Stanford Research Systems
Technical Note

Characterizing Optical Chopper Phase Jitter

ABSTRACT

An optical chopper is used to introduce a steady modulation to a light source. The steadiness of that modulation can be characterized by jitter—the variation in the edge timing of the chopped waveform relative to an ideal clock. Jitter can be expressed in units of time (seconds) or phase (degrees), and so is sometimes referred to as either "period jitter" or "phase jitter." In this technical note, we define jitter in the context of optical chopping experiments and provide a measurement protocol and results using that definition.

Introduction

As its name implies, an optical chopper is used to convert a continuous wave light source to a chopped waveform at a user-defined frequency. Variation of the chop period is known as jitter. Typically, it is critical that the chop period is highly reproducible, and so jitter is a critical figure-of-merit for an optical chopper. Understanding how jitter is measured is therefore essential for comparing optical chopper products.

It is easiest to understand jitter by way of visual example. Consider locking an optical chopper to a stable external reference frequency[1], and feeding both the external reference and the chopped optical signal to an oscilloscope. With the scope configured to trigger on edges of the stable reference, one can easily see how jitter affects the chopped signal by displaying the waveforms with persistence: the jitter of the optical signal will cause its edges to smear out as in Fig. 1.

If you measure N periods, the jitter represents the spread of the individual measurements T_i relative to their average value $\langle T \rangle$, expressed either as a peak-to-peak value or as an RMS (root-mean-square) deviation from

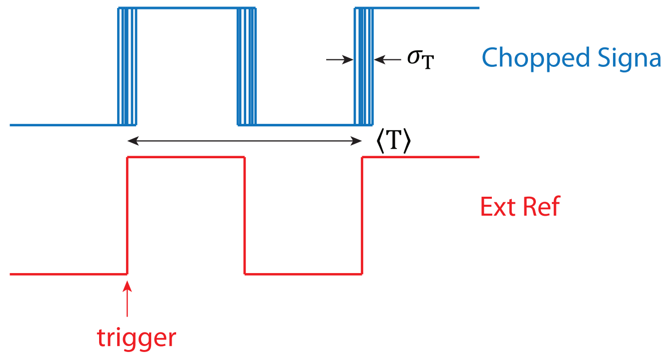


Figure 1: Visualizing jitter with an oscilloscope. The chopped signal edges will "smear out" with a timing distribution characterized by the period jitter, σ_T. This can be converted to phase (in °) by normalizing by the ideal or average period $\langle T \rangle$.

the mean:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_i - \langle T \rangle)^2} \qquad (1)$$

Jitter can be expressed in seconds or degrees:

$$\sigma(^\circ) = \frac{\sigma(s)}{\langle T \rangle} \times 360^\circ \qquad (2)$$

What is the timescale over which jitter is characterized; i.e. how many periods should be collected? Generally, we choose a timescale that is long enough that a stable value for the jitter is reached, but not so long that the long-term frequency drift of the chopper's internal timekeeping becomes noticeable.[2] In pratice this usually amounts to data collection timescales of tens of seconds to several minutes, depending on the chop frequency (with N on the order of several hundred to tens of thousands).

Mechanical or Optical Phase?

Because an optical chopper relies on a mechanically rotating blade that produces several optical periods per mechanical revolution, there is some ambiguity in published chopper specifications with regards to the units of jitter: Are we discussing mechanical phase or optical phase?[3]

[1] Not all choppers can lock to an external signal, so alternatively, one can simply set the chop frequency and external reference frequency to the same value. In this case, any frequency mismatch (due to different timebases for the chopper and reference) will cause the chopped waveform to "walk" relative to the external reference. Even for phase locked optical choppers, the phase lock loop (PLL) responsible for tracking the external waveform may contribute additional jitter, though this is typically negligible compared to the sources of mechanical jitter discussed in this note.

[2] The SR542's crystal oscillator has a spec of ± 20 ppm/yr.

[3] For example, the PerkinElmer/Signal Recovery Application Note 1003 "Low Level Optical Detection using Lock-in Amplifier Techniques"

An optical chopper wheel with n slots will advance by $n\times 360°\mathrm{opt}$ (optical degrees) for every $360°$ of mechanical revolution. We designate these units as optical degrees ($°\mathrm{opt}$) and mechanical degrees ($°\mathrm{mech}$). The distinction is shown for a 6-slot blade in Fig. 2.

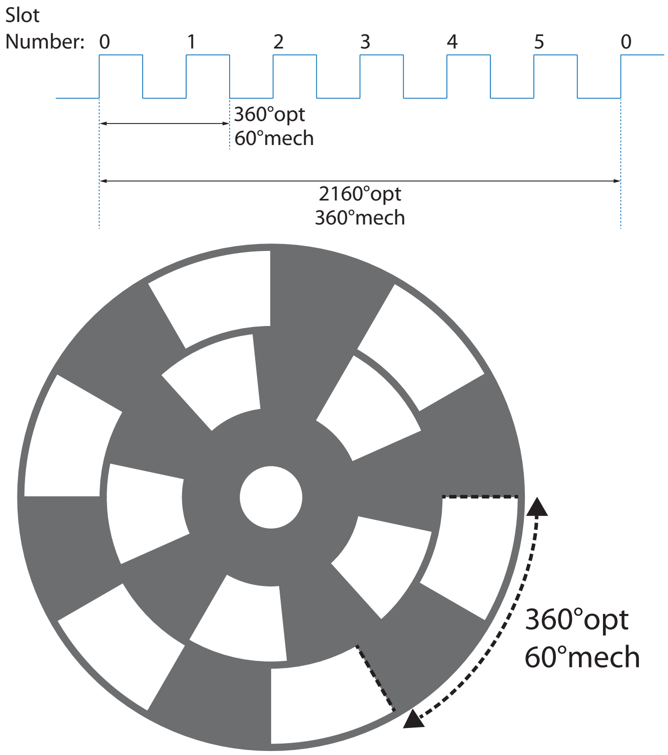


Figure 2: Relationship between optical and mechanical phase for a 6-slot chopper blade.

Expressing the jitter in *mechanical degrees* makes a measurement appear more favorable by a factor of n. For example, $1°\mathrm{mech}$ of jitter is $6°\mathrm{opt}$ for a 6-slot blade and $100°\mathrm{opt}$ for a 100-slot blade! However, the mechanical orientation of the blade is of little interest to an optical chopper user since ideally, all n slots are identical. Stated differently, a rotary mechanical chopper is only one of many methods for modulating a light source, and the jitter specification and its units should be independent of that methodology.

Sources of Jitter

There are several contributions to optical jitter for a mechanical chopper, defined and discussed below.

1. Motor speed stability: The speed of a chopper motor varies when there is non-zero torque exerted on the rotor. These torques can be *stochastic* in nature (e.g. due to turbulent air currents) or *deterministic* and repetitive with each mechanical revolution. Closed-loop control of the motor, as is implemented with the SR542, adjusts the motor drive to maintain fixed speed and thereby compensate these torques. However, the control-loop gain and bandwidth are finite, so there is always some residual and time-varying error. Stochastic torques give rise to phase errors that can be reasonably described as normally-distributed noise, while deterministic errors appear repetitive with ϕ_{shaft}.

One particularly evident source of deterministic torques in electric motors is known as *cogging* torque, a term meant to evoke the discrete rotational steps of a cogged device such as a ticking clock. Cogging torques depend on the rotor's angular orientation, ϕ_{shaft}, and will modulate the shaft speed in a pattern that repeats with each mechanical revolution. For a DC motor, cogging arises due to variation in the magnetic force between the rotor and stator. Cogging is very evident in DC stepper motors and is also present for typical *slotted* brushless DC motors.[4]

By contrast, a *slotless* brushless DC motor—as is used in the SR542—is designed to minimize variation in the rotor-stator interaction force, and thereby provide rotationally uniform torque. Nevertheless, it is challenging to eliminate cogging entirely, particularly at low speeds. At higher speeds, the rotor's inertia tends to smooth over the accelerations caused by any cogging torques.

2. Blade imperfections: A chopper blade will suffer from minor deviations of the aperture locations and widths from their ideal values as a result of any real-world fabrication process (where ideal values are given by perfect symmetry: angular spacing between like edges should be $360°\mathrm{mech}/n$). If the deviations vary from aperture-to-aperture, they will contribute to optical jitter. This jitter will be *deterministic* however, repeating with each mechanical revolution. Meanwhile, systematic deviations that affect all apertures uniformly (such as over- or under-etching of a photo-etched blade) will appear as an error in the duty cycle. These imperfections can be thought of as the blade's fingerprint, unique to each blade.

3. Blade concentricity: If the blade is not mounted concentric with the motor shaft (the axis of rotation), then the linear slot speed as it moves past the user's beam spot will vary sinusoidally with ϕ_{shaft} about a mean value[1], thereby modulating the optical period at f_{shaft}. Blade concentricity can be optimized by tight mechanical tolerances between the shaft, hub, and chopper blade.

states that "The peak-to-peak specification refers to the percentage of a complete wheel rotation or 360 degrees", implying that optical chopper phase jitter is generally specified as a percentage of $360°\mathrm{mech}$.

[4] A *slotted* DC motor uses magnetically-permeable "teeth" around which the stator windings are wound. The stator teeth increase the magnetic flux density, providing higher peak torque per unit applied current at the expense of non-uniform torque as a function of rotor angle. Such cogging can appear as a modulation of the mechanical speed at $n_{\mathrm{teeth}} f_{\mathrm{shaft}}$ (or multiples thereof for rotors with higher pole counts).

Blade warping and out-of-plane tilt will also cause deterministic period error at ϕ_{shaft}, so it is important to handle the chopper blades with care to keep them flat.

Measurements and Results

To assess how each of the above effects contributes to a chopper's jitter, we collect N periods of the optical signal and plot the measured period as a function of time, as well as a histogram of all measurements.[5] Rather than plot in units of period (seconds), we plot in units of optical phase ($^\circ\text{opt}$). Each of the measured periods T_i is converted to a phase error $\delta\phi_i$ as

$$\delta\phi_i = \left(\frac{T_i - \langle T\rangle}{\langle T\rangle}\right) 360^\circ\text{opt} \tag{3}$$

where $\langle T\rangle$ is the average period over all N measurements.

The phase jitter is simply the RMS value of the N phase error measurements, and is visualized as the width of the phase error histogram.

$$\sigma_{\delta\phi} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\delta\phi_i)^2} \tag{4}$$

An example of period error vs. time for a 5-slot blade with a setpoint chop frequency of $1\,\text{Hz}$ is shown in Fig. 3. The raw period measurements vs. time are shown in Fig. 3a. In Fig. 3b, all of the measured period errors are collected into a histogram. The width of the histogram distribution of all period measurements (blue outline), characterized as standard deviation from the mean (σ), is 0.359°opt. This distribution includes all sources of jitter discussed above and represents the jitter that a typical chopping experiment running at $1\,\text{Hz}$ would experience.

For an n-slot blade, every n^{th} period measurement is a repeated measurement of the same slot. We therefore assign a different color to the period measurements that correspond to each of the 5 slots of this blade. Consider slot 1 for example (green). It exhibits an average period error of about -0.65°opt. This means that the edge marking the end of the slot 1 period comes 0.65°opt *earlier* than expected. The non-deterministic jitter sets the width of the green distribution at only 0.070°opt, so the phase error is quite reproducible from revolution-to-revolution and is dominated by the deterministic error. Stated simply, for a single slot, the deterministic sources of phase error determine the mean value, while the non-deterministic sources determine the jitter (standard deviation).

In Fig. 3a, a sinusoidal fit at f_{shaft} is provided as a guide to the eye to highlight that most of the "all slots" optical jitter for the 5-slot blade at this low chop frequency can be attributed to deterministic sources of phase error. Quantitatively, the "all slots" jitter is nearly six times larger than the average of the "single-slot" values. At the end of the day however, a typical chopper experiment is sensitive to the sum of all of the jitter contributions, and the important metric is the "all slots" jitter. Only if a user can arrange an optical shutter to pass every n^{th} optical cycle can they make use of the exceptional reproducibility indicated by the "single-slot" phase error distribution.

Note that *deterministic* does not necessarily imply *sinusoidal*. While the mounting concentricity will introduce period errors that are sinusoidal with ϕ_{shaft}, the blade imperfections can introduce random period errors from slot-to-slot (which repeat with each mechanical revolution, but need not be sinusoidal). Empirically, we find that the cogging errors often appear as $\sim\sin(\phi_{\text{shaft}})$ or $\sim\sin(2\phi_{\text{shaft}})$, but this will depend on the construction of the chopper motor.

Let us next look at the evolution of phase error measurements as a function of chop frequency. The concentricity and blade imperfections will contribute frequency-independent phase errors, as they depend only on geometry. However, the cogging errors will diminish at higher speeds since the position-dependent cogging acceleration will have less time to alter the speed of the spinning shaft. Therefore, some separation of the deterministic contributions can be made by considering the frequency dependence of the period error measurements.

Fig. 4 shows the same 5-slot chopper blade operating $100\times$ faster, with $f_{\text{chop}} = 100\,\text{Hz}$. By comparison to Fig. 3 (the y-axis scaling is preserved for easy comparison), it is easy to see the beneficial effects of increased angular momentum at higher shaft speeds: the overall amplitude of the sinusoidal modulation at f_{shaft} is reduced, and the "single slot" variation of each slot is dramatically reduced. At this speed, the rotor's inertia "smooths" over the cogging torque, and the remaining sinusoidal phase error is likely due to a small concentricity error in the blade's mounting position.[6] Meanwhile, the narrow individual peaks seen in the histogram (Fig. 4b) demonstrate exceptional motor speed control.

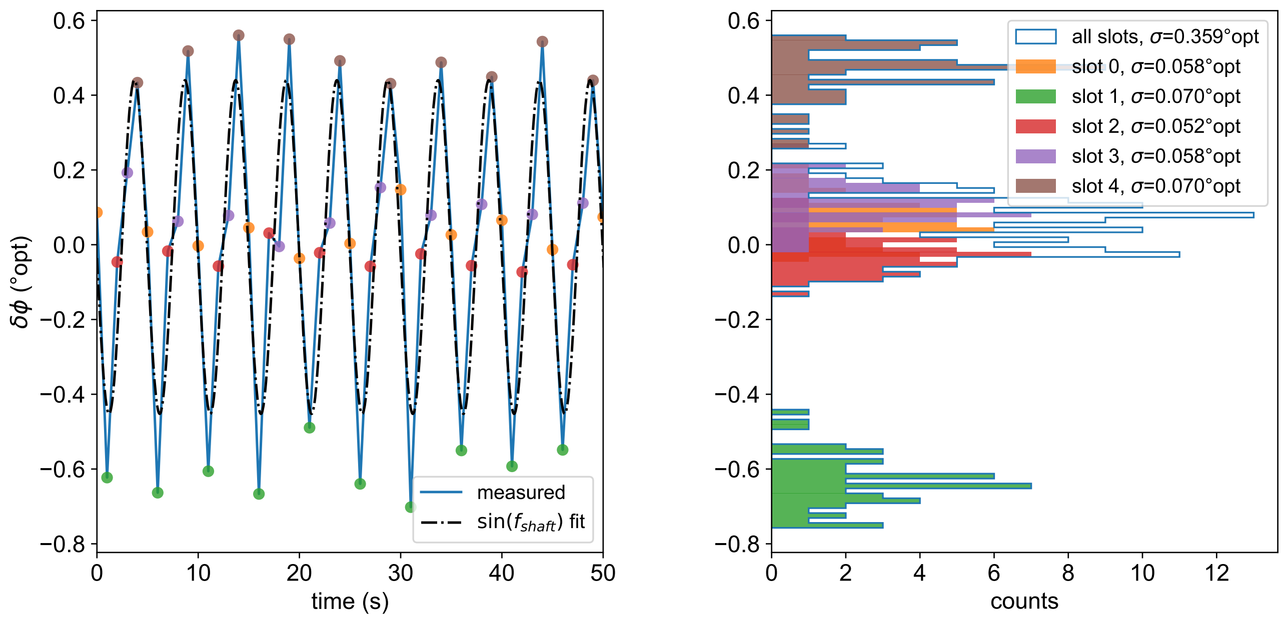
Note that slots 1 and 2 (green and red) overlap with one another, so only 4 peaks are resolved. Furthermore, there is no easy way to guarantee that enumeration of the slots is identical from trial-to-trial, so slot 0 in Fig. 4 is not necessarily the same as that in Fig. 3.[7]

Fig. 5 presents the phase error and jitter for a 30-slot

[5] We use an SR620 Universal Time Interval Counter, though some advanced oscilloscopes can perform this type of period jitter analysis–known as Time Interval Error (TIE)–directly.

[6] A sinusoidal phase error variation with 0.2°opt amplitude corresponds to a mere 0.00055" radial displacement of the chopper blade for apertures measured at a 2" radius[1].

[7] If you connect *both* the Shaft Ref Out and Outer Slots Ref Out of the SR542 to an oscilloscope, you can trigger the scope on the Shaft Ref signal to consistently "enumerate" the slots.



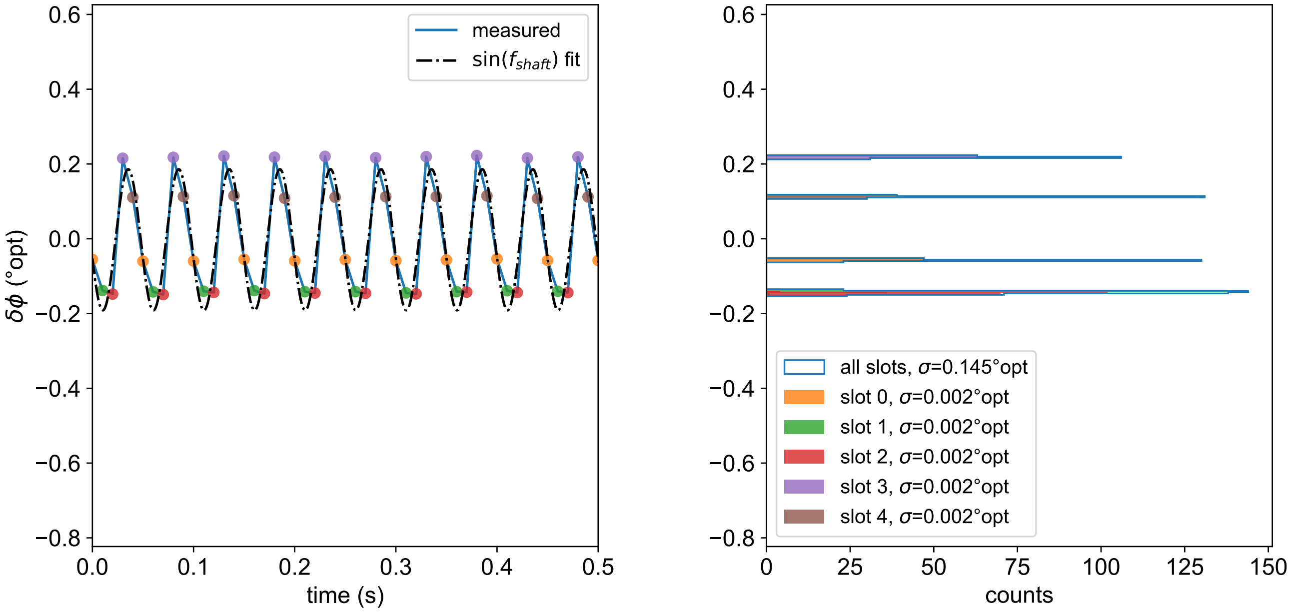
(a) Period error vs. time. Data points are color coded according to their slot number (i.e. every 5^{th} data point is the same color). A sinusoidal fit is made to the data, with a frequency equal to the shaft frequency ($f_{\text{chop}}/5$), as a guide to the eye to highlight the deterministic contributions to the phase error. Only the first 10 mechanical revolutions of collected data are displayed.

(b) Histogrammed data from Fig. 3a. Color coding matches that from Fig. 3a. σ values are calculated for "all slots" and individual slots, and reported as an RMS deviation from the mean phase error.

Figure 3: Phase error measurements for SR542 5-slot blade at $f_{\text{chop}} = 1$ Hz.

blade chopping at 600 Hz. Acquired at the same shaft speed of $f_{\text{shaft}} = 20$ Hz as Fig. 4, the cogging is largely suppressed and the sinusoidal variation of the period is likely due to concentricity error (note the similar sine amplitude to that of Fig. 4). However, the phase error pattern is no longer predominantly sinusoidal. We continue to provide the sinusoidal fit because (1) it helps to identify concentricity errors, and (2) it serves as a reference for ϕ_{shaft}, emphasizing the repetitive nature of the phase errors with respect to shaft orientation.

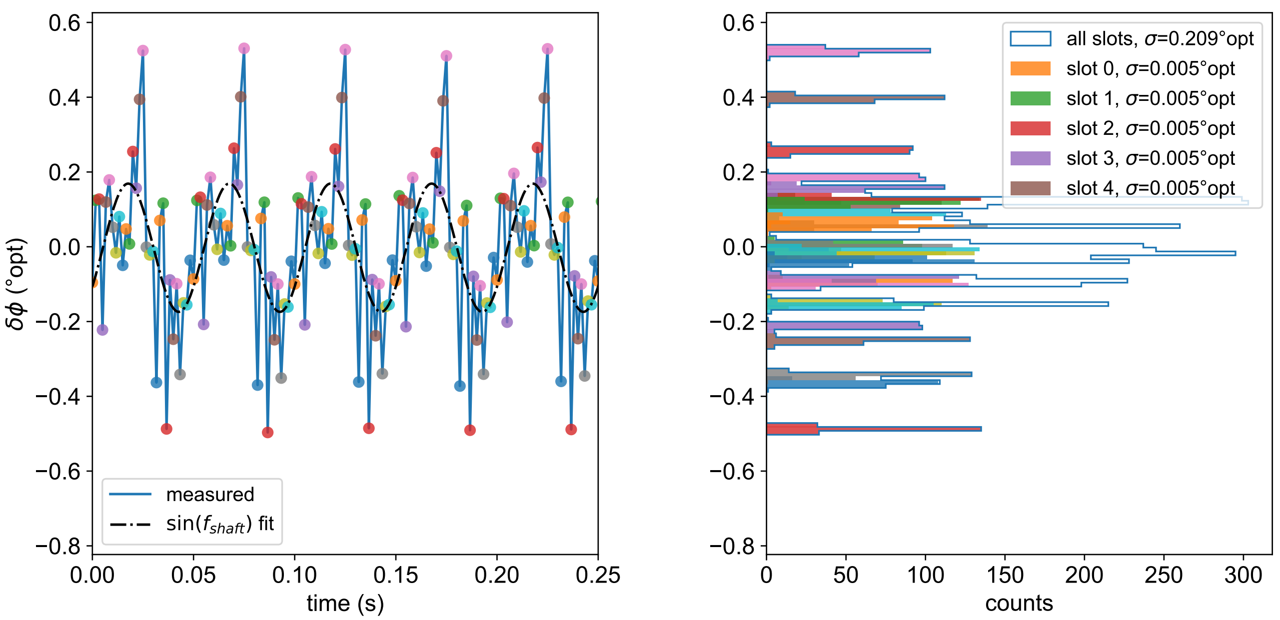
The sine *residual* (the phase errors remaining after subtraction of the sine fit) contains deterministic contributions from both the blade imperfections (to the extent that those are random and not sinusoidal themselves) and stochastic errors which convolve Gaussian noise with that fingerprint. The color coding makes it easy to see a phase error pattern (the "fingerprint") which is highly repetitive with each mechanical revolution.



(a) Phase error vs. time.

(b) Histogram of phase errors.

Figure 4: Phase error measurements for SR542 5-slot blade at $f_{\rm chop} = 100\,$Hz.



(a) Phase error vs. time.

(b) Histogram of phase errors. Only the first 5 slots are shown in the legend.

Figure 5: Phase error measurements for SR542 30-slot blade at $f_{\rm chop} = 600\,$Hz.

Jitter vs. Frequency

Jitter data for 5-slot, 10-slot, 30-slot, and 100-slot chopper blades as a function of chop frequency are shown in Fig. 6. Circles indicate the “all slots” RMS jitter, while triangles indicate the average of the n “single-slot” jitter values at each chop frequency. Also shown in these figures are the published jitter specs for each chopper blade (dashed lines).[8]

The jitter is both blade- and frequency-dependent, but some general trends do emerge from these plots. At low speeds, small forces (both random and deterministic, i.e. cogging) can have a large impact on the phase error, as is evident in the increased jitter observed for both the “all-slots” and ”single slot” metrics at the lowest chop rates. Factory calibration of the SR542 chopper head includes measurement of cogging acceleration. These measurements are used to calculate compensation currents that the SR542 controller applies to null the cogging torques. As a result, we are able to extend the operating range of the chopper to shaft speeds an order of magnitude slower than previous generation choppers. At all but the lowest shaft speeds, the “all-slots” jitter generally approaches some asymptotic value—a noise floor which is set by the frequency-independent contributions of blade imperfections and concentricity error, while the “single-slot” jitter continues to improve due to inertial smoothing.

A tabular comparison of the measured performance and published specifications can be found in Table 1. For simplicity, a single chop frequency is chosen for each blade. Both “all slots” and “single-slot” jitter values are shown, but since the “all slots” measurement is the relevant one for most chopping experiments, that is the value that should be compared to the published specification.

Conclusion

In closing, when comparing jitter specifications across optical choppers, pay attention to the units. The use of *optical degrees* is the most relevant and transparent. Furthermore, the jitter statistics should be calculated using all slots of the blade under consideration.

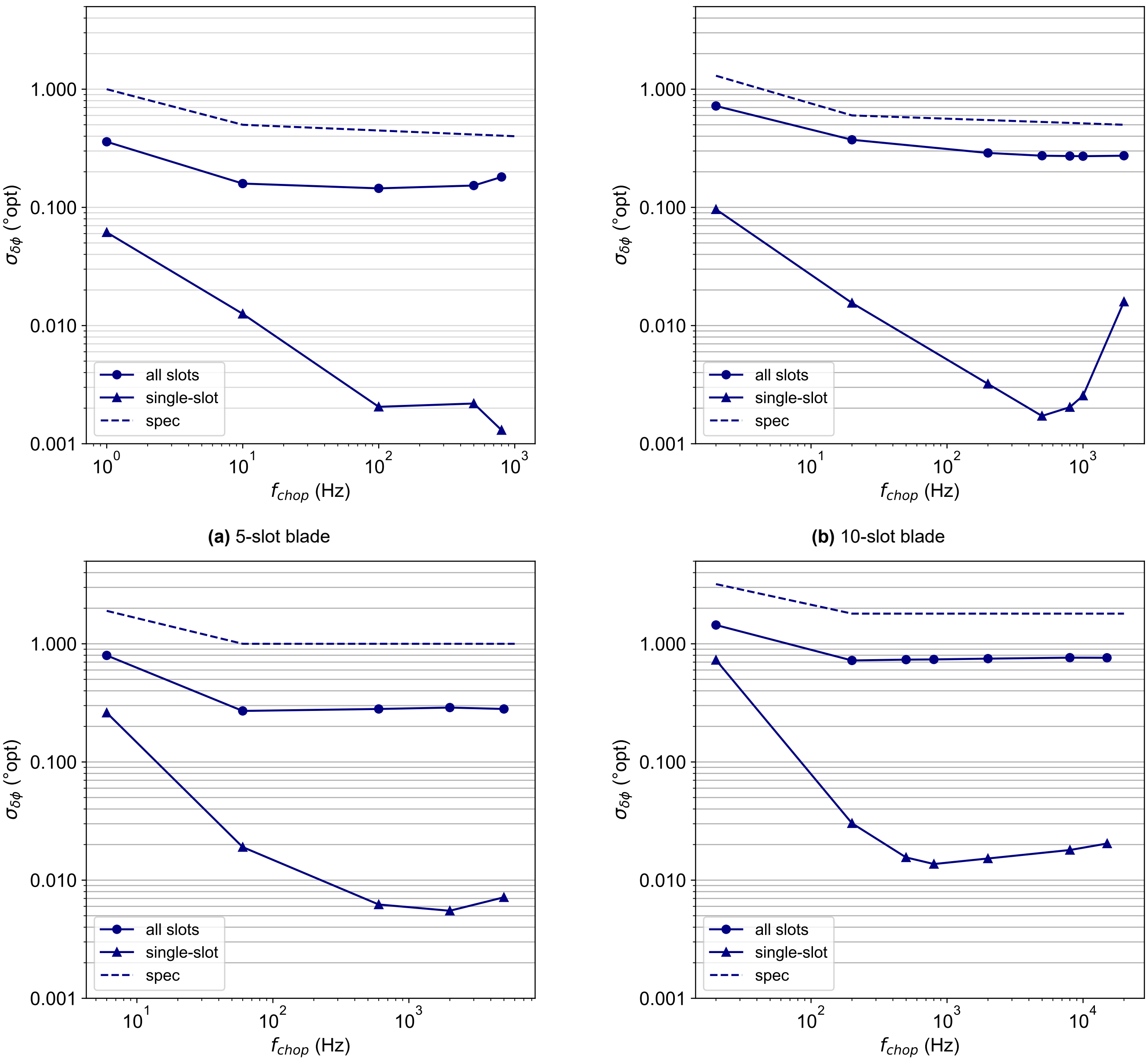
The analysis presented here, using phase error measurements vs. time and a corresponding histogram, is instructive for isolating the various sources of jitter, especially when repeated at several frequency setpoints. Such an analysis can prove useful to understand the strengths and limitations of mechanical choppers, inform the choice of operating parameters for an experiment, or to diagnose larger-than-expected phase noise.

There are several sources that contribute to the overall jitter imparted on a chopped optical beam. These can be stochastic or deterministic and repetitive with mechanical revolution, as in the case of cogging torques, blade imperfections, and non-concentric mounting of the blade. Some of the deterministic sources (cogging and concentricity) will appear roughly sinusoidally with ϕ_{shaft} (or harmonics thereof), while others (blade imperfections) can be scattered randomly as a function of shaft orientation. It is generally advantageous to chop at the highest shaft speed available to you to eliminate errors due to cogging torques. Meanwhile, blade imperfections and concentricity will contribute frequency-independent errors. To minimize concentricity errors, care should be taken so as to not introduce a radial offset when mounting the blade to the hub. Finally, because blade manufacturing errors generally have a fixed lateral dimension, these will impact higher slot count blades more significantly, so it is also favorable to use the lowest slot count possible.

References

[1] Dana F. Geiger. *Phaselock Loops for DC Motor Speed Control*. John Wiley & Sons, 1981.

[8] It should be emphasized that the measurements collected here represent the performance of a particular blade mounted on one particular chopper motor. Actual performance may vary.



(a) 5-slot blade

(b) 10-slot blade

(c) 30-slot blade

(d) 100-slot blade

Figure 6: RMS phase error vs. frequency.

Table 1: Phase jitter at select chop frequencies for assorted chopper blades.

Blade	Slot Count	f_{chop} (Hz)	Published Spec. ($^\circ$opt RMS)	All Slots, measured ($^\circ$opt RMS)	Single-Slot, measured ($^\circ$opt RMS)
O54256	5	100	0.4	0.145	0.002
O54210100	10	200	0.5	0.289	0.003
O5422530	30	600	1.0	0.281	0.006
O54210100	100	2000	1.8	0.749	0.015