Attenuation of Ambient Disturbances in High Performance Translational Exciters

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Abstract

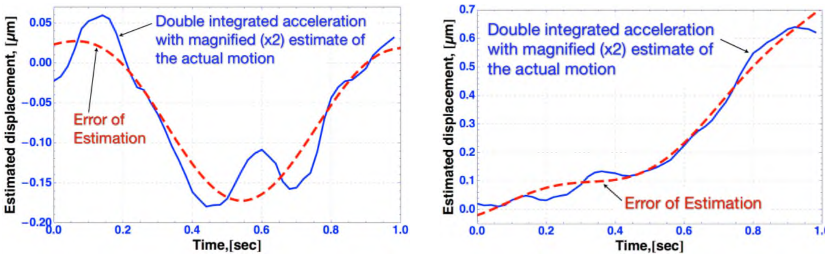
Several factors limit the accuracy of acceleration based displacement estimation. Of special interest in digital, Microsystems Technologies based accelerometers are Vibration Rectification Errors (VRE). We propose an experimental approach for separating VRE from other estimation errors and for quantifying their impact. We implement this approach with a CNC controlled air bearing stages and customized control algorithm.

1 Introduction

Various errors influence the accuracy of acceleration based estimation of displacement. A phenomenon known as the “vibration rectification” has arguably the strongest impact in high performance micro-electro-mechanical inertial sensors, such as the investigated SiFlex Digital 3 accelerometer (Applied MEMS, [1]). The effects of vibration rectification are readily visible when the accelerometer is kept at a constant position but not isolated from ambient vibrations. Estimated displacement of the sensor, obtained by integrating its output signal twice, can drift significantly. This suggests that the sensor is not useful for precision motion tracking. However, the same sensor kept motionless and isolated from vibrations typically exhibits a greatly reduced drift. This observation motivates and guides developing model based cancellation of errors caused by vibration rectification.

2 Estimation errors

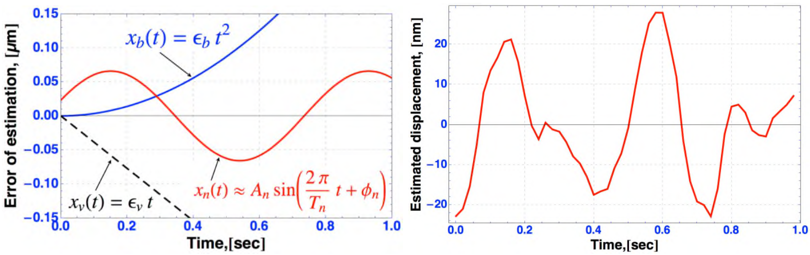
Figure 1 shows representative plots of displacement obtained by double integration of acceleration from the SiFlex digital sensor mounted on a high performance anti-vibration platform model BM4 (Minus K Technology). The plots have substantially different shape and suggest that, over the period of one second, the peak displacement of the platform can reach 600 nm (Figure 1b), the amount unlikely in this test.



(a) **(b)**

Figure 1: Representative estimates of the platform's displacement.

The shape of estimated displacement is inconsistent because of four kinds of errors associated with the conversion of acceleration to displacement. One of these errors is the uncertainty of sensor bias[1], ε_b. It can be assumed constant during short measurements. Double integration of ε_b produces a quadratic drift $x_b(t) = \varepsilon_b t^2$ shown in Figure 2a. The second kind of errors, ε_v, is associated with the initial velocity of the sensor, which has to be estimated from the measured acceleration. Slight fluctuation of this latter signal at the beginning of the integration is the most common cause of these errors. Integration of ε_v produces a linear drift $x_v(t) = \varepsilon_v t$ shown in Fig. 2a.



(a) **(b)**

Figure 2: Representative error components (a) and estimated actual displacement (b).

The third kind of errors is usually a low frequency disturbance, such as the sensor noise, strongly amplified by the integration. From the viewpoint of signal transformation double integration is a dynamic operator with gain inversely proportional to the squared frequency of the integrated signals. Thus it is reasonable to expect that these latter errors have a nearly sinusoidal shape, $x_n(t) \approx A_n \sin(2\pi \cdot t / T_n + \phi_n)$ where the value of T_n is close to the measurement period. The fourth kind of errors is due to

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[1] Computed here as a mean value of the acceleration over the period of integration.

the vibration rectification, an apparent shift $\varepsilon_{VR}(t)$ in the sensor bias, which occurs when inertial sensors are subjected to vibration. Its double integration produces a drift $x_{VR}(t) = \int_0^t \varepsilon_{VR}(t)dt$. In addition to the above errors the estimated displacement contains a mechanical disturbance $x_m(t)$, which is the actual motion of the anti-vibration platform with reference to the Universal Inertial Coordinates of the Earth (UICS). This disturbance distorts the estimates of ε_b and ε_v, and causes vibration rectification. Since in the analyzed case there is no intentional motion of the investigated accelerometer, its double integrated output signal $a(t)$ equals to the sum of the above four errors and the mechanical disturbance $x_m(t)$.

$$\iint_t a(t)dt = x_v(t) + x_b(t) + x_d(t) + x_{VR}(t) + x_m(t)$$

$$\approx \varepsilon_v t + \varepsilon_b t^2 + A_n \sin(\omega_n \frac{t}{T} + \phi_n) + \int_0^t \varepsilon_{VR}(t)dt + x_m(t) \tag{1}$$

Given the above expression we extract from the acceleration based estimates of displacement, such as shown in Figure 1, the linear, quadratic, and sinusoidal components corresponding to the first three terms in Eq. (1). Their example profiles are shown in Figure 2a and their sum gives the dashed lines designated Error of Estimation in Figure 1. The remaining two terms in Eq. (1) can not be separated by estimation techniques.

3 Experimental setup

In this research we focus on achieving the separation of error components and their control by precise generation and measurement of the mechanical disturbance component $x_m(t)$. Since commercial anti-vibration platforms do not provide such capability and suffer from insufficient attenuation of low frequency disturbances, we designed the needed system [2]. Its active components are numerically controlled air bearing stages mounted on a heavy granite slab. The slab is supported by three passive high performance anti-vibration platforms (BM-1, Minus K Technology). Spatial residual motion of the slab relative to UICS is estimated by employing precise inertial sensors: seismometers (Kinemetrics) and laboratory grade accelerometers (Wilcoxon). A component of this motion aligned with the guideways of the air bearing stages, which is the quantity $x_m(t)$ defined above, is fed into the CNC controller of the "master stage". This facilitates a modification of the control effort such that the table of this stage, which carries the evaluated accelerometers, can (1) remain motionless, or (2) be excited in any desirable way with reference to UICS (the condition true only along the controlled axis of the stage). Control requirements that have to be satisfied are characterized in Figure 3, which shows spectral density of vibration recorded by the tested digital Siflex accelerometer mounted on the anti-vibration platform and on the stage. For any frequency it is necessary to correct the position of the stage such that the displacement designated "Currently tested sensor: On the stage" does not go over the line "Currently tested sensor: Specifications". This latter line is defined by the electrical noise of the sensor. Experimental results indicate the feasibility of active vibration cancellation by the stage up to 10 Hz. Above this level sufficient cancellation is assured by the employed passive anti-vibration platforms.

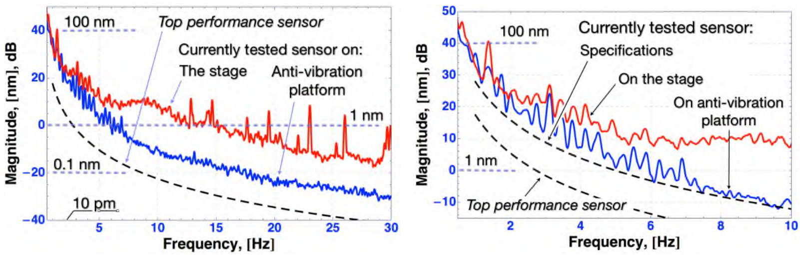

Figure 3: Spectral density of vibration of the stage and anti-vibration platform.

4 Conclusions

Presented experimental setup combines active and passive cancellation of ambient disturbances to facilitate generation of precise excitations needed for testing high performance accelerometers. To investigate the vibration rectification phenomenon in these sensors and design filters for attenuating its impact, the setup is optimized to deliver harmonic translations, relative to the Universal Inertial Coordinates of the Earth, with amplitudes in the range from nanometers up to 50 mm and with extremely low distortion.

References:

[1] H. Goldberg, et. al., An Extremely Low-Noise MST Accelerometer Using Custom ASIC Circuitry, Proc. Sensors Expo, (2000), 479-482.

[2] Spiewak S., et al., A Test Setup for Evaluation of Harmonic Distortions in Precision Inertial Sensors, ASME J. of Manuf. Science and Engineering (submitted)