

# DIGITAL SPINDLE DRIVE TECHNOLOGY ADVANCEMENTS AND PERFORMANCE IMPROVEMENTS

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## INTRODUCTION

Industry requirements for improved Air Bearing Spindle performance and control have resulted in the development of alternatives to the traditional Analog PLL Control architecture. Although PLL systems provide very high performance in narrow RPM ranges, they have inherent limitations when implemented as a universal solution. Often these limitations become as much of a hindrance as the high performance is a benefit.

Recent advances in Digital Control Systems commonly known as Digital PID or PID control systems have eliminated many of the disadvantages of the common PID based control system in spindle applications. These new AdvancedPID™ or APID control systems allow digital based controls to rival PLL based spindle controllers in many applications.

This paper will review 3 years of research and development in spindle control systems and discuss the latest capabilities of these control systems in the specific area of low jitter velocity control.

## EXPERIMENTAL SETUP

Development of the APID spindle controller was done using air bearing spindles from the leading companies in the field. Experiments were performed on:

- ABT "Air Bearing Technology – KLA Tencor" 3 inch and 4 inch air bearing spindles
- Surface Engineering 3 inch air bearing spindles
- NEAT – Danaher 3 inch air bearing spindles
- Westwind 3 and 4 inch air bearing spindles

Data was also collected with an ironless Thingap motor powering a Surface Engineering spindle. Velocity jitter performance was in line with the other spindles, however, we believe the Thingap motor's biggest benefit will come from radial run out improvements not discussed in this paper.

Initial testing resulted in widely varying velocity stability between spindles of the same model. Further analysis determined that the air input orifices were adjusted differently on some serial numbers. This small difference dramatically affected the velocity jitter performance. Minor differences in commutation initialization also had an affect on velocity stability.

Although the different manufacturers and models performed similarly, they all exhibited the same characteristics discussed below. These results allowed us to focus our research on the control model verses the spindle. All the results discussed below came from tests done on a single serial number of a specific model spindle. Air pressure, motor, and encoder feedback were unchanged for all tests.

Commonly available encoders are limited to 100 kHz maximum response frequency. This presented a problem when tests included speeds higher than this limit. A few encoder manufacturers can provide 300 kHz to 500 kHz versions. These were necessary to allow higher than 512 line count encoders to be used. The higher line count was desirable to maximize the quadrature rate fed to the APID controller. Interpolation rates larger than the basic 4 quadrant decode were avoided to preclude the inherent quadrature bursting which occurs at high speeds.

Jitter measurements were done using two tools. An HP5371A Frequency and Time Interval Analyzer with 150ps edge timing capability and a custom jitter analyzer built into the test system. The HP5371A was used to verify the results of the custom jitter analyzer prior to using its data. The Fine RPM resolution plots are from the custom analyzer. The Coarse RPM resolution plots are from the HP5371A analyzer. Data results from the HP5371A analyzer were collected by hand. This was a time consuming process on coarse resolution tests and was

abandoned once the custom jitter analyzer was proven to be accurate. Automating the data collection process allowed testing to proceed more efficiently.

Each measurement consisted of the time between consecutive index pulses. The jitter metric was calculated by taking the standard deviation of groups of 500 consecutive measurements.

Spindles were mounted in a common testing structure with minimal isolation. This test structure was chosen to mimic the real world environment of air bearing spindles used in manufacturing.

The C-2100-D01 Control system was chosen as the test bed for the spindle velocity jitter comparisons due to its integrated signal and communication interface to the custom jitter analyzer. The C-2100-D01 controller also incorporated our latest generation, sinusoidally commutated, high power linear 3 phase servo amplifiers.

For this discussion spindle run out data is not reviewed, and will be released in a future paper.

### CONTROL SYSTEM

Traditional PID control when viewed from a system level has two major flaws. One of the flaws is common with PLL based systems; the other is unique to Digital Control loop architectures.

The first flaw is present on any system using a DC servo or Trap drive approach to commutate the 3 phase brushless motor. DC servo or Trap Drives only flow current through 2 of the 3 phases at any one time. Each time the drive energizes a new set of phases it introduces a torque ripple, affecting the spindle velocity. Historical PLL systems running in a DC drive mode have the same inherent ripple currents affecting velocity stability as these early PID control systems. *Figure 1* below highlights the ripple effect which is the first major flaw with older PID controllers. The advantages of AC servo, sinusoidal commutation, over DC servo control are widely known, so no further discussion is necessary here.

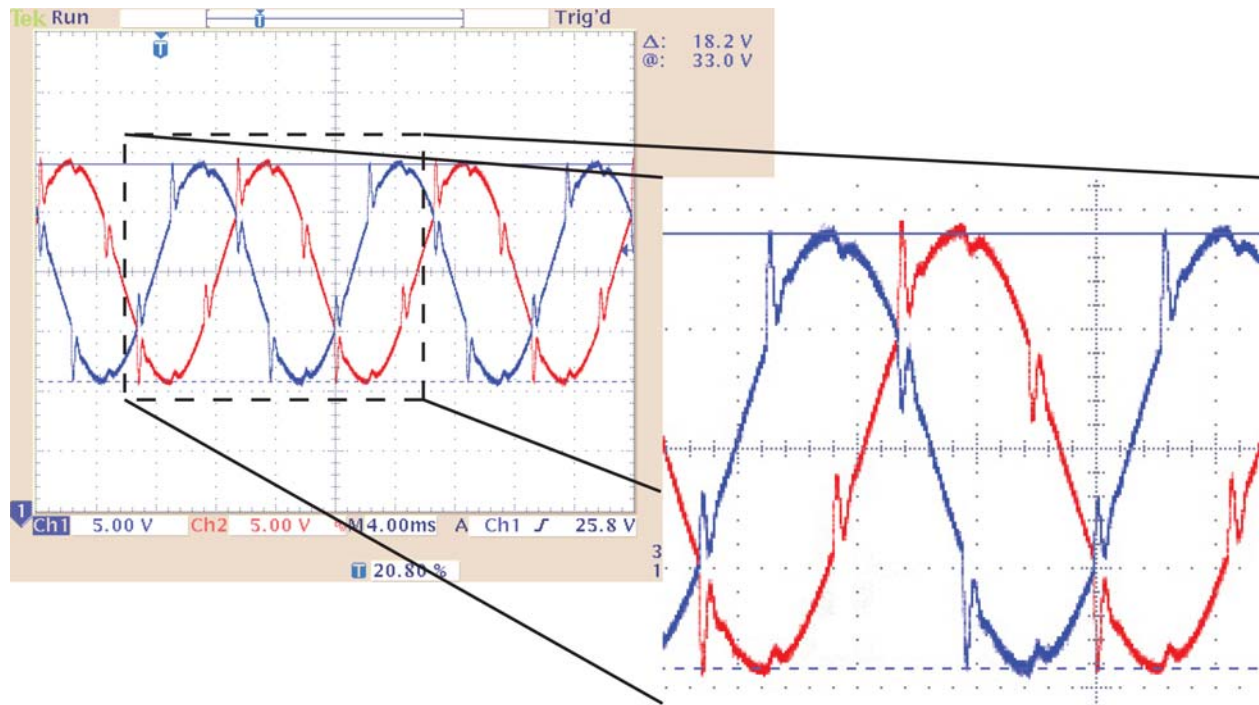


Figure 1.

The second flaw of the traditional PID control system is a result of the inherent quantization in digital based systems. A perfect system is one where there are always an integral number of encoder counts moved for each servo cycle in the control loop. In a real system, the encoder rate is usually not an integral multiple or factor of the servo frequency. This difference creates a beat frequency in the number of counts traveled per cycle. The response to this can be seen as increased jitter.

Figure 2 illustrates how the position traveled per servo cycle changes when the commanded

speed is not an integral number of counts per servo cycle. Further study showed that jitter produced by different beat frequencies varied considerably.

Figure 3 is a benchmark of a traditional PID controller and its quantization based jitter over a coarse range of velocities. This plot shows the system barely passing a 0.0005% standard deviation error test. It displays measurements taken at speeds from 1000 RPM to 15,000 RPM in 500 RPM increments.

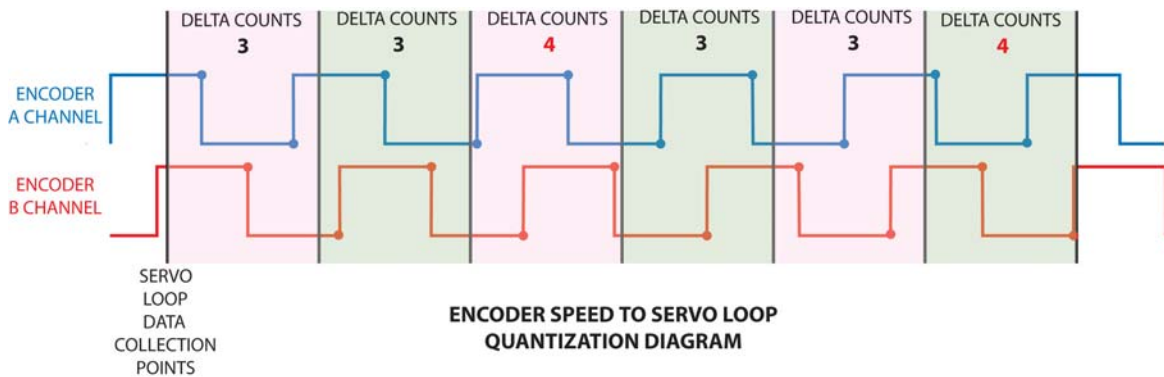


Figure 2.

TRUST TA2100-D01 CONTROLLER  
500 RPM INCREMENTS

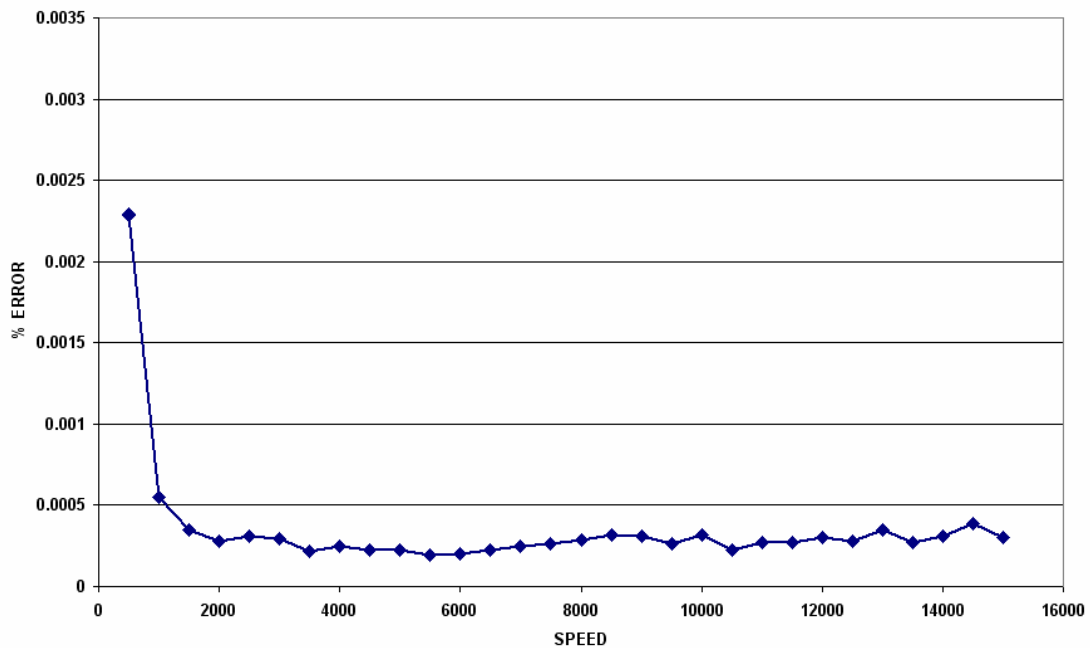


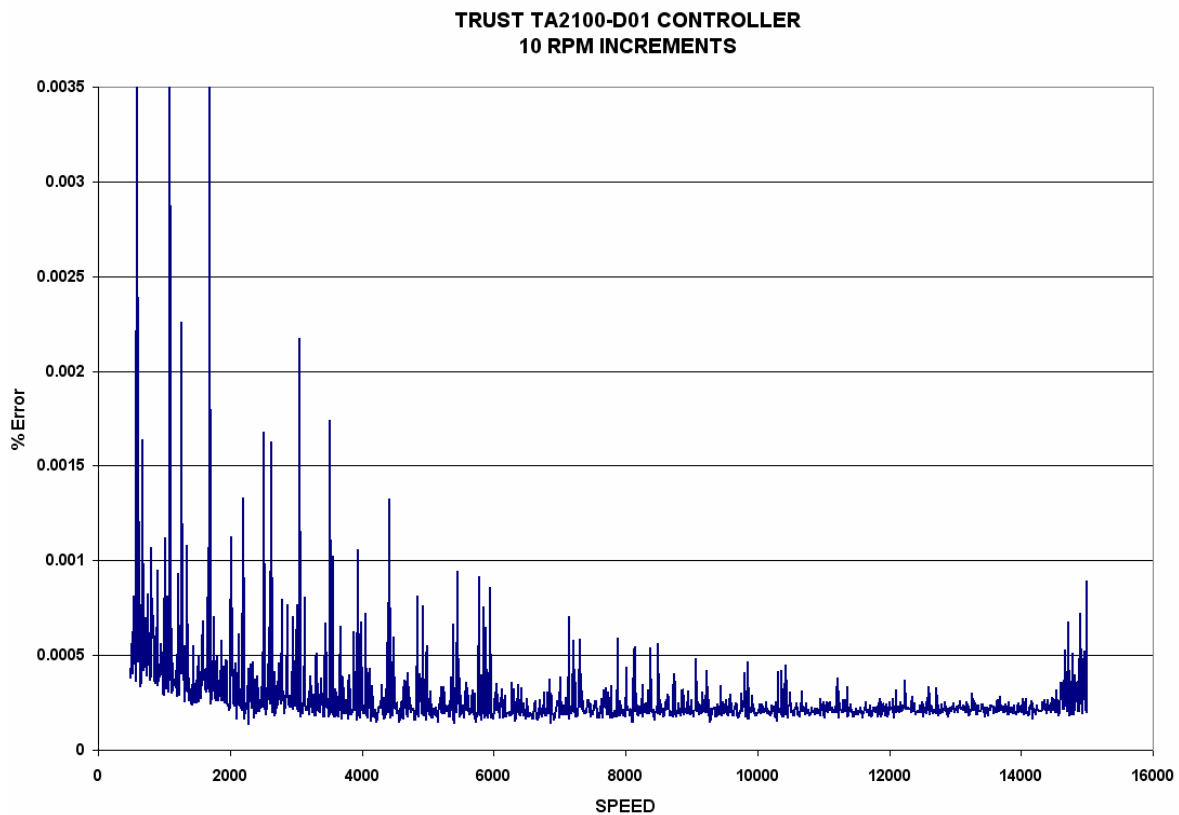
Figure 3.

As you can see, the jitter appears very consistent with a coarse 500 RPM step between measurements. This initial result was very encouraging for maintaining the current control scheme. The velocities chosen happened to avoid any gross problems. More detailed tests done later in the development process showed the quantization errors much more clearly.

During the research occasional instability problems lead us to take a much more detailed stability plot. These time jitter measurements were taken in 10 RPM increments in velocities ranging from 500 – 15000 RPM. The results showed a complete lack of stability below the 0.0005% target. *Figure 4* shows one of the initial Fine RPM plots at a 10 RPM increment. Resulting research showed that the traditional PID control system had artifacts resulting from quantization. This conclusion launched a

research effort to modify the traditional PID control system and develop an APID control algorithm specifically for air bearing spindles and their related nuances.

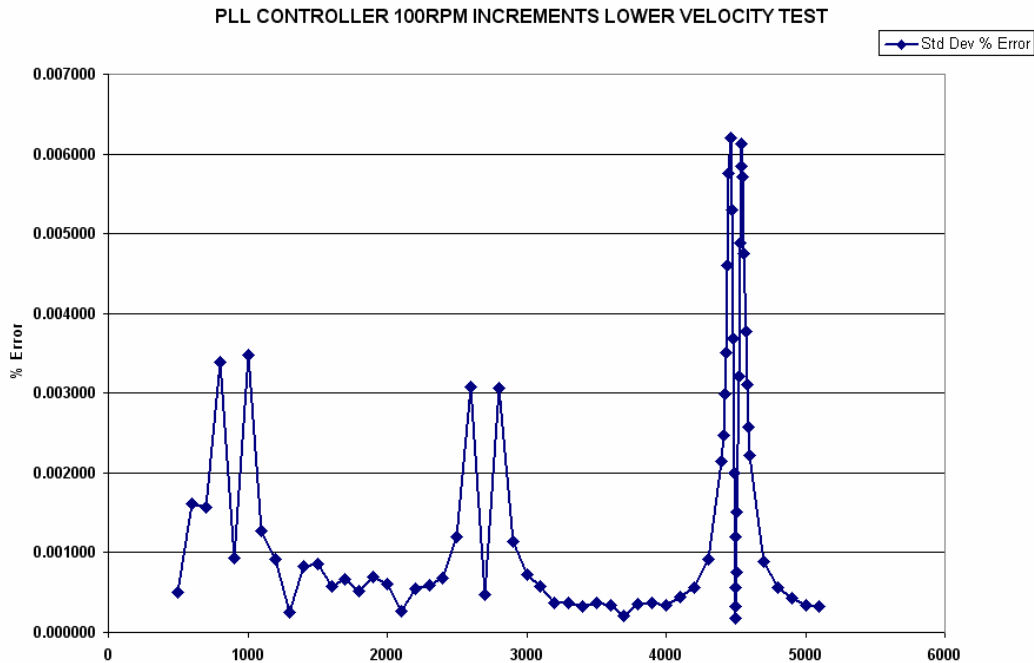
As a note, analog PLL based control systems also have quantization problems. Research was done on PLL based systems during the development of the APID control system. This insight to PLL Control System limitations was one of the factors relating to further development of an APID system instead of a PLL approach. PLL based control systems are tuned through analog filters. Ideal electrical characteristics can be achieved when the PLL is kept to the electrical domain. However, once a mechanical system is introduced, the PLL becomes susceptible to all the issues related to mechanical systems.



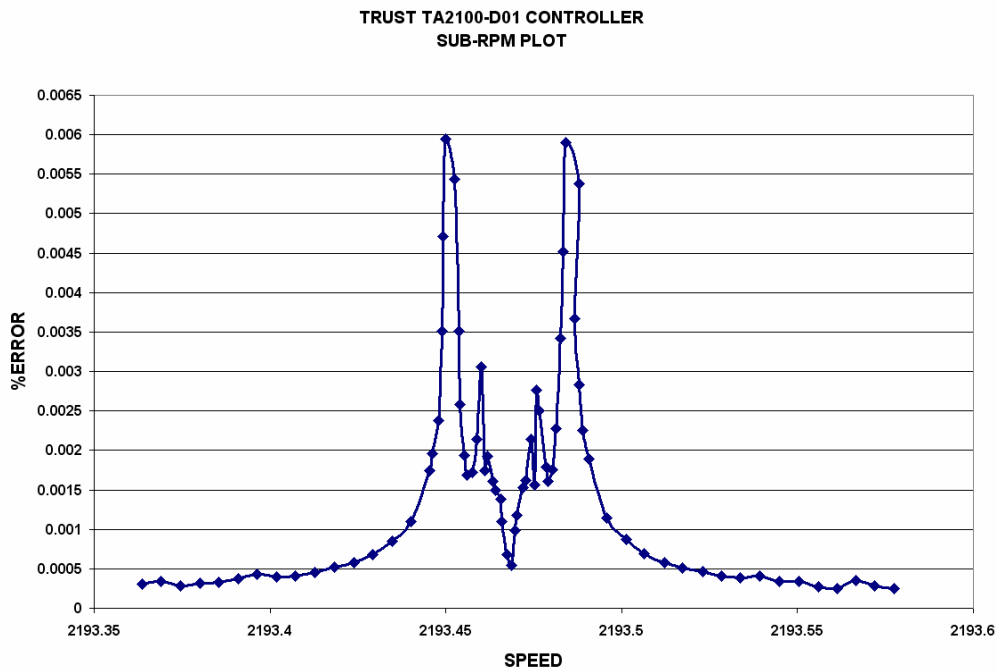
*Figure 4.*

Quantization jitter in the case of the PLL control system is a result of filtering and loop tuning for a broad RPM range. If the RPM requirement was maintained over a narrower range the system is very successful at low velocity jitter control. *Figure 5* shows plot data from a limited RPM test done with an analog PLL based

system. This characteristic double peak signature is common with PID control quantization. However in the PID control system the frequency of the patterns is much higher and they occur in very tight RPM ranges as can be seen in *Figure 6*.



*Figure 5.*



*Figure 6.*

Development of the APID Digital control loop was needed to minimize the velocity jitter caused by quantization of the encoder data by the DSP processor. This quantization is the result of the trajectory engine working in floating point numbers while the encoder works in integral numbers. A beat pattern where the fractions numbers cyclically transition the error value into an additional integer number in error then back to the original error is the cause of the problem. The jitter is worse the more often this pattern occurs. The location and frequency of the pattern are affected by both the velocity of the spindle and the update rate of the digital control loop.

A perfect system is one where there are always an exact integer amount of encoder counts for each servo cycle in the control loop. This perfect balance produces minimal servo loop quantization disturbances and only spindle or environmental disturbances effect the possible velocity stability of the system. In this balanced state, performance better than 0.00005% can be achieved.

Since a production or manufacturing environment requires both speed and load flexibility keeping a system to a narrow set of constraints is not practical. However, the APID Digital control system can overcome or diminish

many of the limitations of the traditional PID control loop and rival or exceed the performance of the analog PLL based system because of its flexibility. One of the big advantages we found with using the APID controller is that it can be adapted to different spindle and motor combinations without needing hardware related changes. Only software parameter changes were necessary to obtain similar performance results.

The research and development performed during the C-2100-D01 spindle development outlined many intuitive benefits of a Digital APID control loop. These advantages are outlined below, not in any order of importance.

- Adjustable control loop update rate
- Adjustable / different gains can be used and modified on the fly
- Trajectory profiles which do not follow a traditional trapezoidal or S curve shape are possible
- Low and Very Low RPM spindle control
- Spindle position control or indexing
- Highly coordinated interaction between the spindle and other axes

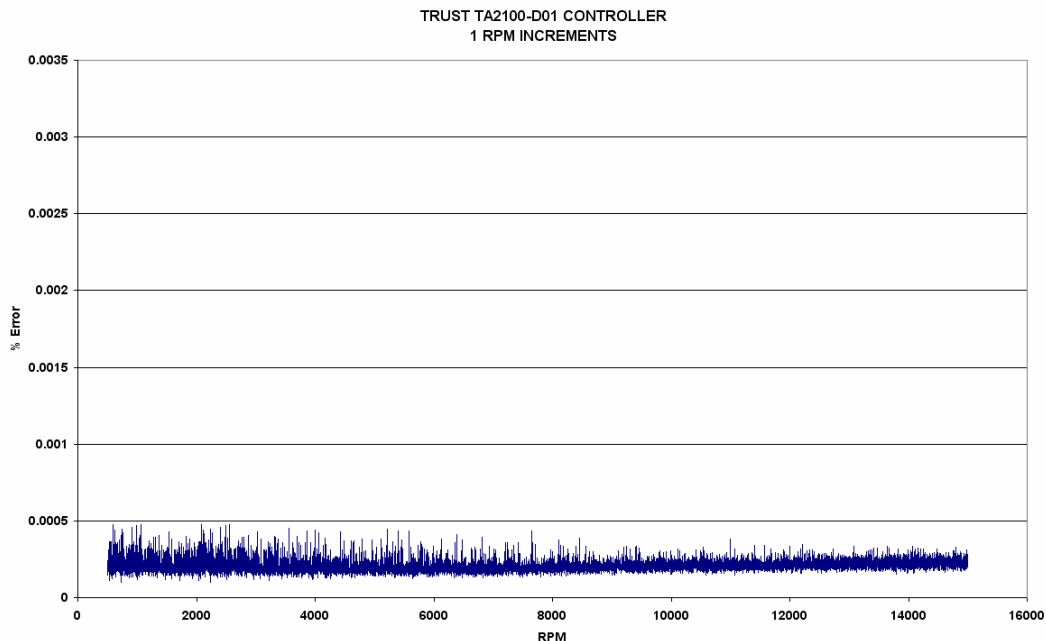


Figure 7.

The non-intuitive benefit of the APID control loop was realized by optimizing the magnitude of the error signal when the cyclical error value changes and by providing a method to average out this disturbance over a long time period so an immediate electrical bump to the spindle does not occur.

We found that using the BiQuad filters in a low pass mode and limiting the magnitude of the corrective signal a high level of velocity stability is achievable. The plot of the APID controlled spindle still shows areas of decreased velocity stability, but there is a dramatic improvement over a traditional PID control system. (See *Figure 7*) The overall spindle performance was better than the 0.0005% target for the system over the 500 – 15000 RPM speed range.

### **CONCLUSION**

Our research showed that even analog PLL based systems can have velocity jitter issues unless they are setup specifically for a spindle

and speed range. Even in these conditions, changes of the load on the spindle will result in poor performance in specific quantization ranges.

By developing the AdvancedPID™ algorithm (APID) which is tailored to air bearing spindle applications, velocity performance numbers similar to PLL based systems when fully optimized are achieved over a wide speed range. Industry requirements for spindle velocity jitter less than 0.0005% are no longer difficult to achieve with either an Analog PLL based system or an APID™ Digital control system. The benefits of the APID system however are improved flexibility for the application, easy conversion to different loads, motors or spindles and enhanced positioning capabilities.

With the APID control system all of the benefits of a digital PID servo system can be combined with most of the benefits of an Analog PLL based system.