euspen's 23rd International Conference & Exhibition, Copenhagen, DK, June 2023
www.euspen.eu

Design considerations for a high speed X-ray chopper

Byron Knapp, Dan Oss, and Dave Arneson

Professional Instruments Company, Hopkins, Minnesota, USA

bknapp@airbearings.com

Abstract
Design considerations are presented for an air bearing chopper operating in vacuum with low jitter at high speed. The chopper is used for time-resolved crystallography at synchrotron facilities worldwide and can be configured for parallel or perpendicular orientation. Stress due to centripetal acceleration in the disk is strongly dependent on speed and disk diameter. Recommended practices established for flywheel design are adopted in this paper for reduced risk of disk failure at high speeds. Evaluation of speed stability reveals 560 picosecond jitter at 30 000 RPM.

Synchrotron instrumentation, air bearing, chopper

1. Introduction

Use of a low-jitter, high-speed air bearing chopper spindle driven by a frequency-locked speed control has enabled a new generation of scientific experiments at synchrotrons worldwide. Traditional X-ray diffraction techniques provide a static view of atomic structure, but by using a chopper, time-resolved X-ray crystallography can provide insight into mechanisms of molecular function [1]. A slot in the rotating chopper disk allows desired X-ray pulses to pass while absorbing unwanted X-ray pulses. To see molecules in action, a reaction is initiated and the dynamic behaviour of a molecule is recorded using short X-ray pulses isolated by the chopper.

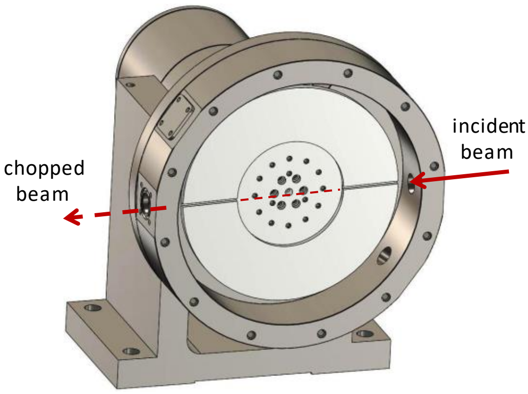

Figure 1. Perpendicular orientation: beam enters the chopper through a window into vacuum chamber, some of the beam travels through a slot in the rotating disk, and a chopped beam emerges.

A chopper assembly typically consists of a motorized spindle with a slotted disk rotating in a vacuum to reduce drag on the disk [2]. The first high-speed chopper for X-ray isolation was designed in 1988 and used a spindle with rolling element bearings [3]. Since then, high-speed choppers for X-ray pulse isolation have improved dramatically in jitter reduction with better bearings, motors, encoders, and controls. Several design alternatives including chopper disk slot configuration, disk material, and orientation of the chopper axis of rotation relative to the beam must be considered. Safety must be a priority when operating choppers with disks rotating at high speeds, which can easily exceed material strength limits. A comprehensive approach to chopper design that addresses these issues is presented.

2. Chopper spindle

Precision air bearing spindles are well-suited for high-speed choppers due to their low error motions and torque ripple. 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 [4]. Rolling-element and magnetic bearings have also been used, but they typically have greater error motion than air bearings [5]. A rolling-element bearing may exhibit speed jitter due to variable friction from bearings and seals, a problem exacerbated by poor lubrication in a vacuum environment. While harder vacuum and minimal bearing friction is possible with magnetic bearings, they will typically involve a complex control system with associated higher costs and difficulty in operation.

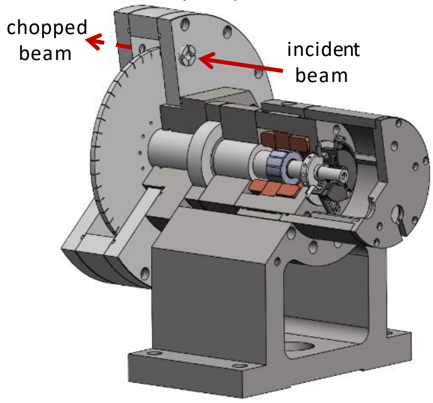

Figure 2. Parallel orientation X-ray chopper.

3. Chopper orientation

Two orientations of the chopper spindle axis of rotation relative to the beam are possible—perpendicular and parallel. In Figure 1, the chopper spindle axis of rotation is oriented perpendicular to the beam and a slot is cut into the face of the disk. The alternative is shown in Figure 2 with slots cut into the periphery of the disk.

With perpendicular orientation (Figure 1), the slot in the disk can pass through the center of the disk so that the shutter opens twice per revolution. If a single slot is used offset from center, the shutter will only open once per revolution. The perpendicular orientation disk provides more material to block the beam leading to higher X-ray attenuation without affecting inertia [3]. Since the entrance and exit of the slot block the beam, the opening time is half as long as an equivalent slot in a parallel disk [6]. This results in improved time resolution, which is shown in Equations 1 and 2. Window opening time for a face slot which cuts through the center of a perpendicular orientation disk is

$$t_{perpendicular} = \frac{w}{4\pi r f} \quad (1)$$

where t is the opening time, w is the slot width, at a radius r, and f is the frequency of rotation. Window opening time for a periphery slot in a parallel orientation disk is

$$t_{parallel} = \frac{w}{2\pi r f} \quad (2)$$

A parallel slotted disk typically has a much higher slot count to realize higher frequency chopping. In addition, slots of different width and slot count can be accommodated by translating the chopper with respect to the beam radially along the disk.

4. Chopper disk stress

Window opening time (resolution) is inversely proportional to disk radius and frequency. For a given slot width, radius and rotation frequency should be selected to avoid failure due to centripetal acceleration. For a flat disk (with no central hole), maximum radial and tangential stresses are equal at the center and they are

$$\sigma_{radial} = \sigma_{tangential} = \frac{\rho\omega^2 r^2(3+\nu)}{8} \quad (3)$$

where ρ is the density, ω is the angular speed, r is the disk radius, and ν is Poisson's ratio [7]. As is shown, stress scales with speed and radius squared. According to recommended flywheel design criteria, designed stress at maximum speed should not exceed half of the yield strength—safety factor of 2 [8]. For the flat disk (with no central hole) using von Mises effective stress in the plane stress case gives

$$S_{yield} = \frac{\rho\omega^2 r^2(3+\nu)}{4} \quad (4)$$

where S_{yield} is the yield strength with a 0.2% strain offset [9].

In the case of a disk with a central hole that is at least 5 times smaller than overall disk diameter, radial stress is zero at the edge of the hole and tangential stress is doubled [7].

$$\sigma_{tangential} \sim \frac{\rho\omega^2 r^2(3+\nu)}{4} \quad (5)$$

Then, von Mises effective stress for the uniaxial case is used along with a safety factor of 2 to obtain

$$S_{yield} = \frac{\rho\omega^2 r^2(3+\nu)}{2} \quad (6)$$

Table 1 Some examples showing the importance of material properties when determining maximum safe speed for a chopper disk with 140 mm diameter and a small central hole (safety factor of 2).

Material	Type	Density ρ kg/m^3	Poisson's ratio ν	Yield S_{yield} GPa	Max speed RPM
Brass	CA260	8 600	0.33	0.45	24 100
Stainless steel	416	7 640	0.28	1.03	39 200
Titanium	Ti6Al4V	4 400	0.34	1.14	53 700

5. Speed stability

The chopper shown in Figure 3 with a maximum speed of 35 000 RPM is evaluated for long-term speed stability. The synchrotron reference frequency is simulated with an HP 33120A Function Generator and an HP 5371A Time and Frequency Analyzer records the period of the encoder reference with 200 ps resolution. A histogram of the period error at 30,000 RPM is shown in Figure 4 with a standard deviation of 560 ps. This standard deviation is 0.28 ppm of the 2 000 µs period.

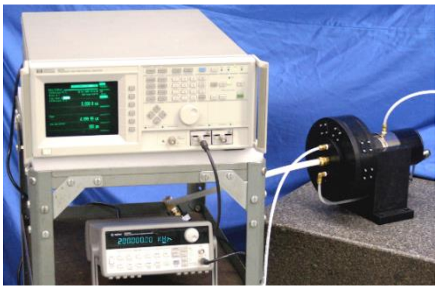

Figure 3. Spindle driven with Frequency Lock Velocity Control and jitter measured with HP 5371A.

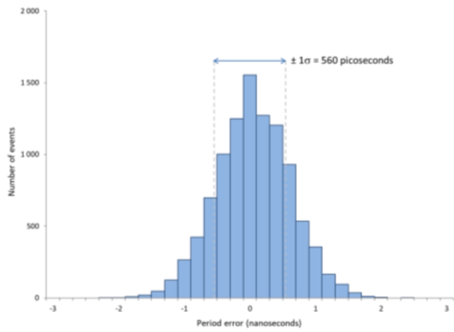

Figure 4. Histogram demonstrating speed stability at 30,000 RPM. The jitter, or standard deviation, of the 10,000-point sample is σ = 560 ps which is an error of 0.28 ppm of the period.

6. Conclusion

Design considerations of an X-ray chopper for time-resolved crystallography are explored including bearing selection, perpendicular and parallel orientation, material strength, and speed stability. A number of requirements are satisfied with a versatile design that can be reconfigured to meet the needs of a variety of X-ray experiments. Speed stability between a reference frequency and the encoder signal is evaluated over thousands of revolutions. The jitter at 30 000 RPM is 560 picoseconds for over 10 000 revolutions.

References

[1] Cammarata M Eybert L Ewald F Reichenbach W Wulff M Anfinrud P Schotte F Plech A Kong Q Lorenc M Lindenau B Räbiger J and Polachowski S 2009 *Rev. Sci. Instrum.* **80** 015101

[2] Mills DM 1989 *Rev. Sci. Instrum.* **60** (7) 2338-41

[3] LeGrand AD Schildkamp W and Blank B 1989 *Nucl. Instrum. Methods Phys. Res. A* **275** 442-6

[4] Knapp B Oss D Arneson D Graber T Henning R and Marsh ER 2012 *Proc. of ASPE* 30-3

[5] Meents A Reime B Kaiser M Wang XY Abela R Weckert E and Schulze-Briese C 2009 *J. Appl. Cryst.* **42** 901-5

[6] Gembicky M and Coppens P 2007 *J. Synchrotron Rad.* **14** 133-7

[7] Den Hartog JP 1987 Advanced Strength of Materials Dover NY.

[8] Bender D 2015 Recommended Practices for the Safe Design and Operation of Flywheels. Sandia National Laboratories: NM. SAND2015-10759

[9] Norton RL 2000 Machine Design Prentice Hall: NJ.