Performance Limits of Active Vibration Isolation Systems for Precision Equipment

D. Tjepkema[1], J. van Dijk[1], H.M.J.R. Soemers[1,2]
[1]*Mechanical Automation and Mechatronics, University of Twente, The Netherlands*
[2]*Philips Applied Technologies, The Netherlands*

d.tjepkema@utwente.nl

Abstract

This paper discusses the performance limits of active vibration isolation systems due to sensor and actuator noise. The contribution of the sensor noise to the overall performance is analyzed for five suitable sensors. In addition, the contribution of actuator noise and ways how to reduce it are discussed.

1 Introduction

Vibration isolation systems are used in precision equipment to facilitate the disturbance rejection from floor vibrations and disturbance forces due to accelerating stages, cables, etc. Active elements can be used to increase the performance of vibration isolation systems, for example by adding artificial damping to suspension modes and structural modes of the supported machine or by lowering the suspension mode frequencies. However, active elements introduce additional noise sources that may limit the performance of those active vibration isolation systems. Because the vibration levels are in general very small, actuators, sensors and electronics with very low noise levels are required.

2 Performance of vibration isolation systems

The performance of a vibration isolation system is determined by the machine's acceleration level. If the expected floor motion is known, based on measurements at sites, and the transmissibility curve of the vibration isolation system is chosen, the machine's acceleration level can be computed. For example, if the floor motion is restricted to 3 μm/s RMS (VC-E curve) and the transmissibility curve is that of a state-of-the-art vibration isolation system with a 1 Hz corner frequency as shown in Figure 1 (left), the resulting machine's acceleration level is that of the grey line in

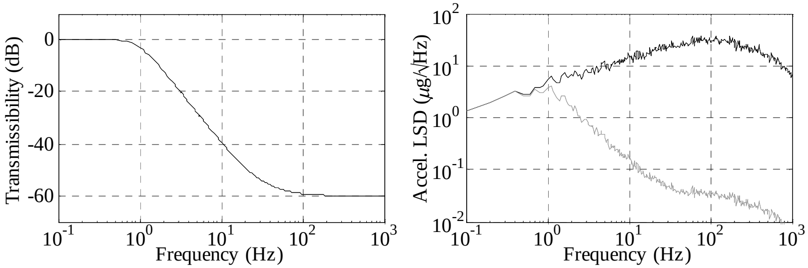

Figure 1: Transmissibility of a state-of-the-art vibration isolation system (left) and corresponding spectra of floor motion in black and machine motion in grey (right).

Figure 1 (right). Then the sensor and actuator noise are expressed as their contributions to the total machine's acceleration level. These contributions may not exceed the desired machine acceleration, in case of using a feedback controller for the active vibration isolation system.

3 Sensor and actuator noise

The noise contributions to the performance of an active vibration isolation system can be evaluated with the use of the block diagram of Figure 2. The transfer function $T_{\mathrm{sens}}(s)$ from sensor noise n_{sens} to acceleration $\ddot{x}$ is $T_{\mathrm{sens}}(s) = -S(s)P_{\ddot{x}}(s)C(s)$ in which $S(s)$ is the sensitivity function and $P_{\ddot{x}}(s)$ is the transfer function from actuator force $\hat{F}_{\mathrm{act}}$ to acceleration $\ddot{x}$. $T_{\mathrm{sens}}(s)$ is usually constant within the controller's bandwidth and has lower values beyond it. The transfer function $T_{\mathrm{act}}(s)$ from actuator noise n_{act} to acceleration $\ddot{x}$ is $T_{\mathrm{act}}(s) = -S(s)P_{\ddot{x}}(s)$ which has typically the highest gain at frequencies beyond the controller's bandwidth. The contributions of those

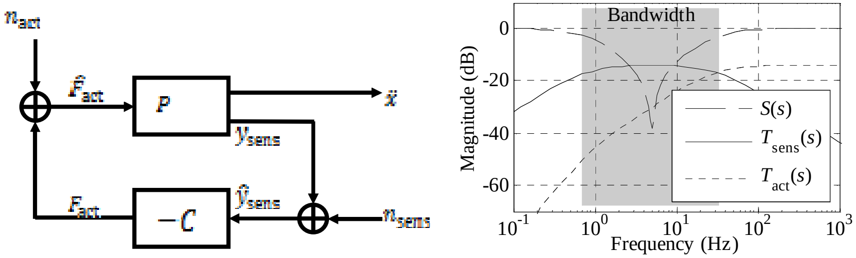

Figure 2: Block scheme of a vibration isolation system subjected to actuator and sensor noise (left) and typical transfer functions of $S(s)$, $T_{\mathrm{sens}}(s)$ and $T_{\mathrm{act}}(s)$ (right).

noise terms to the acceleration spectrum of a 5 kg machine can be calculated by $P_{\ddot{x}\ddot{x}}(f) = |T_{sens}(f)|^2 P_{sens}(f)$ and $P_{\ddot{x}\ddot{x}}(f) = |T_{act}(f)|^2 P_{act}(f)$ in which $P_{sens}(f)$ and $P_{act}(f)$ are the power spectra of the sensor and actuator noise, see Figure 2 (right).

3.1 Sensor noise

We evaluated five state-of-the-art sensors suitable for use in active vibration isolation systems: a piezo-electric accelerometer (MMF KB12VD), a capacitive MEMS accelerometer (Colibrys SiFlex 1500), a geophone (GeoSpace GS-11D), a piezo-electric force sensor (Bruel and Kjaer 8001) and a displacement capacitive probe (Lion precision C5). Using the expressions for the theoretical noise levels as derived in [1], and the specifications in data sheets, the noise spectra $P_{sens}(f)$ are calculated.

The noise in the accelerometers is mainly caused by thermo-electric noise of the capacitive element and is proportional to the sensor's capacitance divided by the square of the sensitivity. The level is constant or even decreasing for increasing frequency. The geophone's noise is mainly caused by the current noise of the opamps used to amplify the measurement signal. The geophone's noise is the lowest at its resonance frequency and is increasing with increasing frequency. The noise of the force sensor is also caused by thermo-electric noise of the capacitive element. However, the contribution to the machine's noise level is much smaller compared to the piezo-electric accelerometer. This is because it has a much larger sensitivity with the same capacitance. Finally, the noise of the capacitive displacement sensor is determined by its resolution, which is about 1 nm RMS for the C5 probe. The noise level is very small at low frequencies but is increasing rapidly with frequency.

Figure 3 (left) shows the theoretical noise levels of those five sensors as their contributions to the machine's acceleration level as well as the desired machine acceleration level. The actual noise levels of the MMF, Geospace and Bruel and Kjaer sensors are measured as well (not shown here). The measured levels resemble the theoretical levels very well and differ only a factor 2 at maximum (when neglecting the harmonics of the 50 Hz power supply). The difference is expected to be caused by the used signal conditioners that increase the noise level a little. From this it is concluded that the performance of the entire sensor system is limited by the fundamental noise levels of the analyzed sensors their selves and not by the electronics required for signal conditioning.

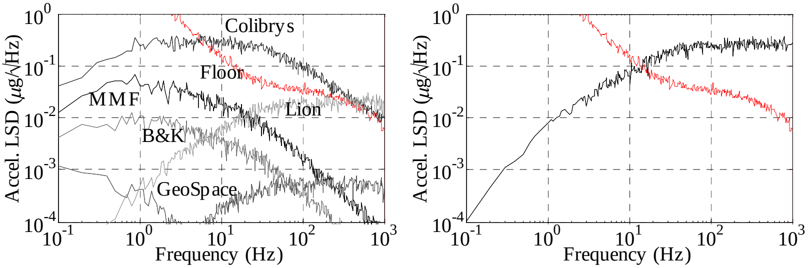

Figure 3: Theoretical contributions of sensor noise to the machine's acceleration level (left) and quantization noise to the machine's acceleration level (right).

3.2 Actuator noise

The actuator noise is mainly caused by the DAC's quantization noise. For example, the 16 bits DAC used in the vibration isolation setup described in [1], generates a voltage that can be converted to an equivalent force with standard deviation 0.5 [mN]. Its resulting contribution to the machine's acceleration is that of Figure 3 (right). It is the highest at high frequencies. To minimize the contribution of quantization noise, it is critical to match the power amplifier to the expected power consumption of the actuator. Alternatively, a transmission mechanism in the actuator could be used to reduce the actuator's noise contribution to the machine's motion level [2].

4 Summary

The contributions of sensor and actuator noise to the acceleration level of the supported machine limit the performance of active vibration isolation systems. A selection of suitable sensors is analyzed and considerations for reducing the actuator noise are given. Future work will focus on optimizing the performance of an active vibration isolation system by choosing the best control strategy for each sensor type and by minimizing the contribution of actuator noise.

References:

[1] Van der Poel, G.W. et al., *Selection of motion sensors for hard mount active vibration isolation*, in Intern. Conf. Motion Vibr. Contr. (MOVIC), 2008.

[2] Claeyssen F., *Amplified piezo-electric actuators for air and space applications*, in AERO India, 2003.