Angular Runout Test Setup for High-Precision Ball Bearings

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Abstract

Ball bearing runout error is generally a limiting factor for the precision of pointing systems and astronomical instruments. A test setup was developed to optically measure the angular runout of a series of off-the-shelf duplex angular contact bearing pairs each having the same cross-section, but different ABEC ratings and manufacturers. A total of 6 bearing sets ranging from ABEC 3 to ABEC 7 were tested. The repeatable, synchronous runout generally improved with higher ABEC quality bearings as expected, although occasionally significant variation were observed with bearings of the same ABEC ratings. Less significant differences were observed for non-repeatable runout as a function of ABEC quality rating. A major finding is that strictly relying strictly on ABEC rating may be insufficient for applications where bearing runout plays an important role.

Introduction

When developing precision pointing systems and astronomical instruments supported by ball bearings, angular runout is often a key factor affecting pointing accuracy, stability, and overall performance. Line-of-sight pointing accuracy on precision pointing platforms are adversely affected by bearing runout since irregular encoder code disk motion can seriously degrade readout accuracy. Pointing mirrors are also vulnerable to bearing wobble particularly non-repeatable angular runout which cannot be easily calibrated out. Estimating angular runout based on bearing catalog individual race radial worst case tolerance will generally lead to a significant over prediction of the angular runout of the bearing assembly. In the case of a duplex bearing pairs, matching up the bearing high spots as marked on precision bearing races will essentially cancel most of the angular runout of the bearing. This will happen at the expense of enhancing radial runout motion. However, radial centerline motion is less of an issue for most optical systems that are more affected by angular pointing errors. The American Bearing Manufacturer’s Association (ABMA) standards do not provide any requirements for the runout of an assembled bearing pair, but instead specify maximum raceway to mounting feature runouts for each bearing race. This will generally not predict the runout of the assembled bearing pair, thus data showing assembled bearing runouts for different Annular Bearing Engineering Committee (ABEC) ratings is not readily available to the designer.

Machine tool spindle bearing runout and disk drive spindle bearing errors are well known limiting factors for their capabilities. Standards for determining the quality of precision spindles have been available for some time. [1]. Eric Marsh and his colleagues at Pennsylvania State University have been prolific contributors to this field of precision metrology [2] [5].

Disk drive spindle runout is traditionally characterized by using two or more non-contacting proximity probes referencing the hub of the spindle, e.g. see [3]. However the runout includes spindle hub machining eccentricities and surface finish errors that must be subtracted out in order to arrive at the bearing contribution. Precision pins or spheres can be fixed at the end of the spindle to avoid minimizing machining geometric errors, but this is not always possible with many spindle designs and the eccentricity of the target to the bearing spin axis is still present.

In the approach reported herein the bearing spin axis angular errors are measured optically and the geometric accuracy of the hub is not a concern. The test setup shown in Figure 1 optically measures the

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angular axis of rotation errors of an assembled, preloaded, duplex bearing pair. The test setup was originally developed to determine whether ABEC 3 bearings would have sufficiently low angular runout to be used in a prototype precision pointing gimbal.

This paper will present measured angular runout data for preloaded ball bearing pairs of a unique diameter and cross section, but three separate ABEC ratings. The goal of this testing is to provide a correlation between assembled bearing runout and ABEC rating. This data will be presented in several forms, including repeatable or synchronous runout as well as non-repeatable or asynchronous runout. [1-3]

Of particular interest to the authors are the repeatability of the angular runout errors and frequency content in terms of mechanical harmonics. The data presented will be useful for estimating angular runout during the design process and the test setup presented allows for bearing-level screening and selection based on minimizing angular runout in bearing applications.

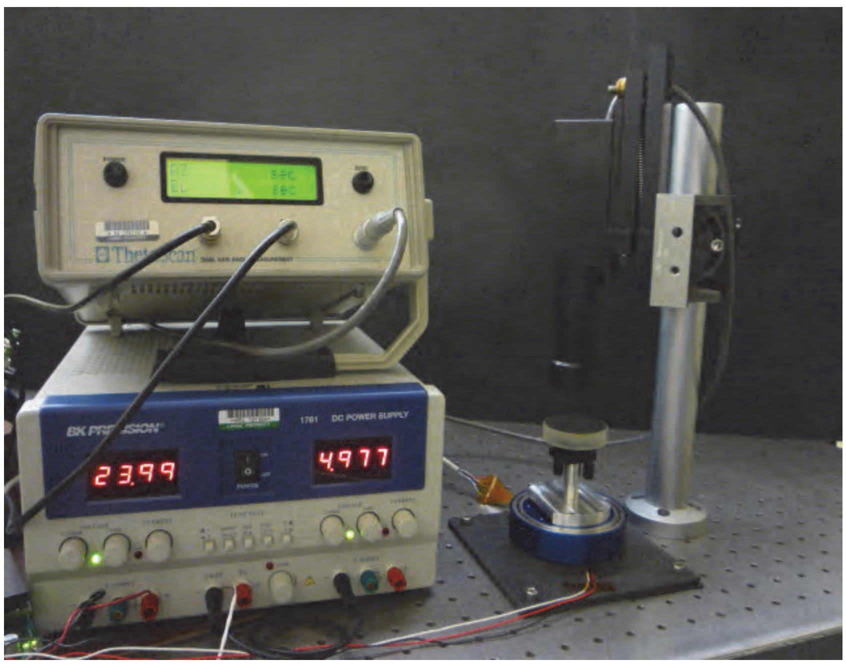


Figure 1. Test Setup Overview

Test Fixture Overview

Each bearing tested was of the same diameter and cross section, so that a single fixture could be used for all testing. The test fixture consists of an aluminum housing and shaft, an integral, direct drive brushless DC motor, and an encoder for motor control purposes. The outer housing is mounted to the bench with the rotation axis parallel to gravity. Figure 2 shows both a photograph and schematic of the test fixture. The features of the housing and shaft that contact the bearing races were diamond turned in order to obtain appropriately precision bearing fits. The diameter tolerancing method is ±5 µm (0.0002 in) from the basic diameter, which permits a line-to-line contact under maximum material conditions. A benign thermal soak allows installation or removal of the bearings without applying excessive force. A mirror with a micrometer adjustable tip-tilt stage is mounted to the shaft. Bearing angular runout is measured using an electronic autocollimator.

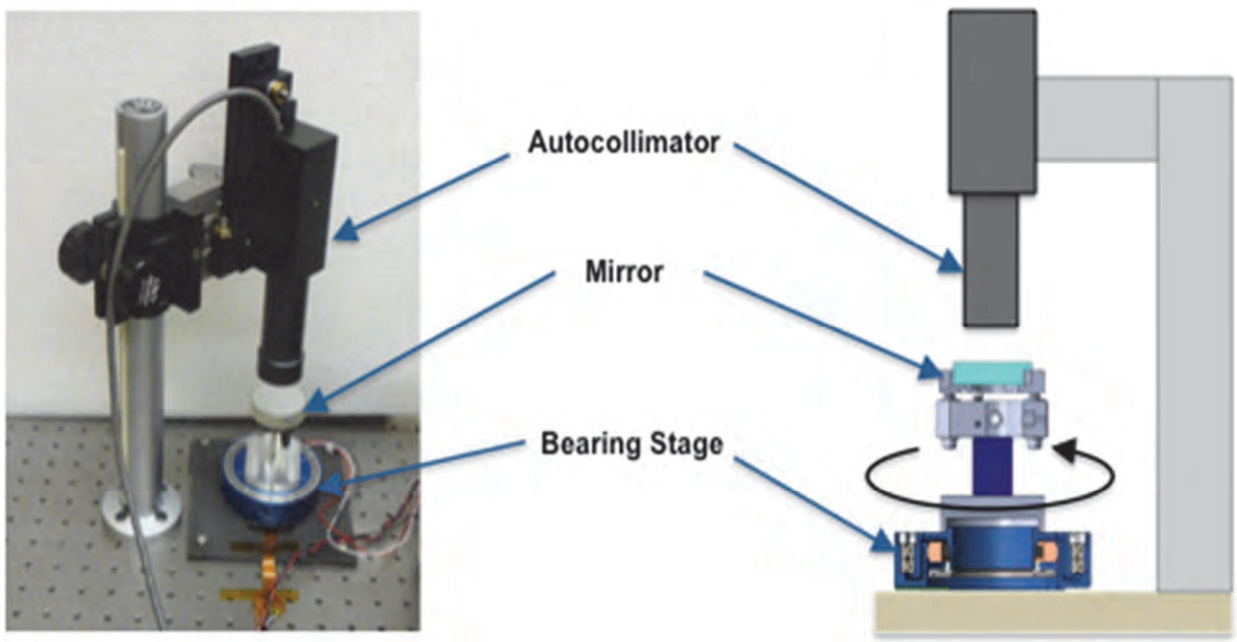


Figure 2. Test Setup Description

The test setup procedure begins with aligning the mirror roughly perpendicular to the bearing axis (see Figure 3). The autocollimator launches a reference beam, which reflects off the mirror and returns to a detector. When perfectly aligned, the reflected beam follows the same path as the reference beam upon return and has no angular difference between beams. However, introducing an angular displacement between the bearing axis and mirror normal or shaft axis will cause the reflected beam to sweep a conical path during shaft rotation, which will project a circular profile on the autocollimator detector. The nominally aligned case and an angular perturbation case are depicted in Figure 3. Recognize that if the bearing set were geometrically perfect then the trace recorded by the autocollimator would remain circular. The deviation from this perfect circle is therefore a direct measure of the bearing angular error.

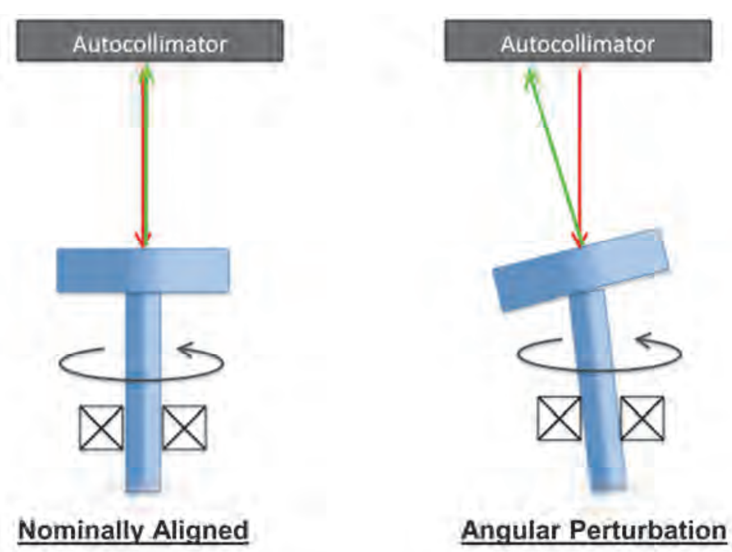


Figure 3. Measurement Method Overview

The degree of mirror tilt is somewhat arbitrary and does not affect the accuracy of the readings. This degree of mirror tilt is measured by the autocollimator and provides the scale factor for the bearing measurements. Also it was determined that if mirror tilt was too small, bearing wobble would cause crossover patterns of the reflected beam, such as a “figure eight” pattern. Therefore, the mirror to bearing axis alignment was intentionally perturbed for all testing cases to trace a nominal 500-microradian diameter path, as a seen by the autocollimator detector. Note that the effect of this approach was to introduce a calibrated, constant tilt of the mirror normal axis relative to the bearing axis.

Each test consisted of ten clockwise revolutions, followed by ten counter-clockwise revolutions. All tests were performed using a constant, low-speed rotation rate of 4.28 RPM (14 seconds per revolution), taking approximately five minutes to complete the full 20 revolutions. Note that the particular motor control speed was selected in order to determine slow-speed, or kinematical, bearing behavior, neglecting the dynamic effects.[4] The autocollimator azimuth and elevation signals were sampled by the data acquisition system at 250 Hz.

Bearing Summary

A total of six unique bearings were tested from three separate vendors. Although the same diameter, cross section and duplex arrangement were used throughout, each configuration had a unique retainer. ABEC ratings include 3, 5 & 7. Also, note that SN6 had a single outer race for the duplex set. The complete bearing summary table is shown in Table 1.

Table 1. Test Bearing Summary

Serial Number	ABEC	OD		Cross Section		Vendor	Ball Dia		Ball	Retainer	Type
		(in)	*(mm)*	*(in)*	*(mm)*		*(in)*	*(mm)*	*Qty*		
1	3	3.0	76.2	0.25	6.35	A	0.125	3.175	52	Nylon	DB
2	3	3.0	76.2	0.25	6.35	A	0.125	3.175	52	Nylon	DB
3	3	3.0	76.2	0.25	6.35	A	0.125	3.175	52	Nylon	DB
4	7	3.0	76.2	0.25	6.35	B	0.125	3.175	52	Brass	DB
5	7	3.0	76.2	0.25	6.35	B	0.125	3.175	52	Brass	DB
6	5	3.0	76.2	0.25	6.35	C	0.125	3.175	60	Teflon Toroid	DB (1-Piece Outer Race)

Test Results

The type of results presented can be described as kinematic or quasi-static since they are done at a relatively low rotation rate. This is to avoid structural resonances in the system so that the measurements can be directly related to bearing behavior. Measured bearing wobble was processed using several methods. The primary method for evaluating synchronous and asynchronous runout was obtained from the elevation versus azimuth plots. A cursory, qualitative analysis compares the acquired test data trace to the perfect circle at 500-microradian diameter, which we will refer to as the “reference diameter”. Several performance aspects should be noted. First, the deviation from the average test data and the reference diameter is defined as “Synchronous Error”. It is synchronous in that it repeats itself every revolution. Second is the portion of the error that does not repeat itself, forming a radial hash band about the average test data. This is defined as the “Asynchronous Error”. These two definitions are illustrated in Figure 4. Finally, hysteresis is observed during cycle reversal, which is most evident in SN5 and SN6 traces. All six traces are shown in Figures 5 to 10, labeled sequentially from SN1 through SN6.

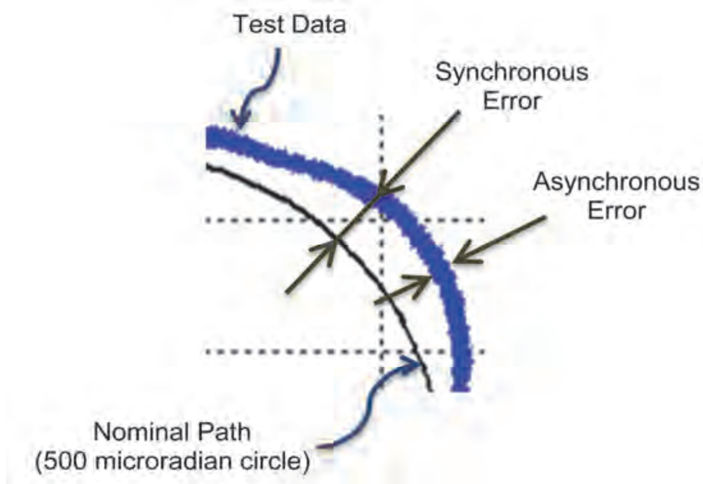


Figure 4. Error Nomenclature

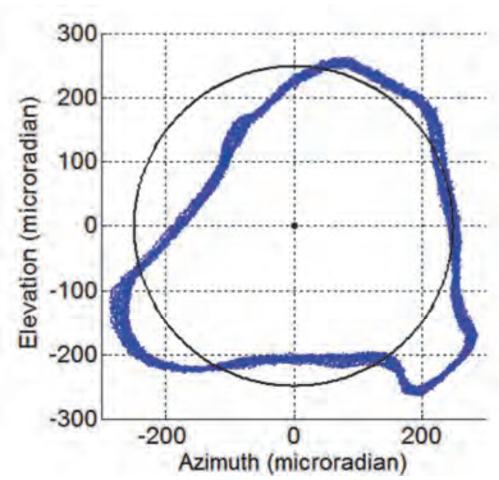


Figure 5. Elevation vs. Azimuth Test Data SN 1 (ABEC 3)

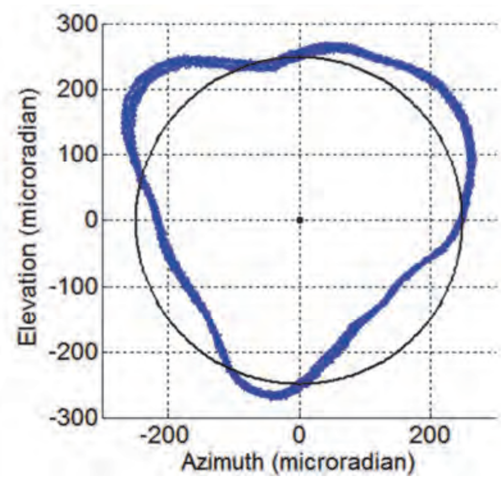


Figure 6. Elevation vs. Azimuth Test Data SN 2 (ABEC 3)

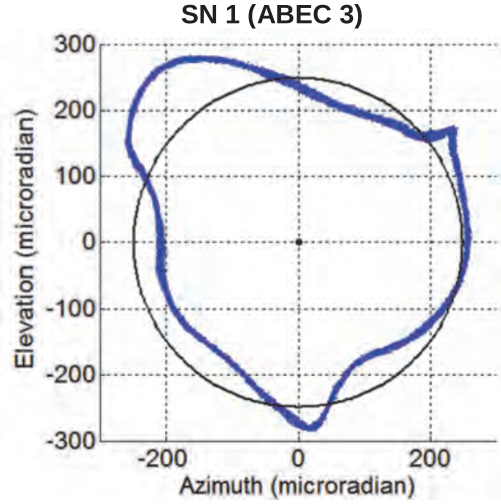


Figure 7. Elevation vs. Azimuth Test Data

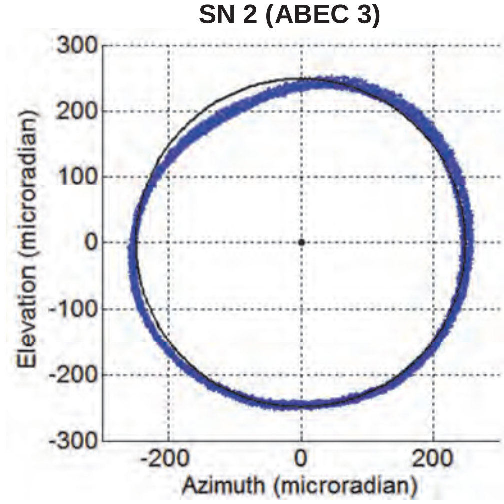
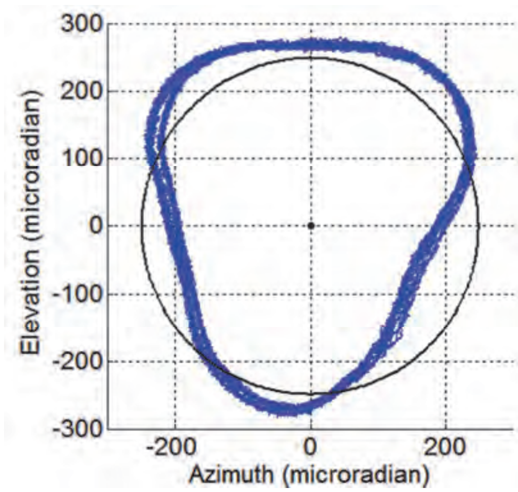


Figure 8. Elevation vs. Azimuth Test Data

SN 3 (ABEC 3)



SN 4 (ABEC 7)

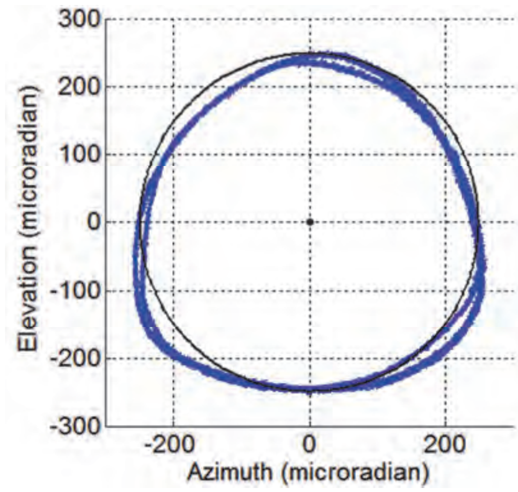


Figure 9. Elevation vs. Azimuth Test Data SN 5 (ABEC 7)

Figure 10. Elevation vs. Azimuth Test Data SN 6 (ABEC 5, Super-Duplex)

Data Processing

It was conservatively assumed that the radial runouts of the two bearings in the duplex pair act in opposite directions, using worst-case runout data from the ABMA standard. These predicted angular runouts are shown in Table 2. A summary of the actual runouts measured from each bearing pair is shown in Table 3. Each bearing pair significantly out-performed the expected angular runout based on this calculation method, most likely due to the fact that the bearings were installed in the test fixture with the high spot markings on each race aligned. The data presented shows that even the ABEC 3 bearings tested offer a very low level of asynchronous angular runout. It is important to emphasize that the angular runout estimation method presented in table is by no means an established approach. In fact, the data from this testing show that this estimation approach provides excessive conservatism and that the best way to determine angular runout is to perform testing on the bearings to be used. The angular runout performance of a given bearing set will depend on workmanship factors, including machining tolerances and ball size matching, but the results presented are also indicative of the order of magnitude one can expect with different ABEC rated bearings of the size range presented.

Table 2. Predicted Angular Runouts Using Different Methods

	Pitch Diameter		Bearing Width		Radial Runout Inner		Radial Runout Outer		Angular Runout Summation Method	Angular Runout RSS Method
	(in)	*(mm)*	*(in)*	*(mm)*	*(in)*	*(µm)*	*(in)*	*(µm)*	*(microradian)*	*(microradian)*
ABEC 3	3.25	82.6	0.25	6.35	0.00040	10	0.0006	15	4000	2884
ABEC 5	3.25	82.6	0.25	6.35	0.00020	5.1	0.0004	10	2400	1789
ABEC 7	3.25	82.6	0.25	6.35	0.00015	3.8	0.0002	5.1	1400	1000

Table 3. Measured Angular Runouts

	ABEC	Synchronous Error Amplitude *(microradian)*	Asynchronous Error Amplitude *(microradian)*	Synchronous Error RMS *(microradian)*	Asynchronous Error RMS *(microradian)*
SN 1	3	116	13.0	52	3.0
SN 2	3	74	11.4	38	2.6
SN 3	3	90	8.4	38	2.0
SN 4	7	30	11.0	22	2.8
SN 5	7	88	12.6	36	3.0
SN 6	5	28	12.0	18	2.6

As shown in Table 3 & Figure 11, one of the ABEC 7 bearings exhibited unusually high angular runout. This ABEC 7 bearing actually had higher angular runout than some of the ABEC 3 bearings. Of course the angular runout measured for this bearing does not necessarily mean that the bearing would be rejectable per the ABMA raceway groove runout requirements. It does however, demonstrate the variation that can be seen from bearing to bearing, even at higher ABEC ratings. Interestingly, the one ABEC 5 sample outperformed both ABEC 7 samples in terms of angular runout. However, the SN 6 ABEC 5 bearing had a one piece outer race which assured that the radial runout high point of the bearing set was perfectly matched eliminating any deleterious scissoring action. The inconsistency of angular runout performance serves to illustrate the importance of “cherry picking” of bearings for high-precision applications. If “cherry picking” is performed on a sample of bearings, it is important to mark the relative clocking between both adjacent inner and adjacent outer races respectively within a given duplex pair, as the race-to-race clocking can influence the angular runout performance. The cherry-picking approach may also be used to screen for linear runouts and drag torque properties. In this case, only one relative clocking between corresponding races was tested. However, it is conceivable that relative clocking could play an influential role in the angular runout performance, such that re-clocking of the inner or outer races relative to each other could increase or decrease the measured angular runout, depending on the relative orientation of the high spots between the two races.

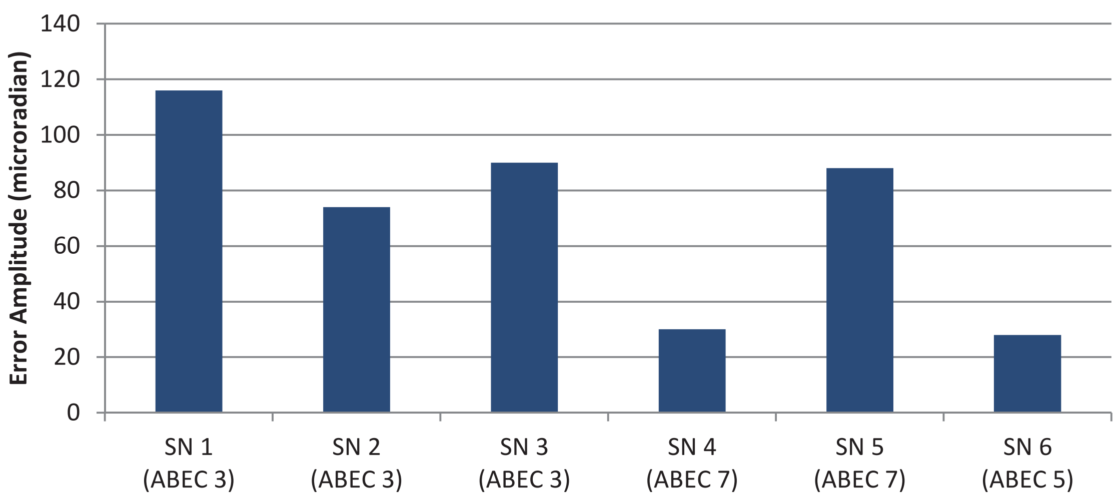


Figure 11. Maximum Synchronous Error Data

As shown in Figure 12, the asynchronous error was very low, and was nearly the same magnitude for each bearing pair, regardless of ABEC rating. The asynchronous error is most likely a manifestation of the ball accuracy (sphericity) and ball-to-ball diameter matching. The later in conjunction with raceway geometry errors dictates preload variations as the balls orbit the bearing. This is one example where the performance of the bearing pair is workmanship dependant and could vary greatly from one manufacturer to another, or even lot to lot. The repeatability of the test setup is another factor. Figure 19 shows the Asynchronous error versus angle plot for SN3.

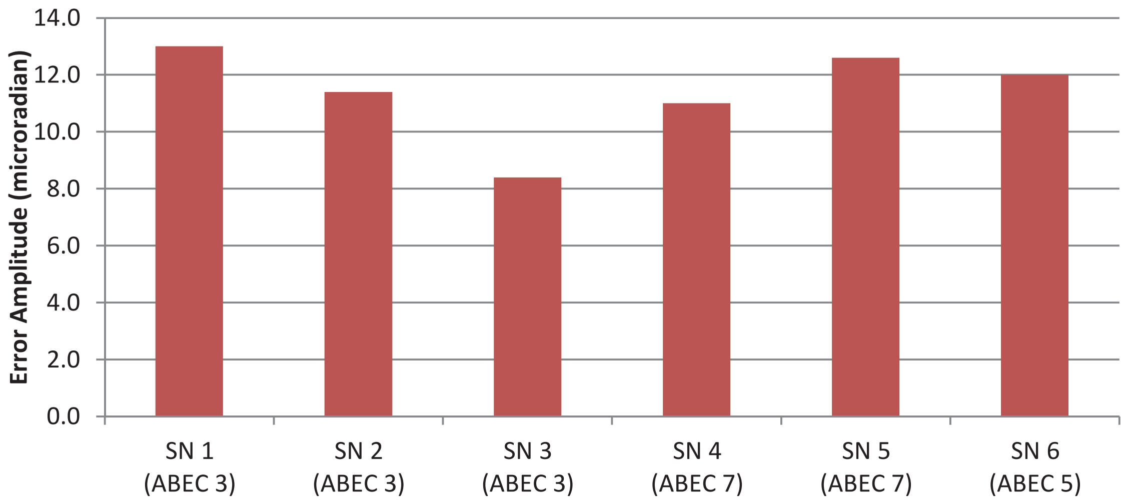


Figure 12. Maximum Asynchronous Error Data

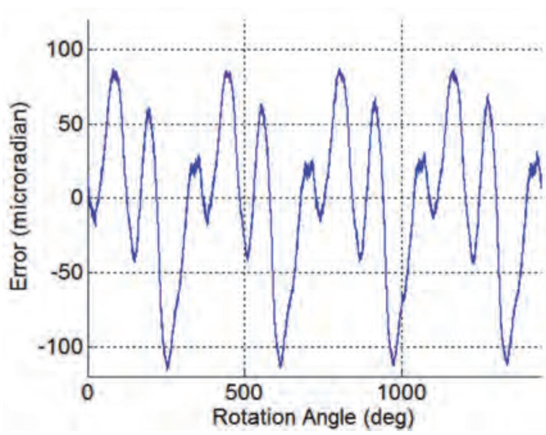


Figure 13. Synchronous Error Versus Angle SN 1 (ABEC 3)

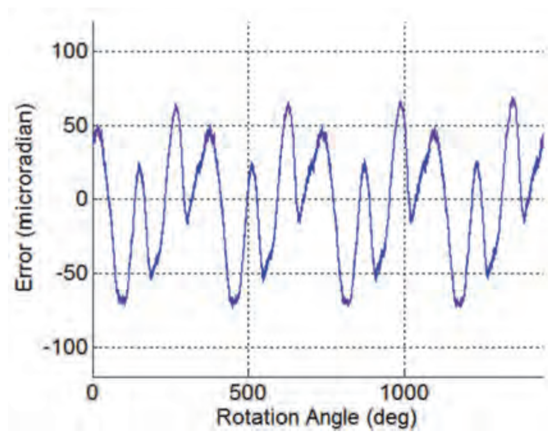


Figure 14. Synchronous Error Versus Angle SN 2 (ABEC 3)

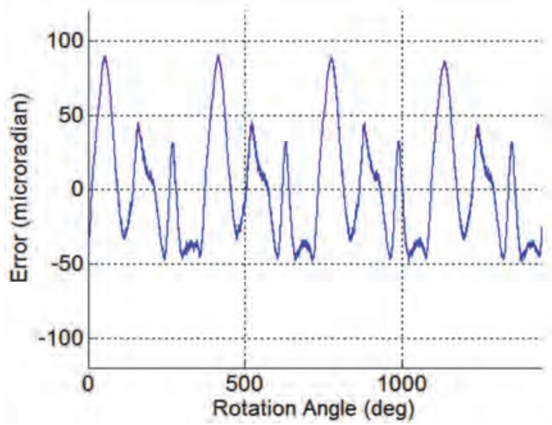


Figure 15. Synchronous Error Versus Angle SN 3 (ABEC 3)

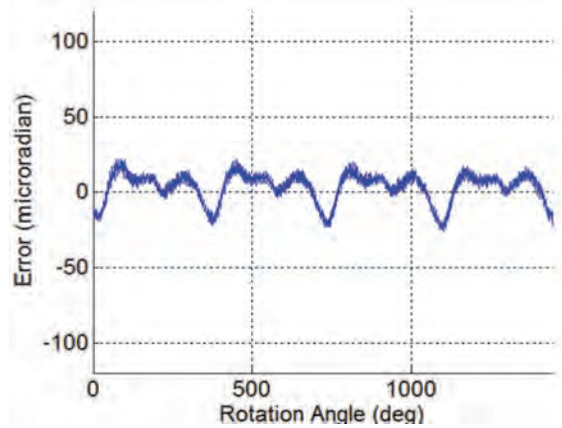


Figure 16. Synchronous Error Versus Angle SN 4 (ABEC 7)

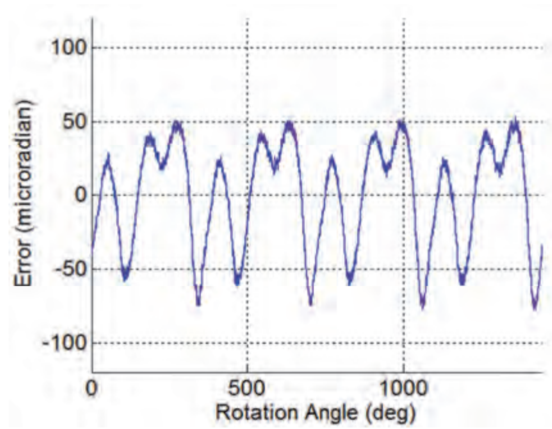


Figure 17. Synchronous Error Versus Angle SN 5 (ABEC 7)

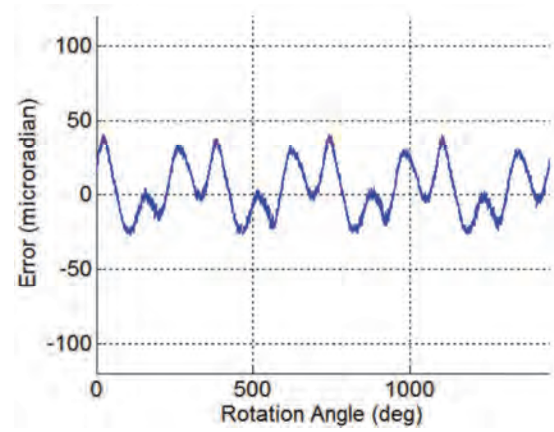


Figure 18. Synchronous Error Versus Angle SN 6 (ABEC 5)

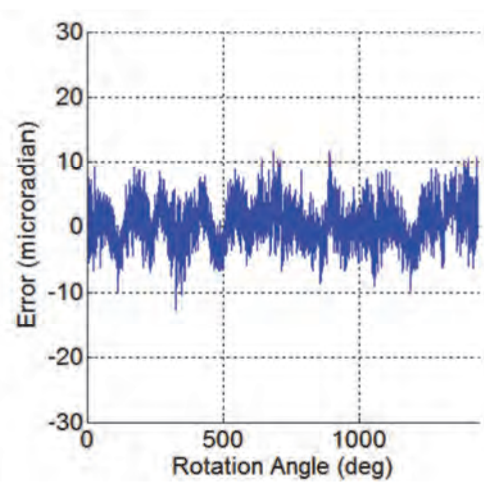


Figure 19. Asynchronous Error Versus Angle

SN 1 (ABEC 3)

A Fast Fourier Transform (FFT) analysis of the data reveals dominate spikes at 1, 2, 3, and 4 cycles per revolution. The largest and most consistent spikes occur at 3 cycles per revolution. The ball pass frequency and ball spin frequency for the bearings tested are all above 10 cycles per revolution. The large spikes at 2, 3, and 4 cycles per revolution and absence of any significant spikes above 10 cycles per revolution indicate that the angular runout of the bearings is dominated by race machining tolerances rather than ball out-of-roundness. Typically, when bearing raceways are machined, a tri-lobing of the race is the largest source of machining error. This is consistent with the dominance of the 3 cycles per revolution FFT spikes.

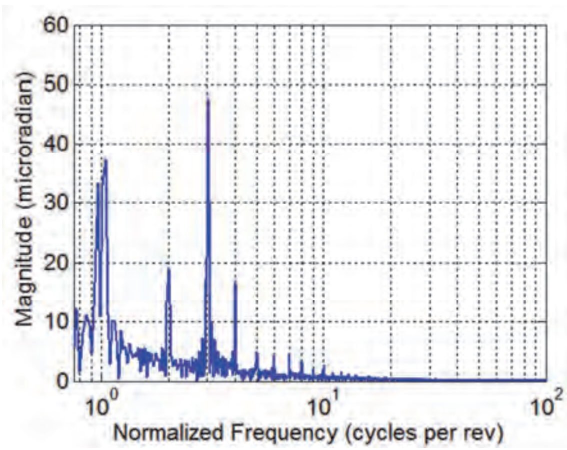


Figure 20. Magnitude vs. Cycles Per Rev SN 1 (ABEC 3)

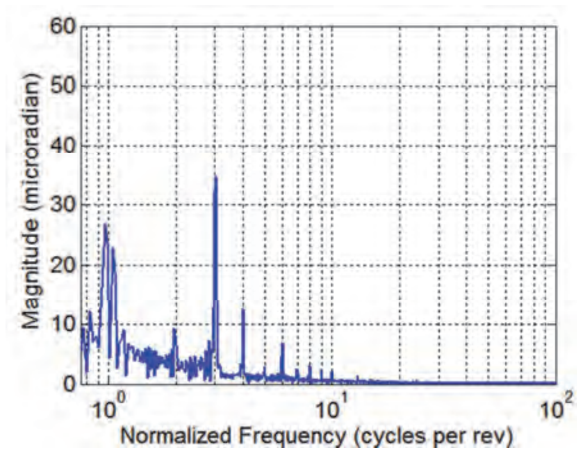


Figure 21. Magnitude vs. Cycles Per Rev SN 2 (ABEC 3)

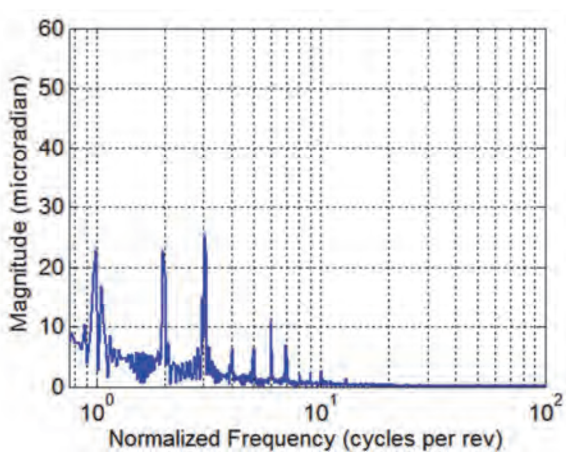


Figure 22. Magnitude vs. Cycles Per Rev SN 3 (ABEC 3)

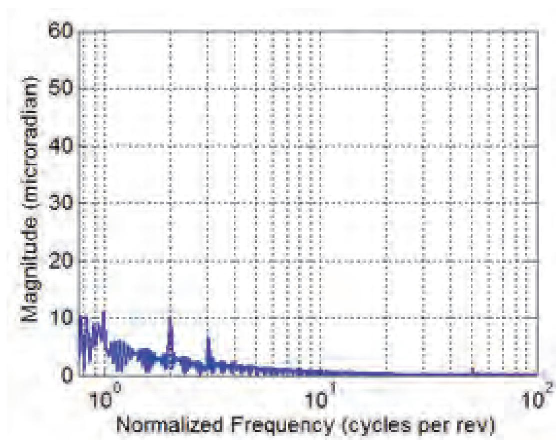


Figure 23. Magnitude vs. Cycles Per Rev SN 4 (ABEC 7)

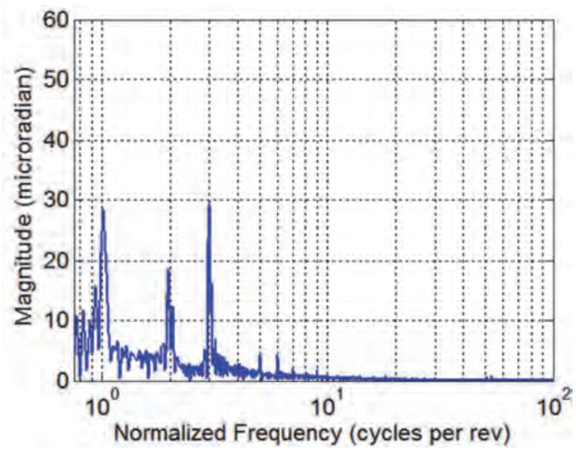


Figure 24. Magnitude vs. Cycles Per Rev SN 5 (ABEC 7)

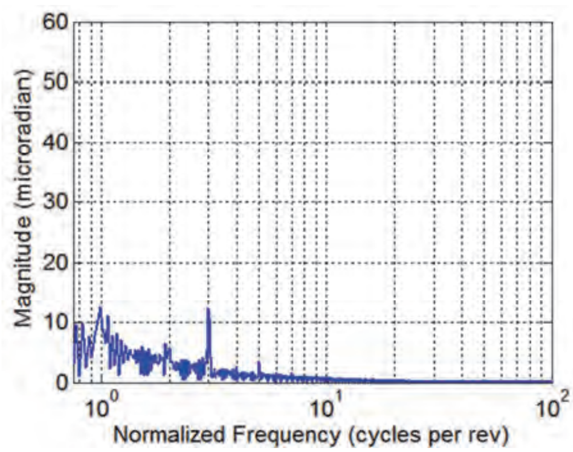


Figure 25. Magnitude vs. Cycles Per Rev SN 6 (ABEC 5)

Lessons Learned

An economical bearing fixture was initially fabricated using standard lathe tolerances, in order to determine if exotic feature grinding was necessary. After processing the initial test data, it was determined that the fixture diametral clearance to bearing race was excessive, which was made evident by a cycle-to-cycle trace precession and large asynchronous error. The error trace precession reversed directions, corresponding to the bearing rotation direction. It was concluded that the economical fixture did not provide adequate relative concentricity control between the duplex pair races. The second bearing fixture, which is the one presented in this paper, had decreased the asynchronous error substantially over the economical fixture and proved that bearing mount tolerances have a large influence over the shaft runout performance to levels similar to the bearings themselves. It can be concluded that it is imperative that bearing mount features be precision machined and ground even when using ABEC 3 bearings and especially for slim section angular contact pairs.

Test results showing relatively low asynchronous error of all three ABEC 3 bearings came as a pleasant surprise. Testing additional quantities beyond those presented is, of course, desirable for statistical data processing. From a design standpoint, the data gathered from this testing may allow much more economical ABEC 3 bearings to be used, while still meeting the same design requirements that based on the predicted angular runout, would have required ABEC 7 bearings. This serves to illustrate the development testing benefits, which lead to the relaxation of requirements and ultimately cost savings. Although designing for the worst-case predicted angular runout would have resulted in a conservative design, it would have unnecessarily driven the design to excessively tight tolerances and excessively expensive bearings.

Conclusions

Three ABEC qualities were measured for synchronous and asynchronous runouts. Although bearings with a higher ABEC rating did correlate with lower measured synchronous runout, it was also observed that asynchronous runout was relatively consistent, independent of the ABEC rating. Also bearings had significantly lower angular runout than estimated using ABMA individual race tolerances. This confirms that such analytical estimates are not a viable substitute for actual runout measurements of the assembled bearing set. Finally, in the case of ABEC 7 bearings, the behavior of two bearings acquired at the same time, from the same vendor and to the same part number did not show consistent performance. For this reason, it is recommended that for critical applications, all bearings be tested prior to assembly and that appropriate spares are procured, if the application demands superior performance consistency.

Acknowledgements

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