Magnetic Bearing Amplifier Output Power Filters for Flywheel Systems

Ramon C. Lebron-Velilla
Glenn Research Center, Cleveland, Ohio

Ralph H. Jansen
University of Toledo, Toledo, Ohio

Alan Palazzolo and Erwin Thomas
Texas A&M University, College Station, Texas

Peter E. Kascak
University of Toledo, Toledo, Ohio

Arthur G. Birchenough
Glenn Research Center, Cleveland, Ohio

Timothy P. Dever
QSS Group, Inc., Cleveland, Ohio

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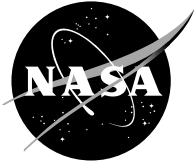
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NASA Glenn Research Center
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ABSTRACT

Five power filters and two types of power amplifiers were tested for use with active magnetic bearings for flywheel applications. Filter topologies included low pass filters and low pass filters combined with trap filters at the PWM switching frequency. Two state and three state PWM amplifiers were compared. Each system was evaluated based on current magnitude at the switching frequency, voltage magnitude at 500 kHz, and power consumption. The base line system was a two state amplifier without a power filter. The recommended system is a three state power amplifier with a 50 kHz low pass filter and a 27 kHz trap filter. This system uses 5.57 W. It reduces the switching current by an order of magnitude and the 500 kHz voltage by two orders of magnitude. The relative power consumption varied depending on the test condition between 60% to 130% of the baseline.

INTRODUCTION

NASA Glenn Research Center has an ongoing effort in flywheel technology development and deployment for spacecraft applications [1]. Flywheel systems can be used to replace batteries for energy storage applications. Flywheel modules can also be deployed in an array which provides both energy storage and momentum control. This kind of system is called an Integrated Power and Attitude Control System (IPACS). A flywheel system consists of a number of flywheel modules and an electronics package which operates the motor/generators, the magnetic bearings, and the telemetry. The benefits of flywheel systems for energy storage applications are high energy density, high power density, long life, deep depth of discharge, and broad operating temperature ranges. In an IPACS configuration an additional mass savings can be achieved through the combination of the energy storage and the attitude control functions.

Flywheel modules for space use are designed to maximize energy density and minimize losses. Typically the energy storage component of the module is a rim composed of high strength carbon fiber. Energy is transferred to and from the wheel using a motor/generator. The flywheel module typically has some or all of these ancillary components: magnetic bearings, touchdown bearings, housing structure, sensors, connectors, and wiring harnesses. The flywheel modules used in this work all have a similar configuration (Figure 1). The rotating components are placed along a hub with the rim in the center of the hub. The motor, magnetic bearings, and touchdown bearings populate each end of the hub. The stationary parts of these components are located within the housing.

The flywheel modules used in this work have active magnetic bearings. An active magnetic bearing system utilizes a position feedback control system to levitate an object by adjusting a set of
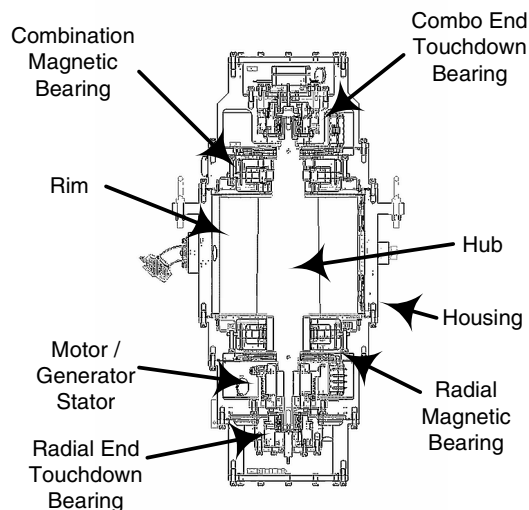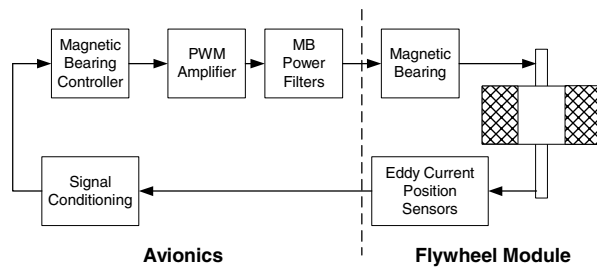

Figure 1 – G2 Flywheel Module

Figure 2 – Active Magnetic Bearing System

Figure 3 - Power Amplifier Spectrum

electromagnets (Figure 2). The flywheel modules have a five axis control system: two radial degrees of freedom at each end of the rotor and an axial degree of freedom. The magnetic bearing controller compares the desired rotor position to the actual and provides a current command to each of the power amplifiers. The power amplifiers track the current command within their bandwidth limit. The current flows through the magnetic bearing actuator producing magnetic fields in the air gaps between the bearing stator and rotor. In turn, the magnetic fields applied across the airgap produce a net force on the rotor. The rotor accelerates, changing its position. The sensors feed the position back as a signal level voltage. The voltage is scaled, offset, and filtered and sent to the magnetic bearing controller.

The necessary closed loop bandwidth of the magnetic bearing system depends on the flywheel module design. Our system bandwidth must be greater than 800 Hz. The bandwidth typically is limited by the actuator and power amplifier. The controller bandwidth can be an issue if a complex algorithm is used which is difficult to execute in real time. Sensors and sensor conditioning becomes a problem if severe filtering must be applied.

PROBLEM STATEMENT

This paper addresses issues that arise with the use of switching power amplifiers for magnetic bearing systems. Switching power amplifiers are more compact and have lower losses than linear amplifiers. Two drawbacks of using them for magnetic bearings are interference with electromagnetic position sensors [2] and heating of the rotor system due to induced eddy currents.

To evaluate the impact of the power amplifier on the flywheel system it is convenient to consider the current and voltage applied to the magnetic actuator in the frequency domain (Figure 3). There are three frequency bands of interest. The first is the magnetic bearing control band from DC
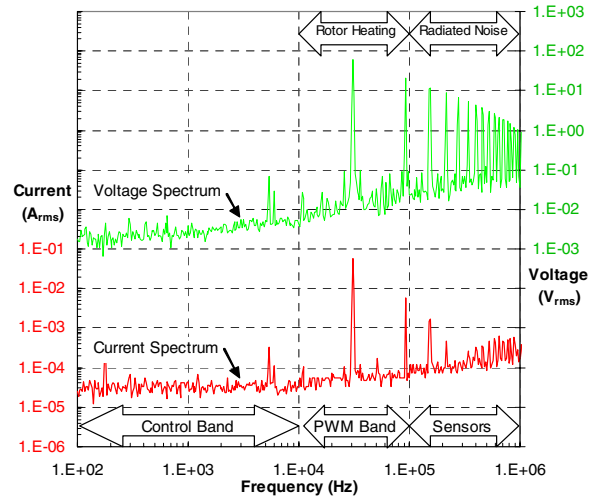
to 10 kHz. Within the magnetic bearing control band, the only currents and voltages applied should be a result of commands from the magnetic bearing controller. The second is the PWM switch frequency band from 10 kHz to 100 kHz. The fundamental switching frequency of the power amplifier falls in this frequency range. The third is the sensor modulation frequency band from 100 kHz to 1MHz. When using eddy current sensors the carrier frequency is typically between 500 kHz and 1 MHz.

The noise generated on the eddy-current position sensors results from radiated interference at the modulation frequency of the sensor. We utilize sensors with modulation frequencies of 500 kHz and 1 MHz. Our discussion will be limited to the 500 kHz sensors because they are utilized in the more sensitive control loops. Experimental data has shown that radiated PWM noise is picked up at the sensor head. The noise that occurs at the modulation frequency of 500 kHz is demodulated in the eddy current sensor conditioning electronics, reducing its frequency into the control bandwidth of the magnetic bearing. Given that the control bandwidth is 10 kHz implies that a low noise environment is required from 490-510 kHz. For example if a noise peak was present at 498 kHz it would be demodulated to a 2 kHz signal which would be well within the control bandwidth. The magnetic bearing feedback control would move the rotor in response to the noise.

Flywheel rotor heating is generated by eddy currents induced in the laminations of the magnetic bearing; this heating is generated by the switching frequency currents flowing in the magnetic bearing as well as control currents.

Eddy currents are present in both the stator and rotor of the magnetic bearing actuator. The rotor heating presents a much more significant issue in a magnetically levitated system than stator heating because the only heat transfer path from the rotor is radiation.

APPROACH

Power filters were introduced between the PWM amplifiers and the magnetic bearing actuator in order to address the position sensor interference and rotor heating issues. The remainder of the paper compares different filter designs.

Two filter topologies were studied. The first was a low pass filter. Three different corner frequencies were evaluated. The corner frequencies were 50, 100, and 400 kHz. The second topology is a low pass filter coupled with a trap filter at the switching frequency of the power amplifier. Two filters of this type were tested with low pass corner frequencies of 50 and 100 kHz. The trap frequency was 27 kHz in each case.

Filters were evaluated by driving them with two types of PWM amplifiers using an air core inductor to simulate the actuator. Spectra of the current and voltage at the load inductor were measured between 100 Hz and 1 MHz. Voltage transfer functions between the input and output of the filter were used to verify the filter topology. Transfer functions between amplifier command and current at the load inductor were used to characterize the impact on the magnetic bearing control bandwidth. Finally the DC power consumption was measured in each configuration. The power consumption of the filters was calculated by subtracting the power with the filter from the power without a filter.

Testing was conducted under two simulated magnetic bearing commands. The first was a zero input condition akin to a levitated rotor at the current zero point. The second command was a one amp, 1 kHz signal meant to simulate a rotating flywheel. This is several times the amplitude that is required to levitate a flywheel rotor at 60,000 RPM spin speed.

RESULTS

The first phase of testing was verification that the filters performed as designed. Each filter voltage input to voltage output transfer function was measured between 1 kHz and 1 MHz (Figure 4) The gain roll off of the three lowpass
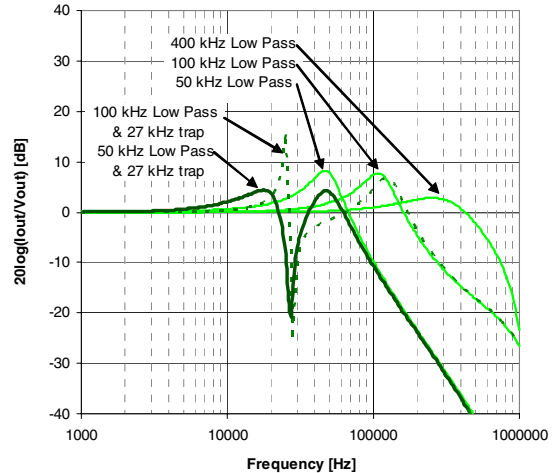

Figure 4 - Voltage out / Voltage in Filter Transfer Functions.

filters can be seen cascading down from the right side of the graph as the corner frequency is reduced from 400 kHz to 100 kHz and finally to 50 kHz. The transfer functions of the two filters which have traps are seen with attenuation at 27 kHz. The 100 kHz lowpass and 27 kHz trap (dashed line) has a significant overshoot region below the trap frequency, with approximately 25 dB attenuation at the trap frequency. The 50 kHz lowpass filter and 27k Hz trap shows some overshoot on both sides of the trap frequency with approximately 20dB attenuation. Both filters converge to their respective low pass filter transfer functions at high frequency.

Current, voltage, and power measurements were made after the filter topologies were verified. Figure 5 summarizes these results. The first lower bar graph is a logarithmic plot of the magnitude of
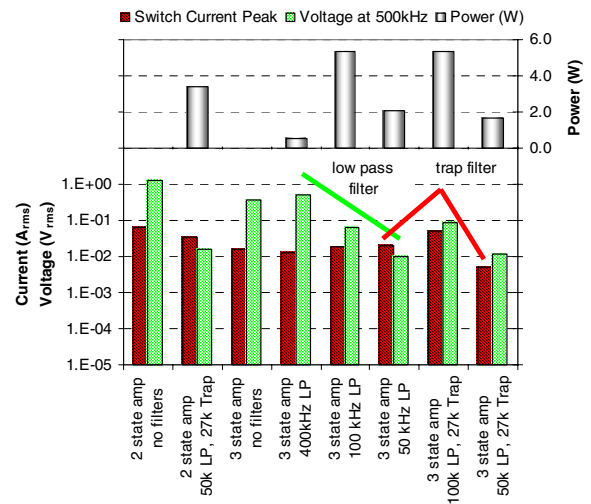

Figure 5 – Filter and Amplifier performance summary

the current at the PWM switching frequency, which was used as an indicator of eddy current heating. The second lower bar graph is the logarithmic magnitude of the voltage at 500 kHz which is used as an indicator of the interference level with the position sensors. The top set of bars is the power consumption of each filter. This was calculated by subtracting the filtered from the unfiltered power consumption.

A few trends emerge from this data. The first is that adding a trap filter reduces the currents at the switch frequency. This can be seen by comparing the 3 state amplifier, 50 kHz low pass data with and without the trap filter. The trap filter does not have the same benefit with the 100 kHz filter. This result is misleading because the trap filter resonates with the particular 100 kHz filter implementation used for this experiment (Figure 4). Another trend is the reduction of high frequency noise as the low pass filter frequency is reduced. This is illustrated in the 3 state amplifier data with the 400, 100, and 50 kHz low pass filters. Trends in the filter power consumption data are less clear because the specific implementations of the filters were done somewhat differently. Clearly some power will be used in the filter; however reduced magnetic bearing noise may balance some of the losses. Additional work will be done to determine the net power use in a flywheel module application.

PWM Amplifier Switching Methods

Two types of magnetic bearing Pulse Width Modulation (PWM) amplifiers were tested in order to determine which one generated the lower amount of noise at the switching frequency of 27 kHz. The two types of amplifiers have an identical full bridge power stage topology (Figure 6). The difference lies in their switching scheme. The first type is a 2 state amplifier, where the conduction of positive or negative current is controlled by controlling the duty cycle of the positive and negative "leg" of the full bridge.
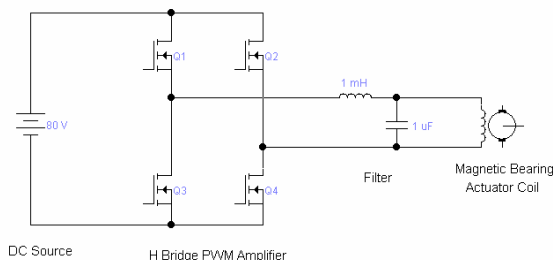
In this operating regime, the amplifier will generate a voltage that switches to the positive and negative source rail during each switching cycle. This holds true even when the current command is 0 Amps. The objective of continuous switching, even at zero amps, is to make the transition from positive current to negative current as smooth as possible. The second type of amplifier is the three-state switching, where the control of positive current is performed by switching the amplifier positive leg only and the control of negative current is performed by switching the negative leg only. In this regime, the amplifier will generate a voltage that switches between zero and positive source rail for positive current, or between zero and negative source rail for negative current. The advantage of this switching scheme is that there is no switching (all the bridge switches are OFF) when the current command is zero. From the system noise perspective, this is very attractive since the zero current point is the typical operating scenario for a levitated rotor under balanced conditions.

Figure 7 compares the two amplifiers output current spectra when the current command is zero amps and the amplifiers output terminals are connected to an air core inductor. The air core inductance value is 6.8mH, an inductance value similar to the inductance of the magnetic bearing actuator coil. The amplifiers were tested without a filter. Clearly, the two-state amplifier shows a dominant frequency component at the switching frequency of 27 kHz and higher order harmonics. This component is absent or significantly reduced in the spectrum of the three-state amplifier that is also switching at 27 kHz.
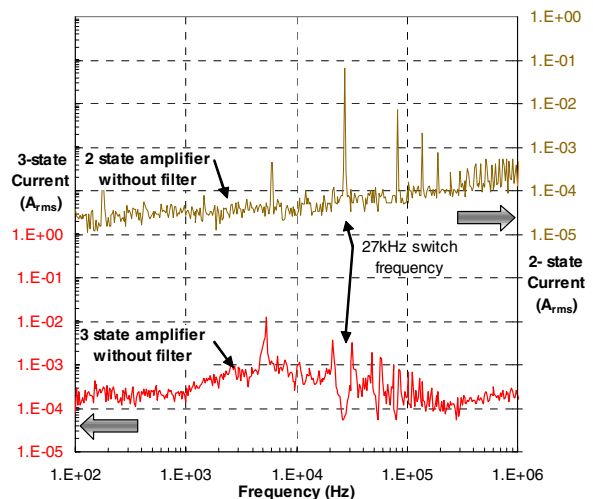

Figure 7 - Two-state vs. Three-state PWM amplifier Current Spectrum with Zero Amps command (No filter)

Figure 6 - PWM amplifier and filter topology

Voltage Spectra for the two amplifiers operating under the same conditions are shown in Figure 8. The upper chart line in Figure 8 shows that the two-state amplifier voltage spectra contain approximately 50 V_{rms} component at 27 kHz. The spectrum also shows noisy behavior in the range from 100 kHz to 1 MHz. In contrast, the lower chart line in Figure 8 shows the three-state amplifier voltage spectrum where the component at 27 kHz is well below the 5 V_{rms} mark. The
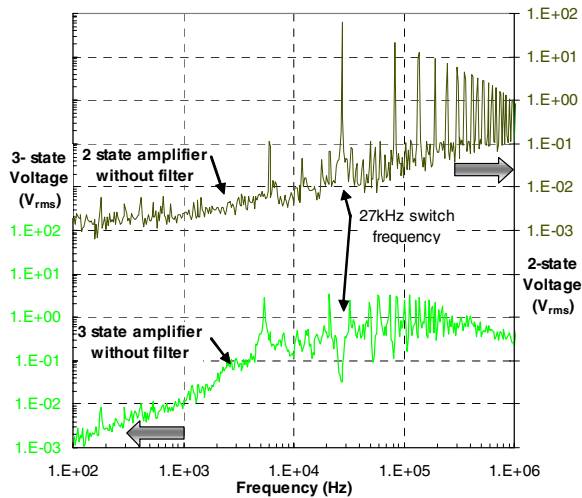

Figure 8 - Two-state vs. Three-state PWM amplifier Voltage Spectrum with Zero Amps command (No filter)

measured noise in the frequency range between 100 kHz and 1 MHz is also considerably lower, reaching levels lower than the 0.5 V_{rms} mark at 1MHz. In terms of power consumption, tests revealed that input power into the two types of PWM amplifiers was significantly different at zero current command. The three-state amplifier showed an input power consumption of 1.73W, for the zero amp command, and 3.93W for the 1 amp peak-to-peak current command test condition. On the other hand, the two-state amplifier showed a power consumption of 3.31W, for the zero amp command, and 4.32W for 1 amp peak-to-peak current command test condition. Therefore, as expected, the three-state amplifier requires less input power for a zero current command because there is no switching action at this operating condition. The power difference is not as dramatic for the 1 amp peak-to-peak current command because, at this operating point, both amplifiers will be switching.

Performance of the Selected Combination of filter and PWM Amplifier

Combinations of amplifiers and filters were tested to find the best combination of low power use, small switch frequency currents, and low noise at the position sensor frequency of 500 kHz.

Figure 5 compares the results of the current and voltage frequency content measurements and also compares the power losses for the different amplifier and filter combinations tested. Careful examination of these results reveals that the best option in terms of filter performance and power consumption is the three-state PWM amplifier in combination with the 50 kHz low pass filter and the 27 kHz trap filter. This combination has the lowest switch frequency current component and second lowest 500 kHz voltage component with low power consumption.

Figure 9 shows the schematic diagram of the selected filter. The 700 uH inductor and the 0.047 uF capacitor provide the 27 kHz trap or band reject filter, and the 1mH inductor and the 0.01uF capacitor provide the 50 kHz low pass filter. The 390 ohm resistor and 0.033 uF capacitor provided damping.
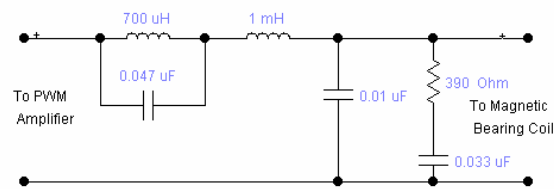

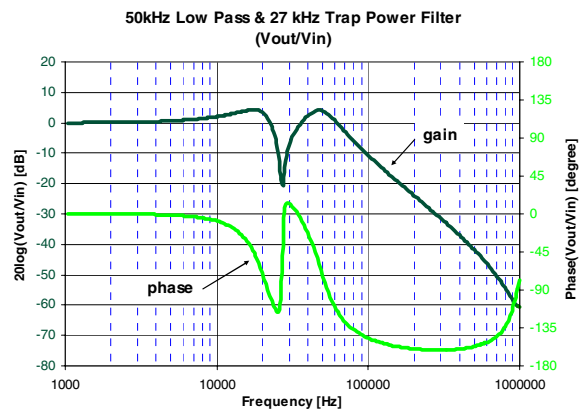Figure 9 - Circuit schematic of selected 27 kHz trap and 50 kHz Low Pass filter

Figure 10 - Measured Transfer Function for Selected Filter [20*log(V_{out}/V_{in})] in decibels and degrees

Figure 10 shows the tested voltage transfer function of this filter. For our tests, the trap filter was finely tuned to provide maximum attenuation at precisely 27 kHz. Similarly, the PWM amplifiers were synchronized with an external oscillator to operate with a switching frequency of exactly 27 kHz.

Figure 11 shows the comparison of the current spectra between the unfiltered two-state PWM amplifier and the synchronized three-state amplifier with the 27 kHz Trap and the 50 kHz low pass filter. The current command for this condition was 0 amps. The spectra show that the combination of the three-state amplifier and the selected filter is very effective in reducing the switching frequency noise in the current flowing in the magnetic bearing coils.
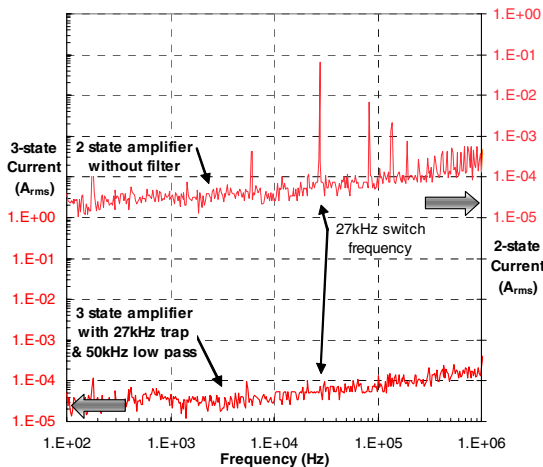

Figure 11 – Current Spectrum of Two-state amplifier with No filter vs. Three-state amplifier with 27kHz trap and 50kHz low pass filter with Zero Amps command

Figure 12 also shows a drastic reduction of switching noise in the voltage from the PWM amplifiers at 0 amp command. This reduction is evident in both the switching frequency and also in the frequency range from 100 kHz to 1 MHz. Low noise in the frequency range around 500 kHz, as explained previously, is extremely important to reduce the radiated emissions that can be picked up by the magnetic bearing position sensors.

Figure 13 shows the current spectra when the current command into the PWM amplifiers is 1 amp peak to peak with a frequency of 1 kHz. This command frequency is well under the control bandwidth of the PWM amplifier, and well under the effect of the trap and low pass filter as can be observed in Figure 10 and Figure 15. The 1 Amp peak-to-peak command is intended to simulate
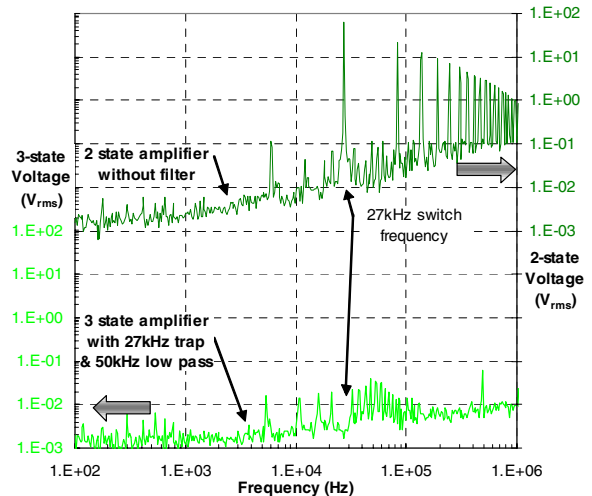

Figure 12 – Voltage Spectrum of Two-state amplifier with No filter vs. Three-state amplifier with 27kHz trap and 50kHz low pass filter with Zero Amps command

the load that the amplifiers supply when levitating a rotating flywheel. The current spectra show the large component that corresponds to the 1 kHz command. Examination of the current spectra for the two configurations reveals a significant reduction in the 27 kHz noise measured in the current of filtered three-state amplifier.
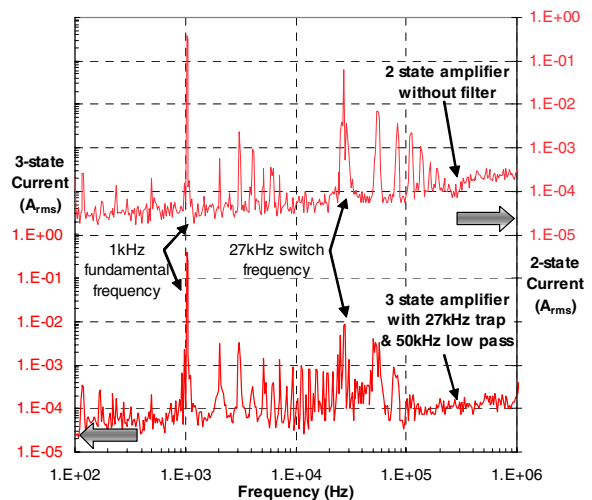

Figure 13 – Current Spectrum of Two-state amplifier with No filter vs. Three-state amplifier with 27kHz trap and 50kHz low pass filter with 1 kHz, 1 Amp p-p command

The voltage spectra for these two configurations in Figure 14 reveal not only a reduction in the 27 kHz noise from the switching action, but also a considerable reduction in the
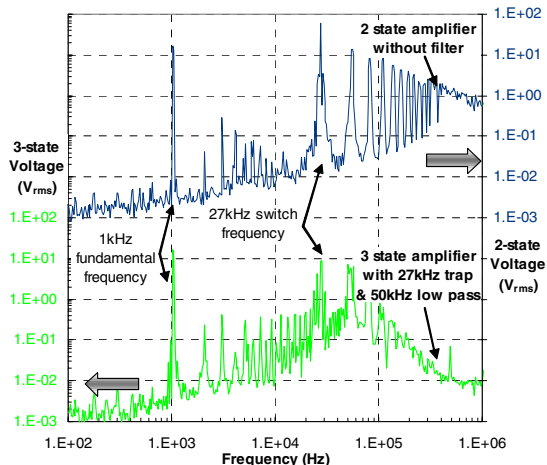
Figure 14 – Voltage Spectrum of Two-state amplifier with No filter vs. Three-state amplifier with 27kHz trap and 50kHz low pass filter with 1 kHz, 1 Amp p-p command

noise floor in the frequency range from 100 kHz to 1 MHz. This is logically the effect of the 50 kHz low pass filter.

Transfer function Bode plots were generated by test in order to characterize the frequency response of the PWM amplifiers with and without filters. The objective was to verify that the use of the filter does not reduce the PWM amplifier control bandwidth below 1 kHz, and also to verify that the filter does not introduce a phase lag higher than 45 degrees below 1 kHz. Figure 15 shows Bode plots for the two-state amplifier with no filter and the three-state amplifier with the 27 kHz trap and the 50 kHz low pass filter. The

upper chart line Figure 15 shows the phase response while the lower chart line shows the gain. The filter reduces the gain bandwidth from 5 kHz to approximately 4 kHz, and the 45 degree phase lag point is still greater than 1 kHz. The transfer function was generated with the ratio of the command signal voltage and the amplifier output current. The formula is [$20log(V_{com} / I_{out})$]. These Bode plot tests clearly demonstrate that the control bandwidth requirements for the magnetic bearing actuators are still met with the three-state amplifier and the selected filter.

Command	Two-State Amp No Filter	Three-State Amp and 27 kHz Trap and 50 kHz Low Pass Filter
0 Amps	3.31 W	1.90 W
1 Amp p-p	4.32W	5.57 W

Table 1. Power Consumption Comparison of Two-State Amplifier with No filter, and the three-state amplifier with Low Pass and Trap Filter

In terms of power consumption, Table 1 considers the power consumption of the two-state amplifier with no filter, and the power consumption of the three-state amplifier with low pass and trap filter. As expected, the zero amp current command requires lower power when the three-state amplifier is used. On the other hand, the filter represents a power penalty when the amplifiers are operating with a 1 amp peak to peak current command. The rationale for selection of the filtered three-state amplifier lies in the fact that the zero amp command condition is more typical and characteristic of the steady state operating scenario for the magnetic bearing with a balanced flywheel. Under these circumstances, the filter power penalty can be accepted for transient nonzero current command conditions.

CONCLUSIONS

Several power filter and amplifier combinations were evaluated to determine the best topology for an active magnetic bearings system for flywheels. Each system was evaluated based on current magnitude at the switching frequency, voltage magnitude at 500 kHz, and power consumption. Test data was taken at two conditions, zero amps commanded and 1 amp at 1 kHz commanded.

Several observations were made. The three state amplifier had reduced switching currents, high frequency noise, and power consumption compared to the two state amplifier. Addition of
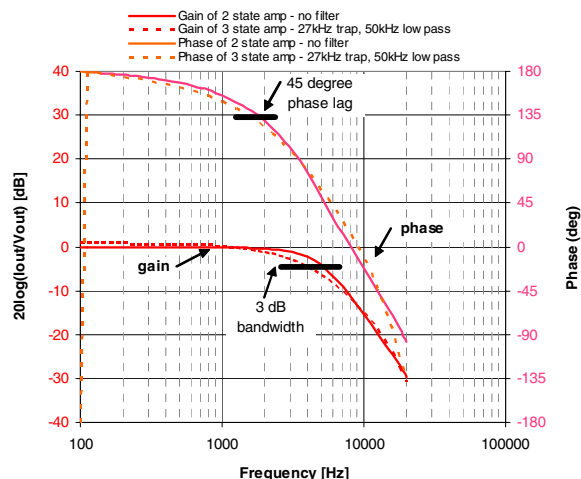

Figure 15 – Iout/Vcommand Transfer Function of Two-state amplifier with No filter vs. Three-state amplifier with 27kHz trap and 50kHz low pass filter with 1 Amp p-p command

low pass filters reduces high frequency noise. Adding a trap filter reduces the magnitude of switching frequency current. The addition of the filters uses some power.

The base line system was a two state amplifier without a power filter. The recommended system is a three state power amplifier with a 50 kHz low pass filter and a 27 kHz trap filter. This system consumed 1.90W which is 60% of the energy of the base line system under the zero amp command. Under a 1A, 1 kHz command the recommended system consumed 5.57 W which is 130% of the baseline. Since typical operation is closer to the zero amp condition, the recommended system will reduce average power use. The baseline system has a switching current magnitude of 62.9 mA compared to 4.9 mA for the recommend system under a 1A, 1 kHz command. With the same test conditions the baseline system has 1.25V of noise at 500 kHz compared to 0.012V for the recommended system.

Changing from the base line to the recommend system will reduce the switching current by an order of magnitude, the 500 kHz voltage by two orders of magnitude, and the average power consumption. The flywheel system will be more efficient, cooler operating, and more stable as a result.

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Ramon C. Lebron-Velilla, Ralph H. Jansen, Alan Palazzolo, Erwin Thomas, Peter E. Kascak, Arthur G. Birchenough, and Timothy P. Dever

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