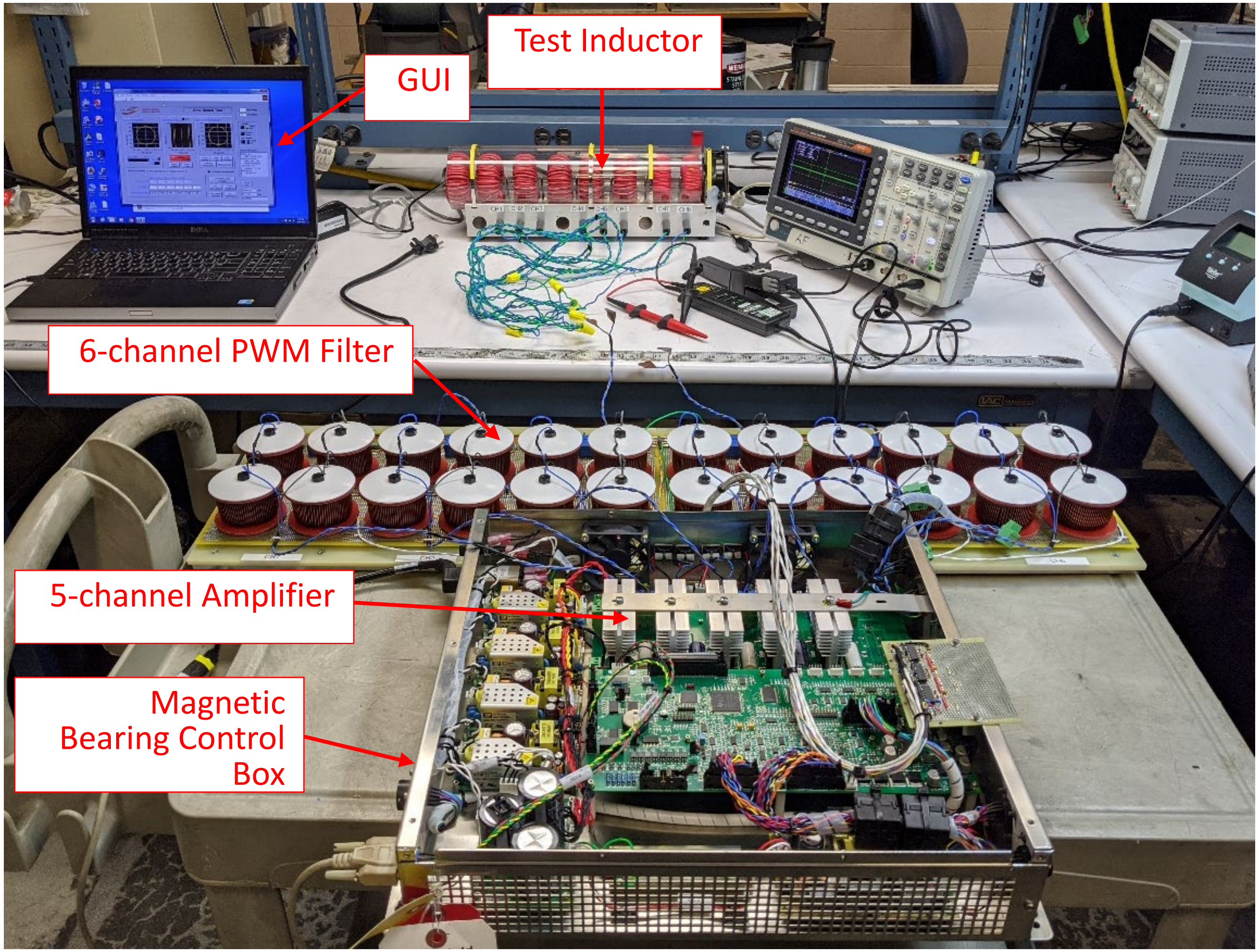




This topology was chosen to achieve high attenuation of 25kHz PWM frequency with minimal effects on the overall transfer function gain and phase at 2kHz, which is the upper limit of the targeted AMB control bandwidth.

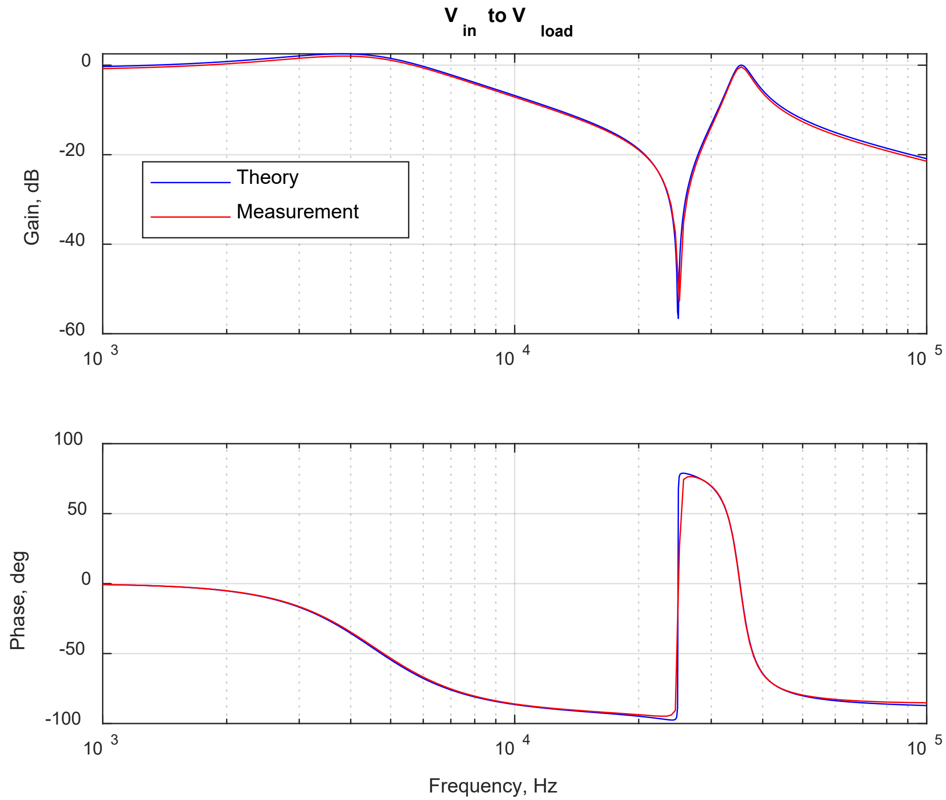
PWM Filter for Active Magnetic Bearings

Experimental setup



PWM Filter for Active Magnetic Bearings

Nominal filter transfer function with 5A DC output current

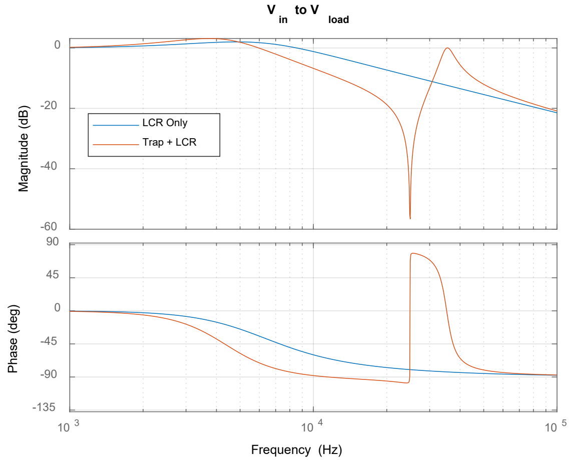


Theoretical attenuation at 25kHz: -57dB

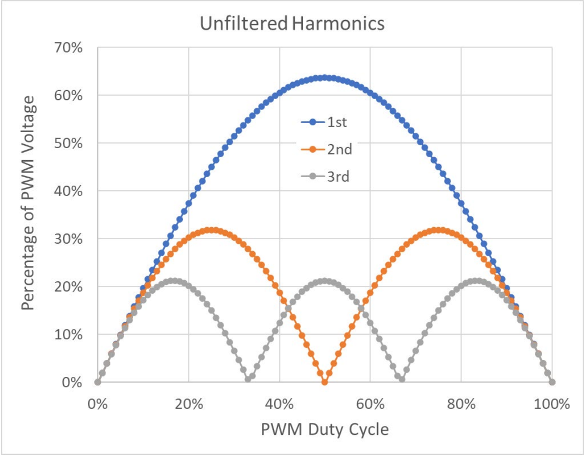
Measured attenuation at 25kHz: -53dB

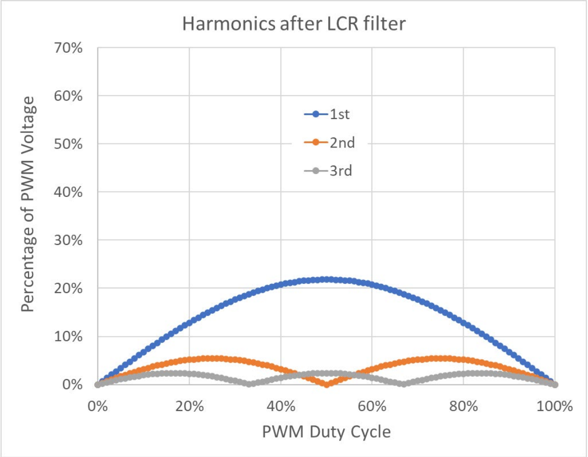
PWM Filter for Active Magnetic Bearings

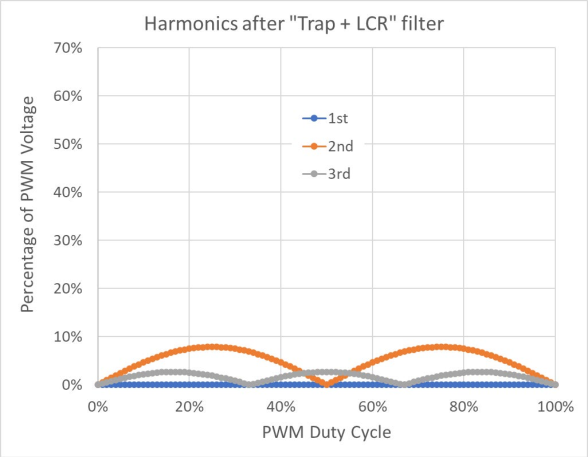
"Trap" + LCR filter provides very strong attenuation for the PWM fundamental but unfortunately slightly less attenuation for higher-order harmonics, even compared to the LCR filter alone.



The attenuation of the fundamental harmonic, however, is very important as the higher-order harmonics are smaller to begin with and get further attenuated in any case. Below is an illustration for the first three harmonics.







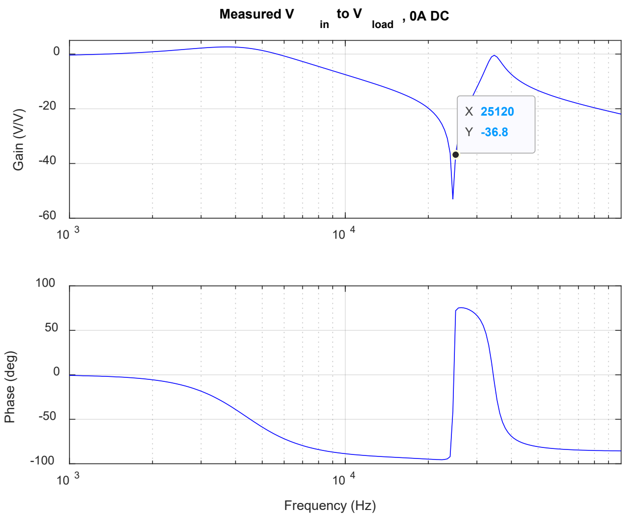
PWM Filter for Active Magnetic Bearings

Output current effect on the filter attenuation

The notch frequency changes when the output current changes, because the inductance changes.

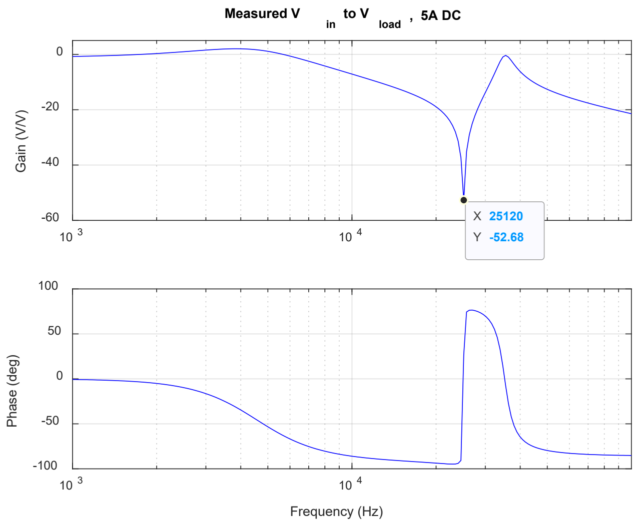
Measured “input voltage to output voltage” filter transfer functions

I_{out}=0A



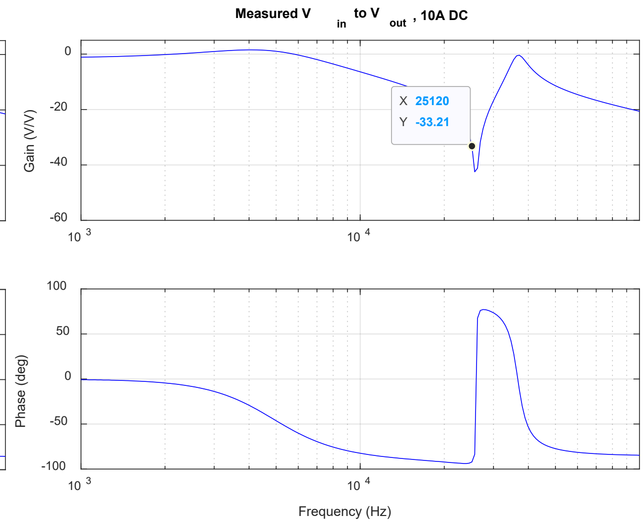
Attenuation @ 25.12kHz: ≈-36.8dB

I_{out}=5A DC



Attenuation @25.12kHz: ≈ -52.7dB

I_{out}=10A



Attenuation @25.12kHz: -33.2dB

PWM Filter for Active Magnetic Bearings

Open-loop DC-current operation

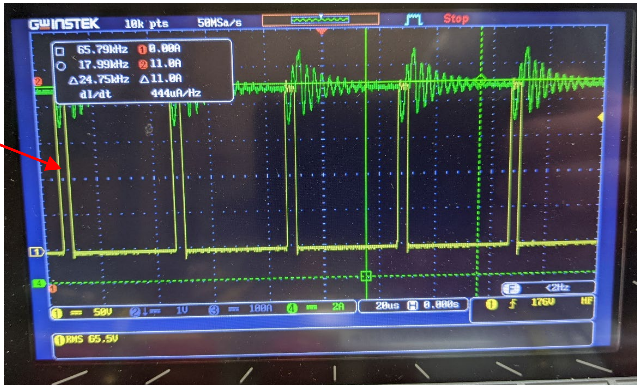
Yellow - voltage; Green - current. PWM duty cycle is the same with or without filter.

The measured current oscillations are amplified by noises injected into clamp-on current probe.

Without filter, I_{out}=5.52A

With filter, I_{out}=5.04A

8,360V/ µs



Without the filter, I_{out}=11.0A

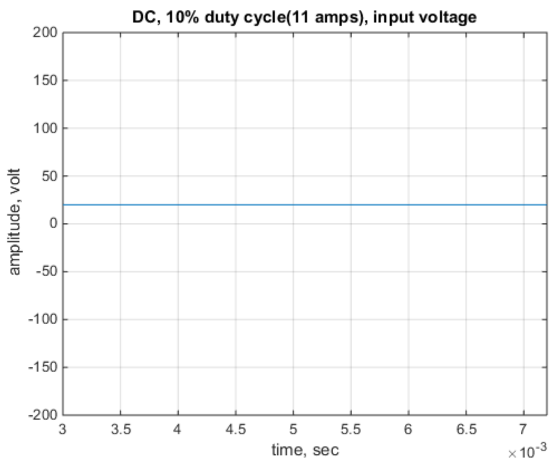
≈10V/ µs

With the filter, I_{out}=10.0A

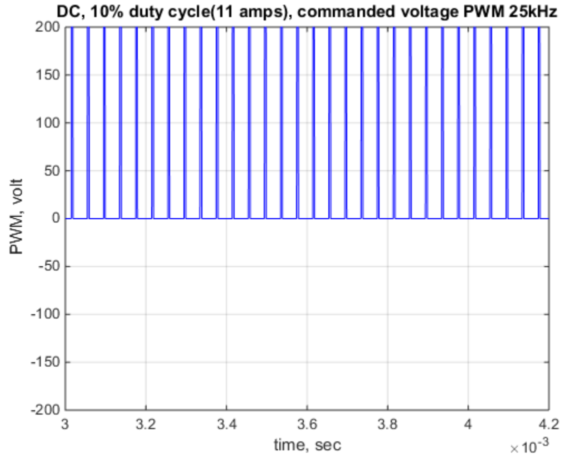
Filter reduces dV/dt by more than 800 times: from 8,360V/µs to approximately 10 V/µs.

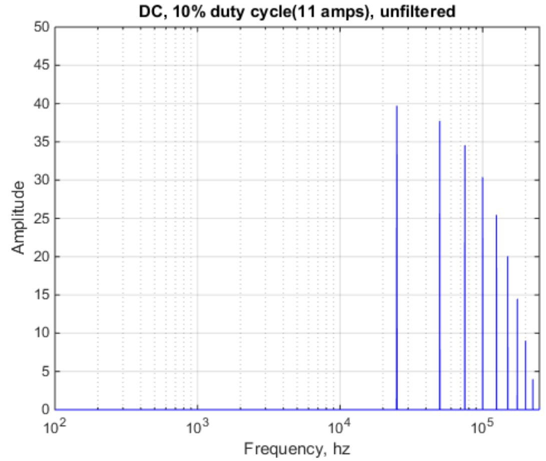
PWM Filter for Active Magnetic Bearings
Predicted Unfiltered and Filtered

Input Signal, 20 V DC

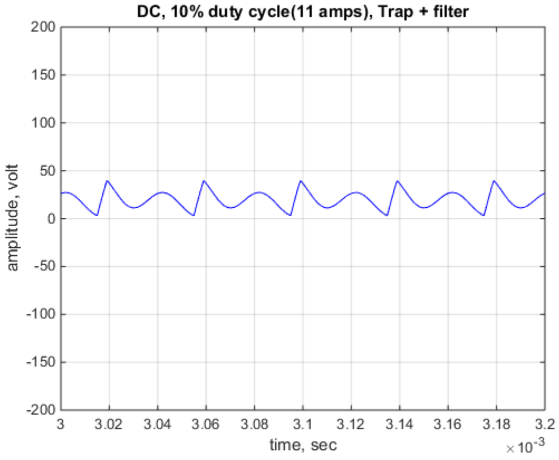


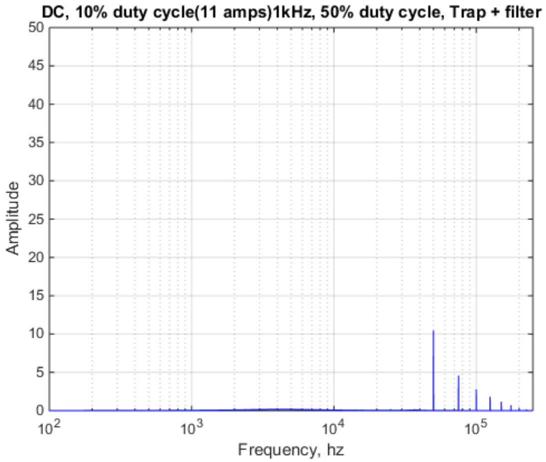
PWM of Input, Unfiltered





PWM Filtered with Trap+LCR

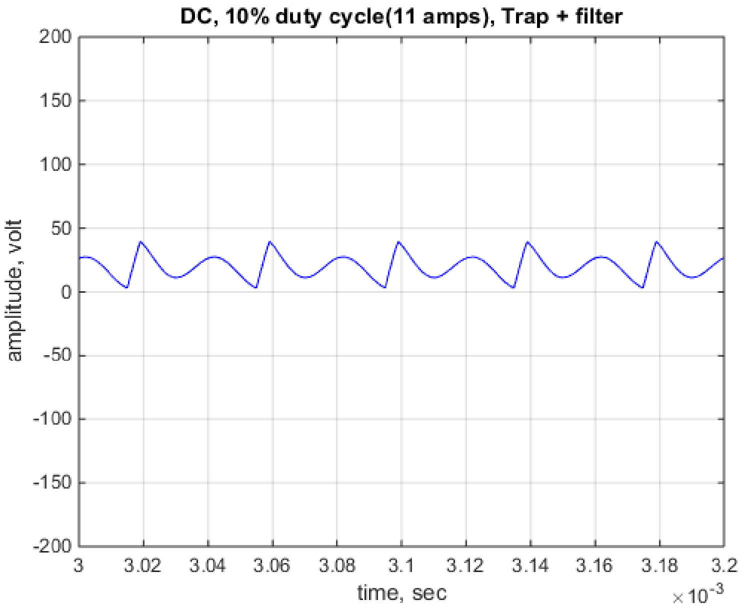




PWM Filter for Active Magnetic Bearings Predicted vs. Measured – Filtered

Filtered (Trap+LCR) Output of 20 V DC PWM

Predicted

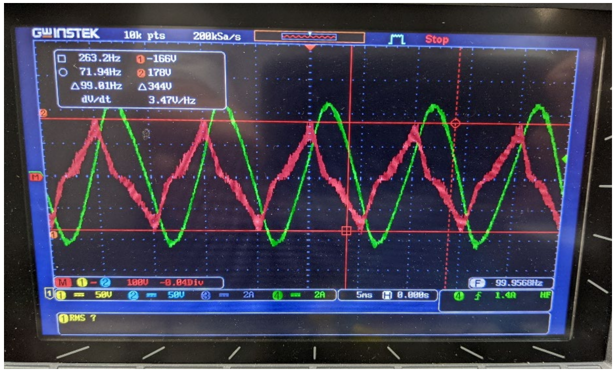


Measured

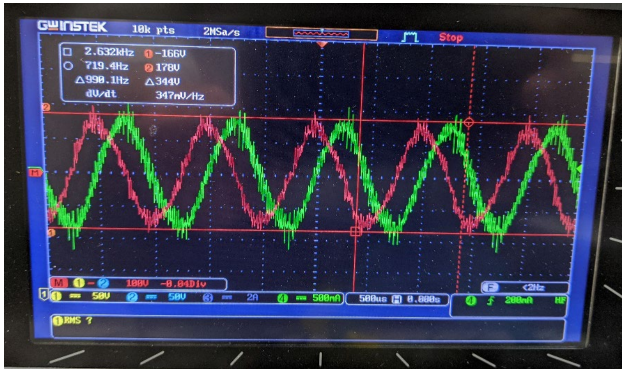
PWM Filter for Active Magnetic Bearings

Closed-loop AC-current operation

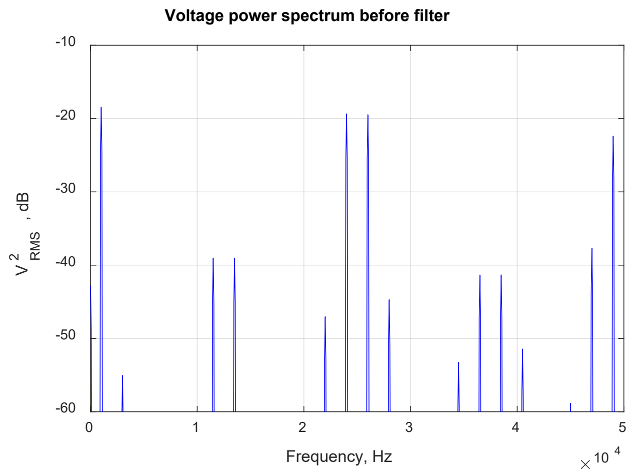
Red - voltage; Green - current.

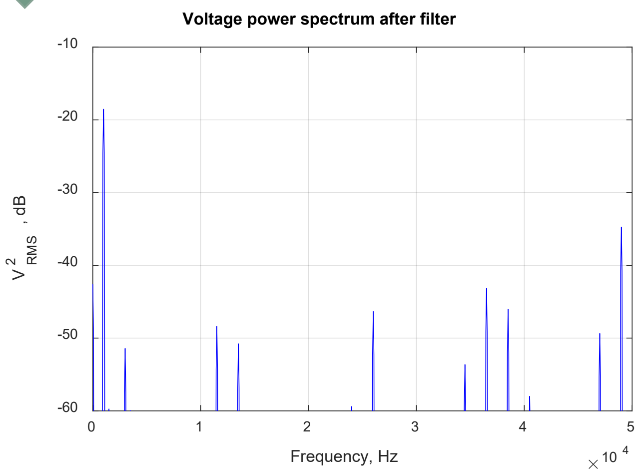


I_{out}=4.4Apk, 160 Vpk, 100Hz.



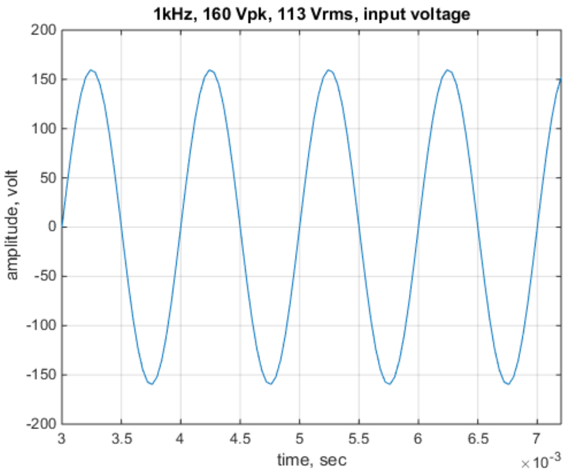
I_{out}=0.8Apk, 160 Vpk, 1kHz.



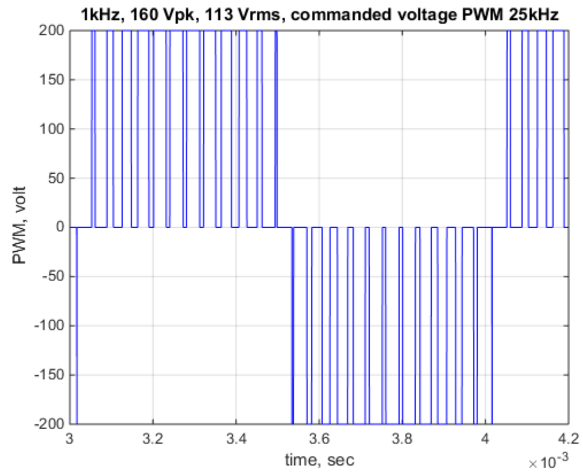


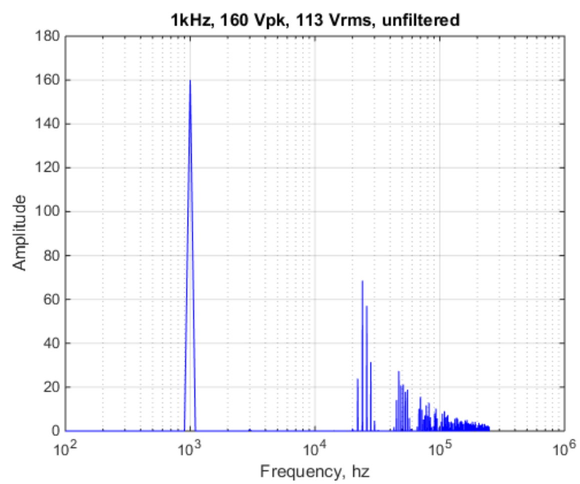
PWM Filter for Active Magnetic Bearings Predicted Unfiltered and Filter

Input Signal, 160 Vpk, 1kHz

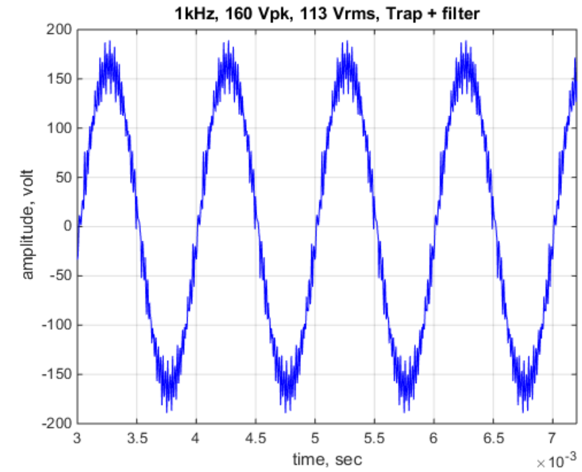


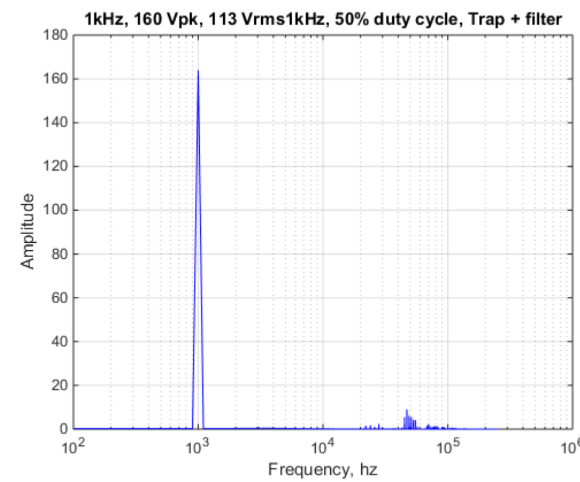
PWM of Input, Unfiltered





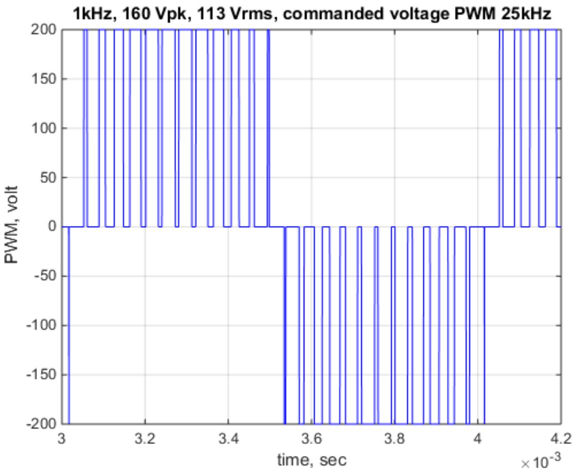
PWM Filtered with Trap+LCR



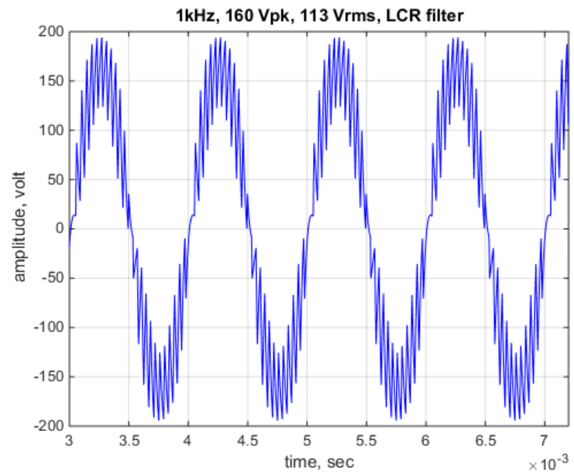


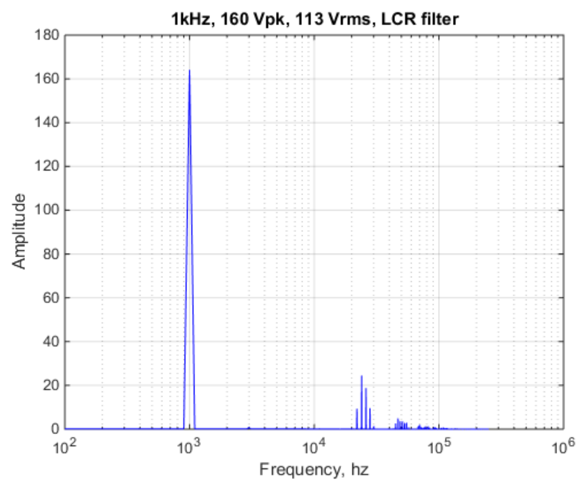
PWM Filter for Active Magnetic Bearings Predicted LCR vs. Trap + LCR Filter

Input Signal, 160 Vpk, 1kHz, PWM of Input, Unfiltered

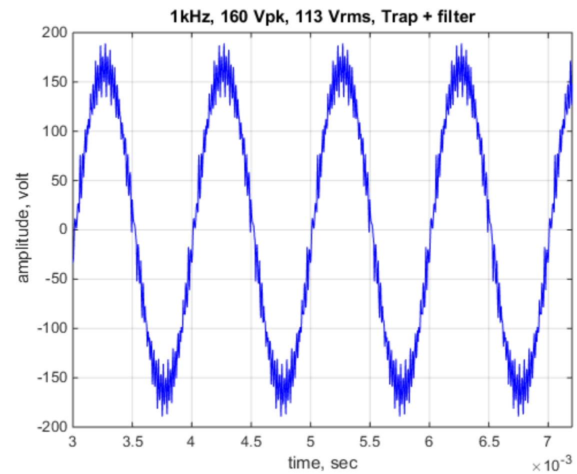


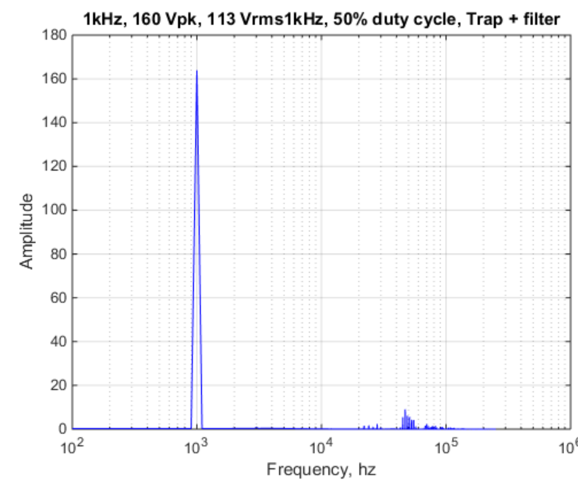
PWM of Input, LCR only





PWM Filtered with Trap+LCR

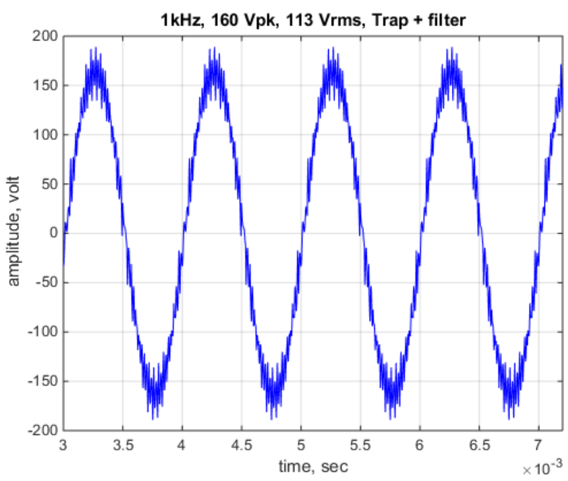




PWM Filter for Active Magnetic Bearings Predicted vs. Measured – Filtered

Filtered (Trap+LCR) Output of 160 Vpk, 1kHz PWM

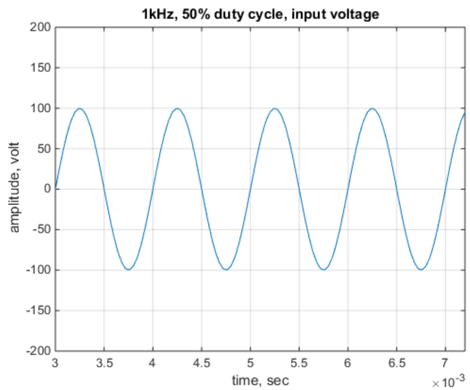
Predicted



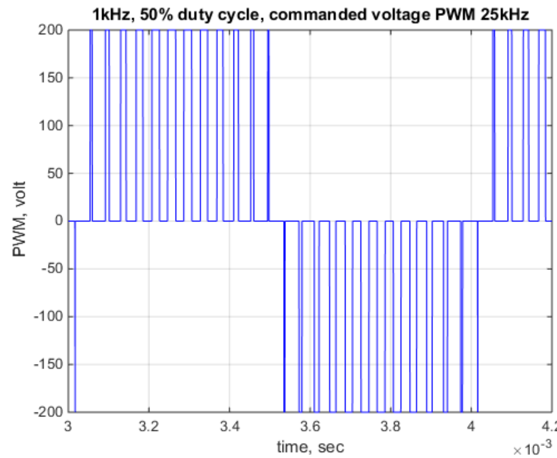
Measured

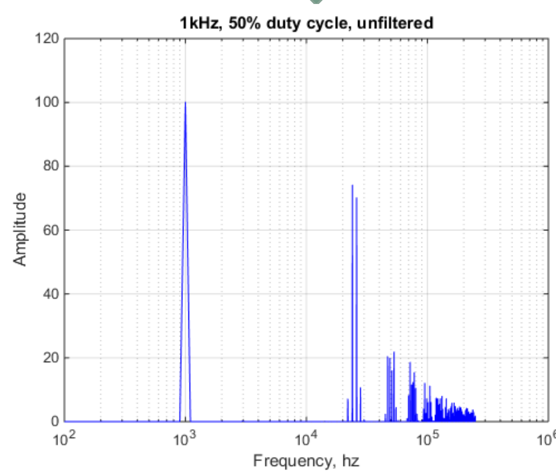
PWM Filter for Active Magnetic Bearings Predicted Unfiltered and Filter

Input Signal, 100 Vpk, 1kHz (max duty cycle is 50%)

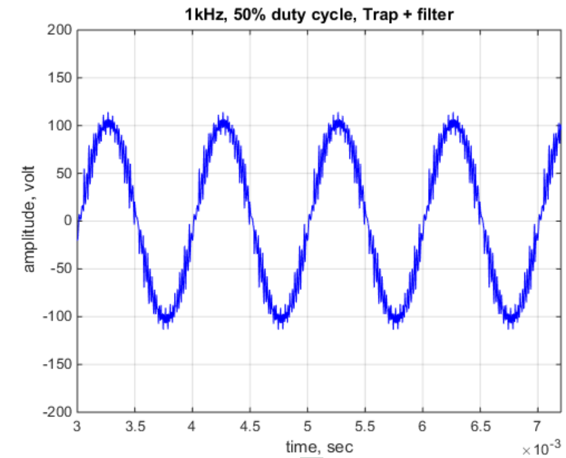


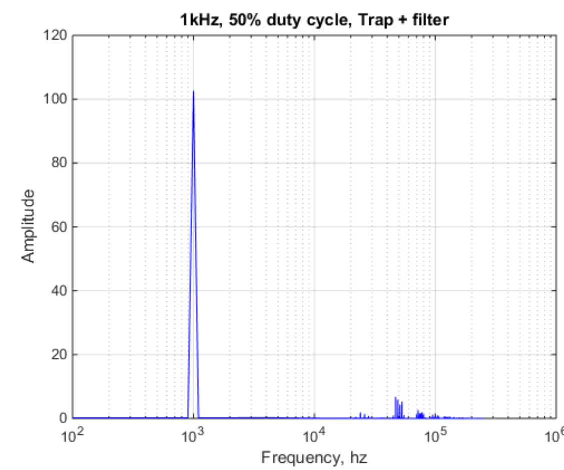
PWM of Input, Unfiltered





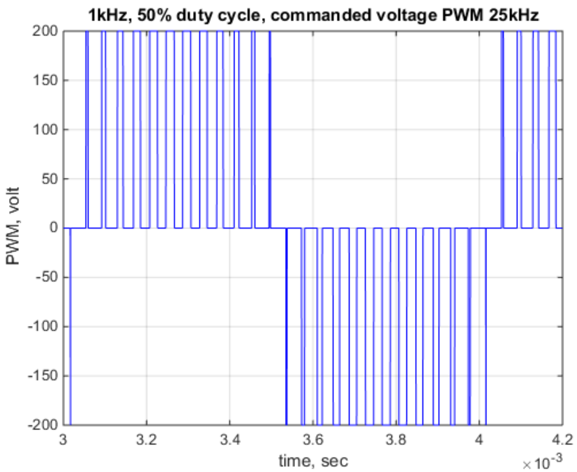
PWM Filtered with Trap+LCR



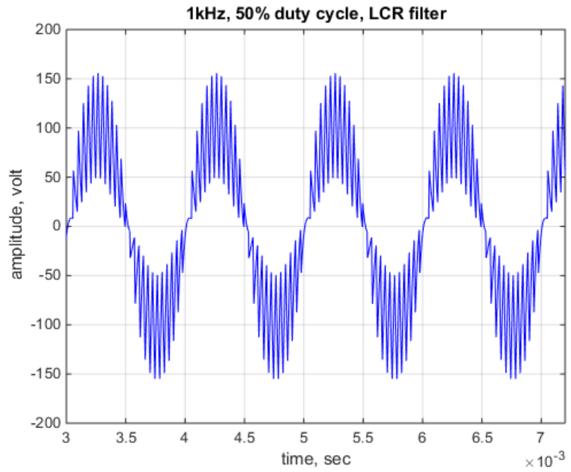


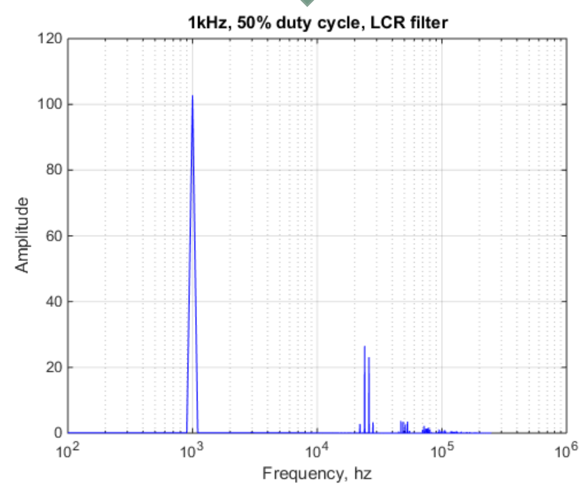
PWM Filter for Active Magnetic Bearings Predicted LCR vs. Trap + LCR Filter

Input Signal, 100 Vpk (50% max), 1kHz, PWM of Input, Unfiltered

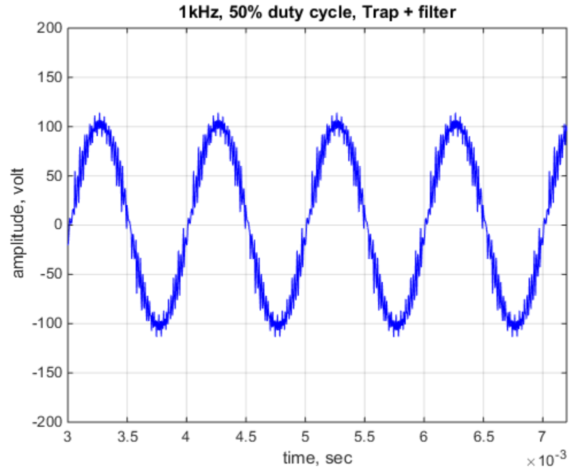


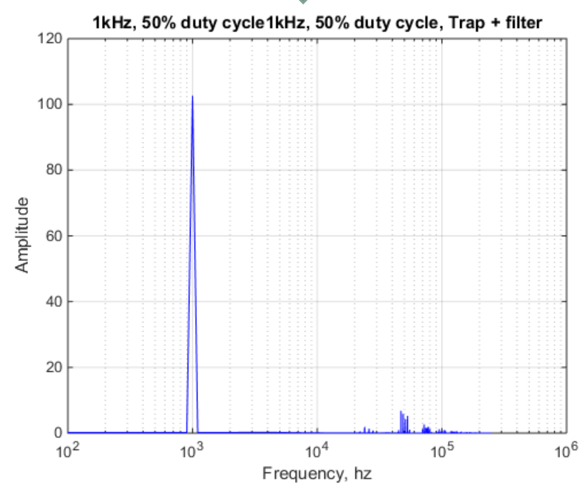
PWM of Input, LCR only





PWM Filtered with Trap+LCR

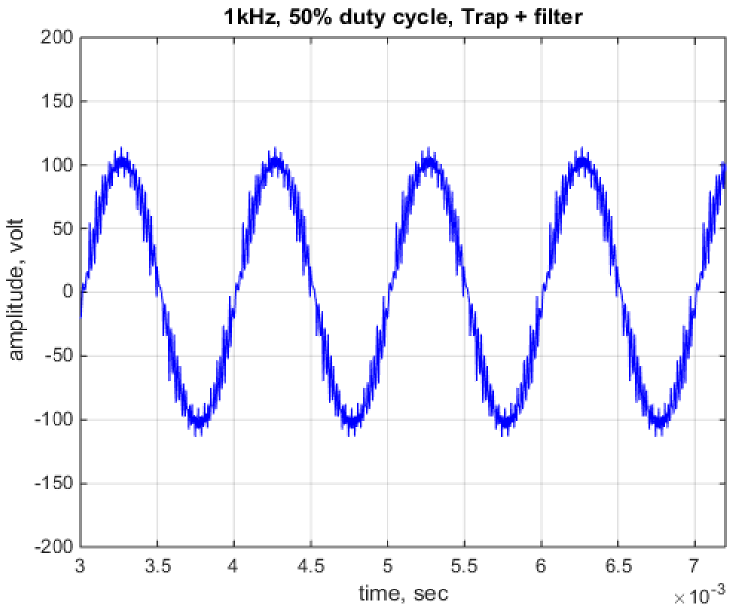




PWM Filter for Active Magnetic Bearings Predicted vs. Measured – Filtered

Filtered (Trap+LCR) Output of 100 Vpk (50%), 1kHz PWM

Predicted



Measured

Actuator control over a long cable

Time-varying electrical signals (voltages and currents) in cables propagate as waves.

Signal propagation speed: $$V = \sqrt{\frac{1}{L_0 C_0}}$$

L_0 is the cable inductance per unit length.
C_0 is the cable capacitance per unit length.

Wavelength: $$\lambda = \frac{V}{f}$$

For DC signals (f=0), $\lambda=\infty$ and the signal wave nature can be ignored.

Actuator control over a long cable

Difficulty of the actuator current control over a long cable depends on how close the cable length is to the wavelengths associated with PWM harmonics of significant amplitudes.

1. **The cable length is significantly shorter than the shortest spatial wavelength λ of interest (normally less than ¼ is sufficient).**

The cable effect analysis can be reduced to adding a lumped cable capacitance in parallel with the inductor.

2. **The cable length approaches the shortest significant spatial wavelength from the PWM spectrum.**

The current control in the actuator would be very complicated or even impossible as the difference between the current output by the amplifier and the current entering the actuator will be time dependent. Reflected waves can cause voltage spikes. Standing spatial waves can be also formed.

Actuator control over a long cable (1.2 km)

Experimental setup

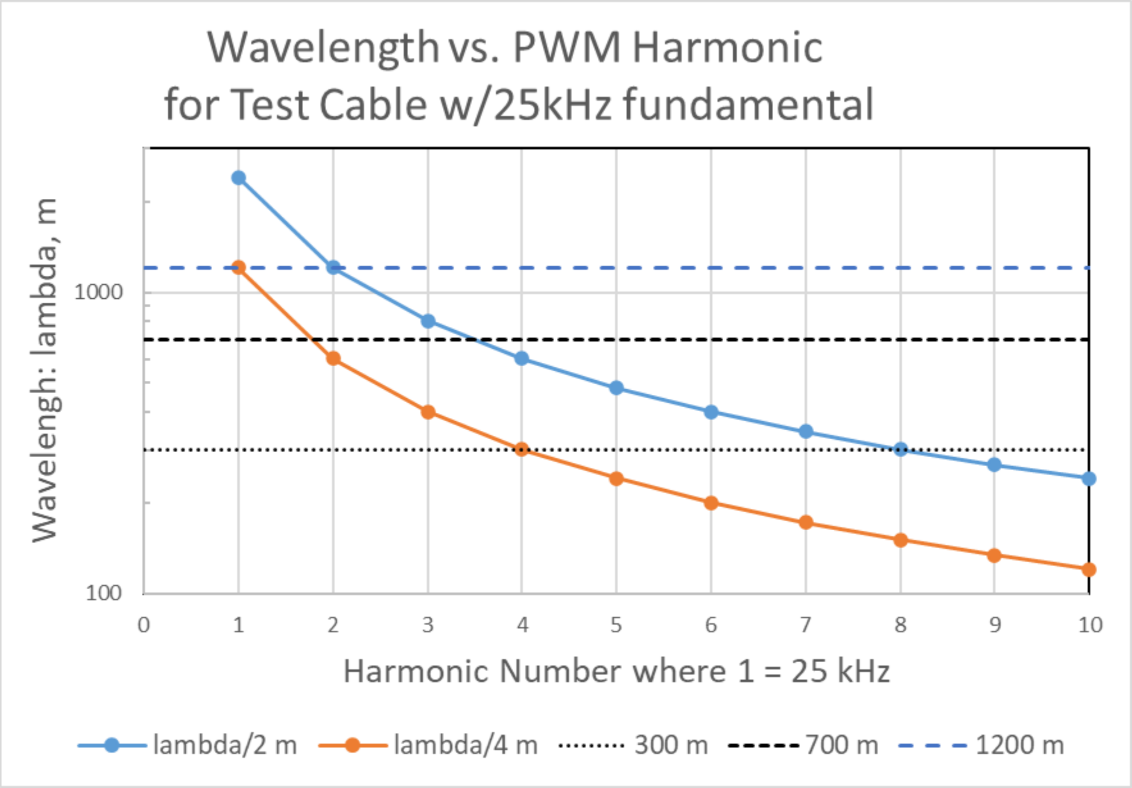
1. Load (two scenarios):
   a) Radial actuator of a commercial 350kW 15kRPM air compressor.
   b) Axial actuator of the same air compressor.
2. Cable: two lines of a 1.2km-long, 3-Phase, 12AWG shielded cable.
   - Inductance per unit length L_0=0.578μH/m
   - Capacitance per unit length C_0=119pF/m
3. Amplifier PWM fundamental frequency: 25kHz.

The electromagnetic wavelength for this cable at 25kHz is 4.8km – only four times bigger the cable length.

Wavelengths for higher-order PWM harmonics will be comparable and even shorter than the cable length.

Actuator current control thru direct application of the PWM voltage pulses at the amplifier end of the cable will be problematic but should be possible for the targeted 2kHz bandwidth with a PWM filter.

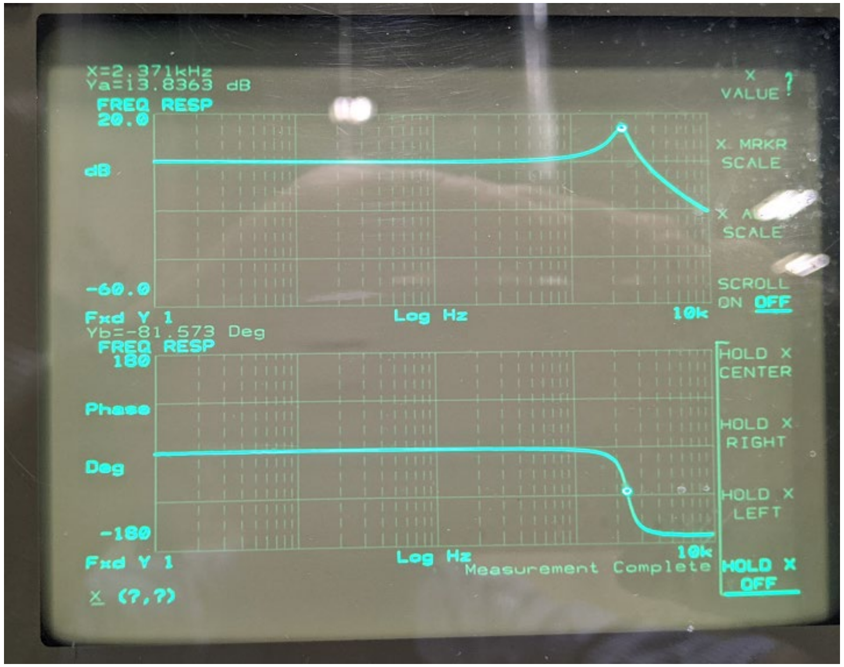
Wavelength vs Harmonic for Test Cable 25 kHz switching frequency = 1



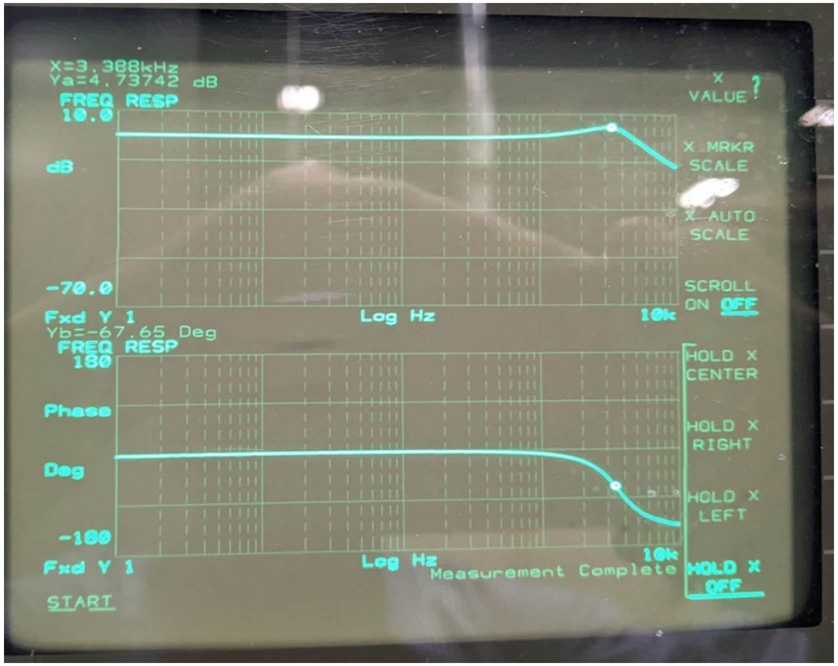
- Standing wave avoided if cable length < ½ wavelength
- Standing wave likely if ½ (or 1, 1-1/2, etc) wavelength of a significant harmonic nearly matches cable length
  - Problem mitigated if amplitude of such harmonic is low

PWM Filter for Active Magnetic Bearings

Measured transfer functions from the currents injected into a long cable to the currents output into the actuators.



Radial Actuator

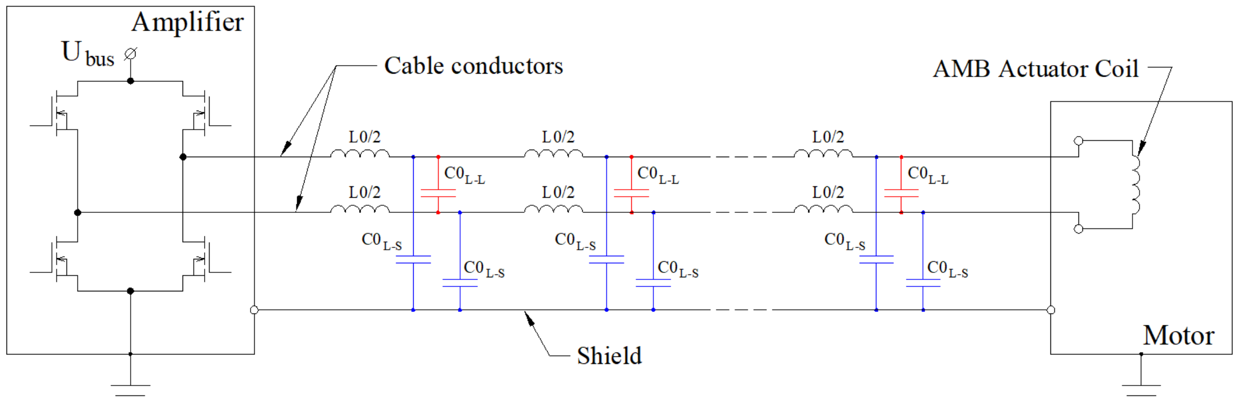


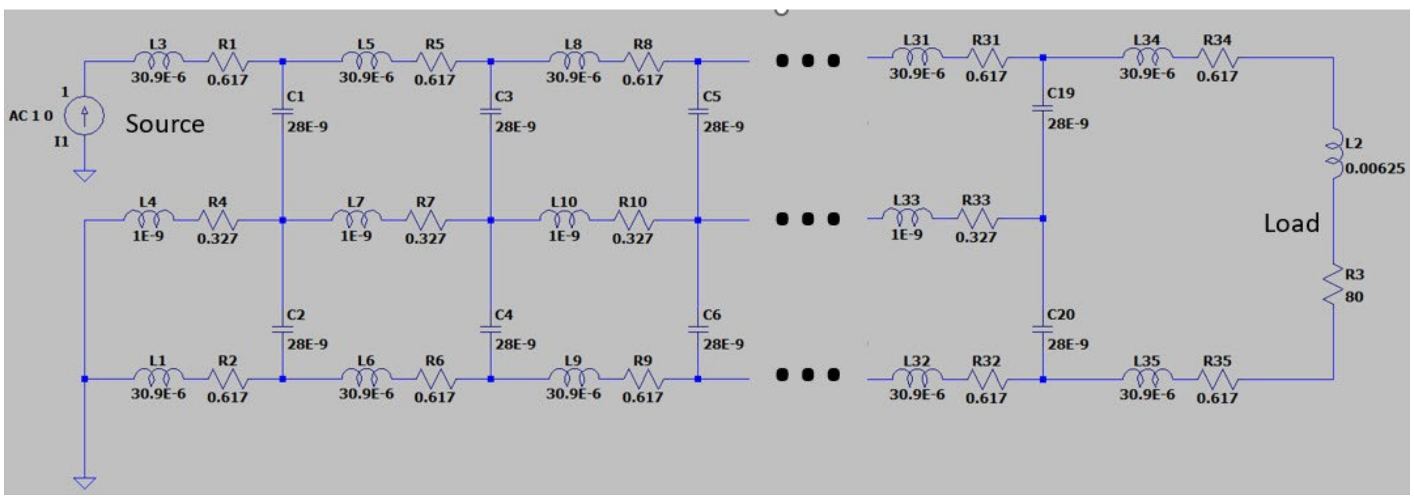
Axial Actuator

cable/+act, input is (after any filter) into cable, output is current into load
You would need to drive current below 1 kHz

PWM Filter for Active Magnetic Bearings

Finite difference “long cable + actuator” model in LT Spice.



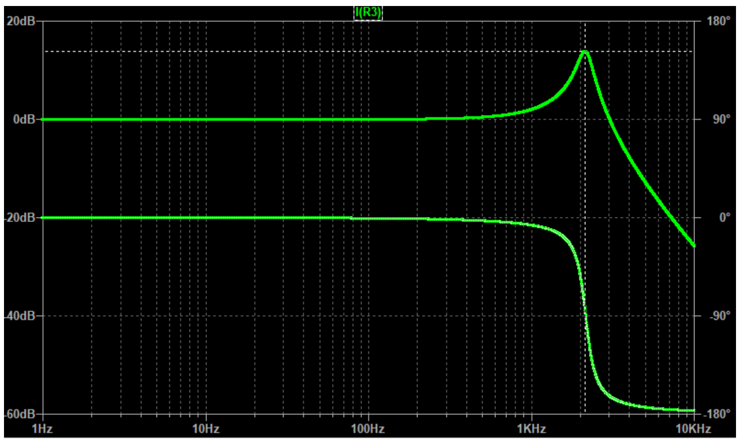


PWM Filter for Active Magnetic Bearings

Output Current / Input Current Transfer Functions

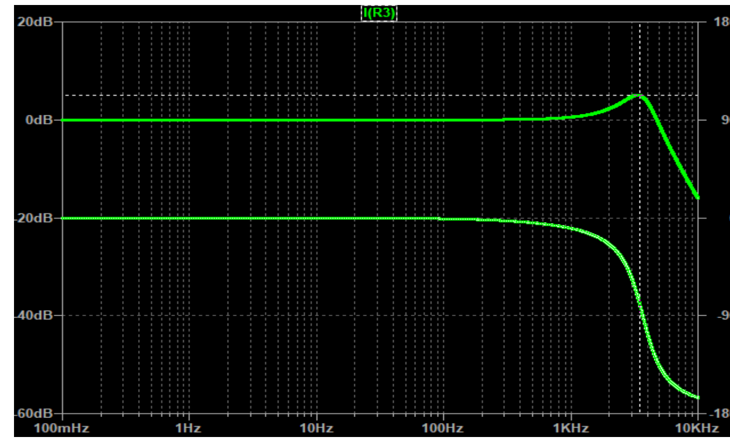
Long Cable + Radial Actuator

Analysis

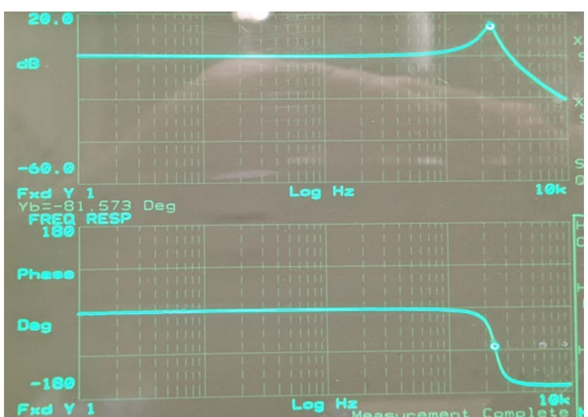


Long Cable + Axial Actuator

Analysis



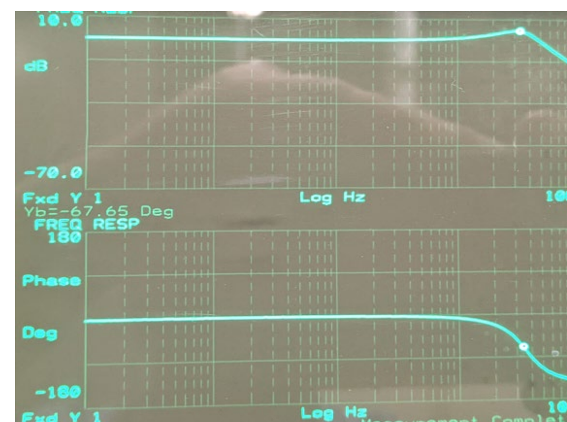
Measurement



Resonance Characteristic Comparison

Bearing	f, Hz		Gain, dB	
	Predicted	Measured	Predicted	Measured
Radial (X2)	2132	2371	13.937	13.836
Axial (Z)	3356	3388	5.116	4.737

Measurement



Conclusions

1. Combination of a “Trap” filter and a 2nd order LCR filter has been shown very effective in suppressing PWM harmonics.
2. This combination filter is especially well suited for systems with narrow separation between PWM frequency and control bandwidth.
3. A filter prototype was built and its effectiveness demonstrated in a system with 25kHz PWM frequency and 2kHz control bandwidth
   a) Attenuation of -52.7 dB PWM frequency was demonstrated at nominal current
   b) Reduction of max dV/dt from 8,360V/μs to approximately 10 V/μs
4. The filter enabled control of the actuator currents in a commercial 350kW 15kRPM air compressor over 1.2km cable.
   a) The compressor was levitated and spun to full speed with the long cable driving either one radial channel or the axial channel
5. Finite-difference LT-Spice model was used to analyze “long cable + inductor” systems. The model predictions were in a good agreement with the experimental measurements.