Vacuum Compatible, High Speed Air Bearing Chopper

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Abstract

Third generation synchrotron sources such as the Advanced Photon Source (APS) and the European Synchrotron Radiation Facility (ESRF) have enabled deeper investigation into the dynamic structure of matter using time-resolved X-ray crystallography. Traditional X-ray diffraction techniques provide a static view of the atomic structure. Time-resolved X-ray crystallography can provide insight into the mechanisms of molecular function by capturing images of intermediate structures. To see the molecules in action, the reaction is initiated and the dynamic behaviour of the molecule is recorded using short X-ray pulses. The use of a low-jitter air bearing chopper spindle in a vacuum, driven by a frequency-locked speed control has enabled a new generation of scientific experiments at synchrotrons worldwide.

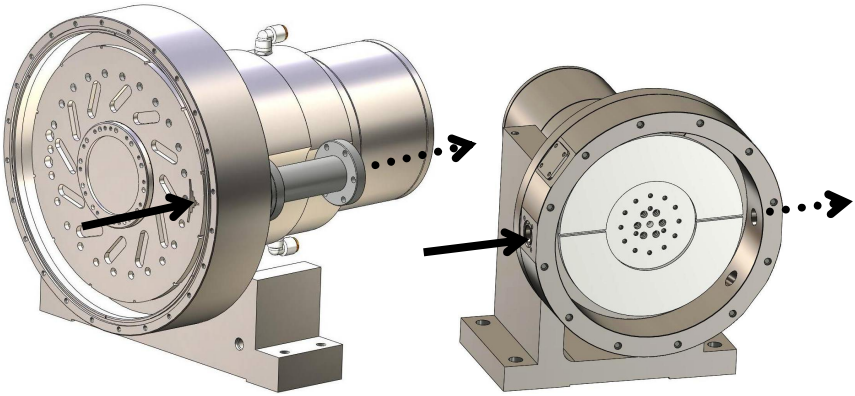
1 Fast mechanical choppers

A chopper assembly typically consists of a motorized spindle with rotary encoder, a vacuum chamber, and a slotted disk as a shutter. Choppers were commonly used to isolate pulses of neutrons when Schildkamp and Pradervand designed the first high-speed X-ray chopper using a spindle with rolling element bearings in 1988 [1]. Subsequently, high speed choppers have continued to enable various synchrotron experiments including X-ray imagining to study the velocity and structure of fuel injection sprays [2]. Gembicky et al. described the use of a precision air bearing spindle with ±3σ jitter of less than 2 ns for speeds up to 30,000 RPM [3]. Safety must be a high priority when operating choppers with large disks rotating at high speeds approaching material strength limits. Gembicky and Coppens have shown that to obtain short window opening times with a high disk peripheral velocity, it is advantageous from a kinetic energy standpoint to use a small disk at a high rotational velocity rather than a larger disk at a lower rotational velocity [4].

2 Chopper spindle design considerations

Owing to their low error motions and torque ripple, precision air bearing spindles are the ideal choice for choppers. Despite the common misconception that air bearings are not vacuum compatible, staged capillary seals can be used to provide vacuums down to 10^{-6} Torr. Rolling-element and magnetic bearings can be used, but they typically have greater error motion than air bearings. Furthermore, a typical air bearing spindle will be more cost effective with reduced complexity compared to a magnetic bearing spindle. A rolling-element bearing will typically require lubrication and will generate debris that could be detrimental to the vacuum system.

The air bearing chopper spindles shown in Figure 1 have been used for heat load reduction of high intensity X-rays (Figure 1.a) and isolation of short-pulse X-rays (Figure 1.b). In the case of the parallel configuration heat-load chopper, temperature-controlled deionized water is circulated through channels in the continuously rotating disk. A fluid rotary union with an air bearing capillary seal supplies the water to the rotating components. The heat load chopper disk fully blocks an 800 W, 2 mm diameter, 7-20 keV white beam and reduces the heat load on downstream optics.



a) *b)*

Figure 1: a) Water-cooled heat load chopper with vacuum chamber partially removed; spindle axis parallel to X-ray beam. b) High-speed chopper with vacuum chamber partially removed; spindle axis perpendicular to X-ray beam.

The long-term stability of the high speed air bearing chopper spindle shown in Figure 1.b is evaluated in this work. The spindle under test is a captured thrust, groove compensated air bearing spindle with vacuum chamber integral to the housing (Model

ISO-2RCH, Professional Instruments Company, Minnesota, USA). A frameless motor and encoder is mounted directly to the rotor of the air bearing spindle.

3 Speed stability evaluation

This paper demonstrates a new technique for jitter measurement of an air bearing chopper spindle. Often, speed stability is evaluated by measuring the time elapsed between consecutive index pulses of the rotary encoder. For synchrotron applications, the long-term stability between the reference frequency and rotational frequency should be evaluated over thousands of revolutions, and will typically include sub-harmonic variations that may not be captured by the single revolution jitter test.

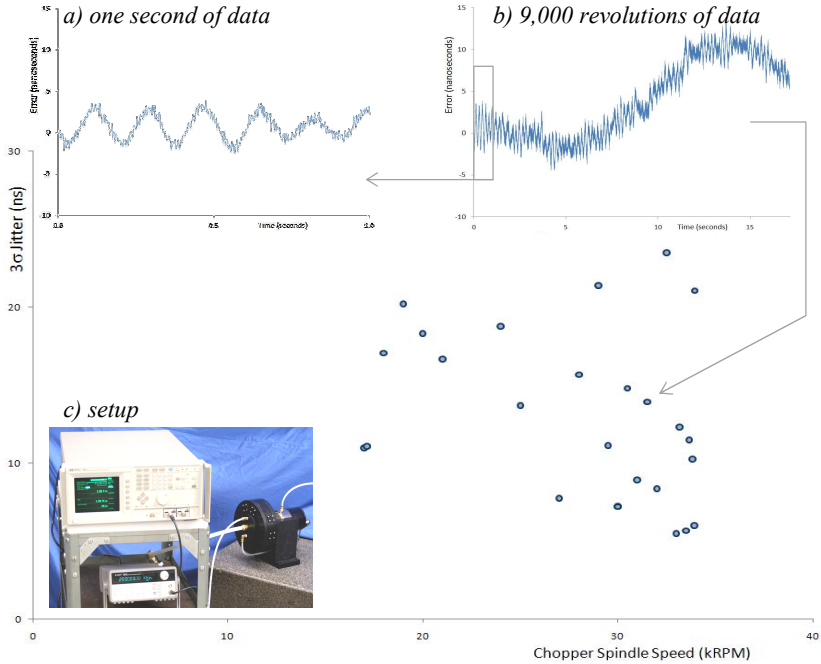


Figure 2: Three times the standard deviation (3σ) of the period error accumulated over 9,000 revolutions. The maximum 3σ error is 25 ns from 17,000 through 34,000 RPM. The insets include a) accumulated error at 31,500 RPM over one second, b) accumulated error at 31,500 RPM over 9,000 revolutions, and c) the setup.

The spindle in Figure 1.b is driven with a brushless DC motor and a linear amplifier using Frequency Lock Velocity Control. An HP 33120A Function Generator is used to simulate the synchrotron reference signal while recording the period of revolution with the HP 5371A Time and Frequency Analyzer (150 picosecond RMS single shot

resolution). The accumulated period error is measured over 9,000 revolutions over a speed range from 17,000 RPM to 34,000 RPM. The vacuum chamber is evaculated to a partial vacuum of approximately 10 Torr. The results of the test demonstrate that the long term speed stability is better than 25 nanoseconds 3σ as shown in Figure 2. Note that a 600 µm wide slot on a 140 mm diameter perpendicular disk rotating at 34,000 RPM has an open window time of 1,203 ns. The inset trace of Figure 2.b illustrates a typical result for long-term stability at 31,500 RPM. There are two sub-harmonic components of variation that would typically be neglected using the single revolution jitter evaluation method. The 5.6 Hz variation with 4 ns PV amplitude illustrated in Figure 2.c is thought to be a result of control tuning and is critically important in synchrotron applications. The 0.05 Hz 17 ns PV component however, is assumed to be an artifact of the test setup—the spindle is mounted to a floor-supported, massive granite base which uses a passive air isolation system.

3 Conclusions

Design considerations and test results for a low jitter air bearing chopper spindle with integral vacuum chamber are described. Parallel and perpendicular configurations of the fast mechanical chopper are currently in use for a variety of beamline experiments. A new technique for jitter measurement is introduced which captures the long-term stability of chopper spindle speed. The accumulated period error over 9,000 revolutions is found to be better than 25 nanoseconds 3σ over a speed range from 17,000 RPM to 34,000 RPM.

References:

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