Acceleration Based Evaluation of Motion Errors in a High Performance Translational Exciter

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Abstract

We present the application of a digital, Microsystems Technology based accelerometer for the characterization of translational motion with ultra low nonlinear distortion, below 1 part-per-million (ppm). This motion is employed in developing filters for canceling vibration rectification in high performance accelerometers.

1 Introduction

Acceleration based displacement estimation involves double integration. From the viewpoint of signal transformation it is a dynamic operator with gain inversely proportional to the squared frequency of the integrated acceleration signals. Therefore low frequency disturbances in these signals are strongly amplified and greatly deteriorate the achievable accuracy of displacement estimation. One of critical disturbances is the Vibration Rectification Error (VRE) - an apparent shift in the signal bias that occurs when inertial sensors are subjected to vibration. Since VRE is caused by the sensors' nonlinearity, its impact can be strongly reduced by identifying this nonlinearity and using filters which suppress VRE before the integration.

We have developed an algorithmic approach to the cancellation of VRE and an experimental setup which facilitates the identification of nonlinear distortion in inertial sensors [1]. The key challenges of this effort have been (1) generation of low distortion translational harmonic excitation applied to the investigated sensors and (2) accurate measurement of the residual distortion in this excitation [2, 3]. At present we achieved the precision of motion generation and measurement better than one part-per-million and reduced the residual distortion to a sub-nanometer range.

2 Generation and measurement of accurate harmonic motion

The excitation is generated by precise air bearing stage (Aerotech ABL2000) equipped with an integral optical scale (Heidenhain LIF181) and driven by motion controller employing Internal Model Principle. Due to design constraints translations of the investigated accelerometers are not collinear with the position sensor of the stage, as can be seen on the photograph of the experimental setup in Figure 1. Therefore another sensor is employed, a Laser Doppler interferometer (Polytec OFV-552), mounted collinearly with the translations of tested accelerometers.

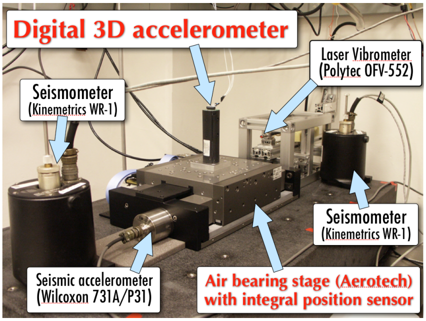
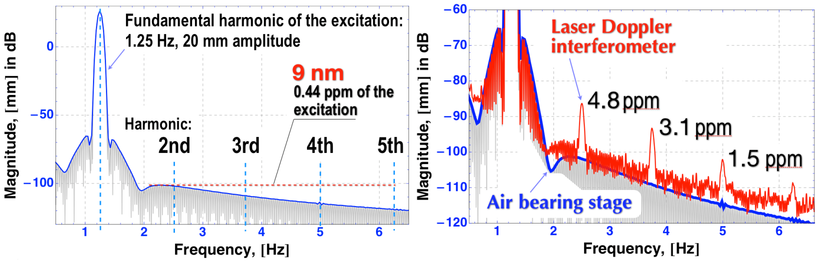


Figure 1: Experimental setup.

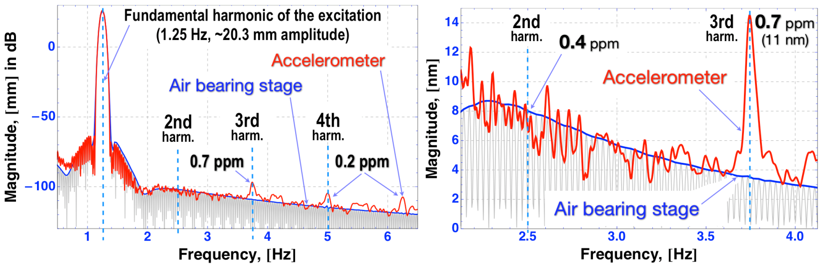
In most measurements there is a discrepancy between the stage displacement provided by the optical scale and by the laser interferometer. It is most clearly visible in the magnitude spectra of the displacement, such as shown in Figure 2. In the case under consideration the stage is excited sinusoidally with frequency 1.25 Hz and amplitude 20 mm. The magnitude spectrum of its motion measured by the optical scale shown in Figure 2a does not feature any harmonics above the noise level, which is below 9 nm (0.44 ppm of the excitation) for frequencies above 2 Hz. However, the spectrum of the laser interferometer, which is shown in Figure 2b for the low amplitude components of motion, indicates harmonics up to 4.8 ppm.



(a) (b)

Figure 2: Magnitude spectrum of the harmonic excitation measured by the integral sensor of the stage (a) and by the laser interferometer (b).

Further insight into motion errors [3] is provided by a digital accelerometer (Colibrys Model SiFlex Digital 3) mounted on the stage as shown in Figure 1. One of its horizontal axes is collinear with the beam of the laser interferometer. Magnitude spectrum of the signal from this axis, after conversion to displacement, is shown in Figure 3a. It is very close to the spectrum of displacement from the integral sensor of the stage (Heidenhain scale). A zoom on the frequency range between the 2nd and 3rd harmonics, which includes the highest apparent distortion in the acceleration based estimate of the displacement, is shown in Figure 3b. It reveals very small deviations, not exceeding 11 nanometers (0.7 ppm of the excitation), from the displacement measured by the optical scale. This leads to a conjecture that, in the case under consideration (1) nonlinear distortion in the signal from the laser interferometer is significantly stronger than the actual distortion of generated motion, and (2) digital accelerometer provides a more accurate estimate of this motion.



(a) (b)

Figure 3: Magnitude spectrum of the excitation measured by the optical scale and by the digital accelerometer (a) and a zoom on the 2nd and 3rd harmonics (b).

The availability of the digital accelerometer not only enables achieving more accurate results, but establishes a “triple redundancy” in the metrology of motion. Both features are instrumental in identifying various disturbances which affect the measurements and attenuating their impact. Of particular importance are the translational and rocking motions of the granite base on which the air bearing stage and the laser interferometer are mounted. We continuously monitor three key components of this motion (translation, pitch angle, and roll angle) by means of seismometers and seismic accelerometers shown in Figure 1. These quantities are needed to transform the measured accelerations and displacements between the involved metrology frames.

3 Evaluation of precision translational stages

Accurate, acceleration based estimation of displacement facilitates enhanced evaluation of precision motion systems. Of particular interest is the resolution of measurements which, in the case of the involved digital accelerometer, is better than 0.1 nm for frequencies above 15 Hz and 10 pm above 50 Hz. We present two brief illustrative examples in which we evaluate the pitch error motion of the involved air bearing stage. In the first example we estimate this error at the 3rd harmonic of the excitation dealt with in the previous section. For the sake of brevity (in this abstract) we assume that the optical scale and the accelerometer are error free. Knowing the Abbe offset (97 mm) and treating the 11 nm position difference between the readings of these sensors (Fig. 3b) as the Abbe error, we estimate the pitch error as 0.023 arcsec. In the second example we estimate a similar error in the case of a significantly faster and weaker excitation (10 Hz, 127 μm amplitude). We base the analysis on the results shown in Figure 4 and obtain a practically negligible pitch error of $9*10^{-4}$ arcsec.

It is noteworthy that the displacement estimated by the optical scale and by the digital accelerometer are in a good agreement and indicate approximately 5 ppm nonlinear distortion of motion. However the displacement estimated by the laser Doppler interferometer is different (164 ppm error). We attribute this discrepancy to increased vibrations of the laser head induced by translations of the stage.

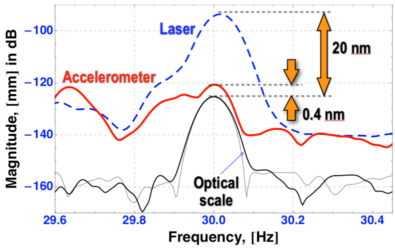


Figure 4: Magnitude spectrum of the excitation at the 3rd harmonic measured by the optical scale, digital accelerometer, and the laser.

4 Conclusions

Presented results demonstrate the feasibility of achieving precision better than one part-per-million and resolution down to picometers in the acceleration based estimation of displacement. At present such performance requires using digital, Microsystems Technology based accelerometers. Our focus is on developing corrective filters that will facilitate achieving similar performance in less expensive, smaller and more robust analog accelerometers.

References:

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