Low-frequency Vibration Isolation in Six Degrees of Freedom: The Hummingbird.

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Abstract

TNO Science and Industry and MECAL have developed a six degree of freedom vibration isolation system that suppresses both floor vibrations and direct forces on a table top. The achieved reduction of transmissibility and compliance is 40 dB between 1 and 50 Hz in vertical direction, and 30 dB between 1 and 20 Hz in horizontal direction. Key elements of the system are a newly designed absolute vibration sensor, and two solutions to the horizontal tilting problem.

1 Vibration isolation problems and limitations

Many high-end technological systems have sub-optimal performance due to ground vibrations and force disturbances. Prominent examples are laboratory facilities for calibration, optical measurement systems, space equipment, but also advanced microscopes and lithography systems.

Ground vibrations and force disturbances, caused for instance by traffic or equipment, often peak between 1 and 50 Hz [1]. These disturbances result in a loss of performance in systems with internal flexible modes in and far above this frequency region. There is currently no commercial solution for significant vibration isolation in the entire frequency band of 1 to 50 Hz.

For frequencies above 10 Hz, passive vibration isolation is an attractive option, if two drawbacks are acceptable: the strong amplification of disturbances around the vibration isolation system's resonance frequency, and the increased compliance for moving masses. For frequencies below 10 Hz, it is more complicated to obtain significant vibration isolation. The required low resonance frequency (<0.1 Hz) is difficult to obtain in normal dimensions, and leads to an even higher compliance of the payload for moving masses.

Active vibration isolation, using inertial motion sensors to provide absolute motion information of the payload, can reduce both the transmissibility. For lower

frequencies however, the measurement performance of inertial motion sensors is insufficient. Therefore, the first step to obtain significant vibration isolation at low frequencies with active vibration isolation is to realize an absolute vibration sensor with sufficient signal to noise (SNR) ratio.
The second limitation is the susceptibility of horizontal motion sensors to gravity. When the payload is tilted, the motion sensor can not distinguish between gravity and inertial motion of the payload. This leads to a strong reduction in performance and possible oscillation of the payload.

2 Key design elements of the Hummingbird

The Hummingbird system is designed to provide a reduction of ground vibrations and force disturbances by at least 30 dB between 1 and 50 Hz, in all DoF. The system consists of a frame with three passive suspensions, and a bread board table top of standard dimensions (see Figure 1). Vibration isolation modules, consisting of collocated horizontal and vertical actuator-sensor pairs, are added between the frame and the table top.

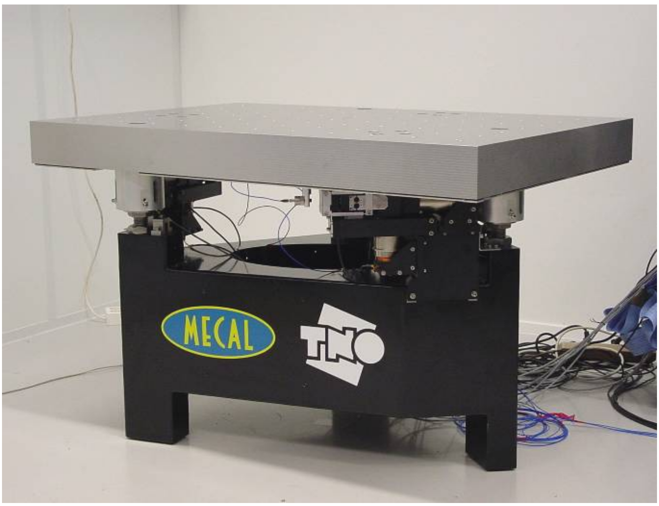

Figure 1: The Hummingbird, a six degree of freedom (DoF) active vibration isolation system that reduces both ground vibrations and force disturbances between 1 and 50 Hz.

2.1 Vibration sensor and configuration

To obtain the desired low noise level for the Hummingbird, an accelerometer with an extremely low resonance frequency of 2 Hz is developed. Below this frequency, the sensor provides acceleration information with extremely high SNR. Above this frequency, the sensor provides absolute position information which is extremely accurate within the band width of interest. The equivalent performance of the sensor is 1 ng / rt Hz between 0.05 and 2 Hz, and 0.02 nm / rt Hz between 2 and 140 Hz. By attaching the newly developed vibration sensor rigidly to the table top, a controller and actuator can minimize both the acceleration and the position signal.

2.2 Susceptibility of horizontal sensors to gravitation

As the vibration sensor is attached to the payload, it experiences the same tilt as the payload. Due to gravity, the sensors will measure a false acceleration of the payload. For horizontal sensors, this leads to a strong disturbance on the measurement signal. In closed loop, this will lead to a strongly reduced performance in horizontal direction, and possibly uncontrollable oscillation of the payload. Two solution paths were studied in detail: (1) Numerical compensation and (2) mechanical compensation of the horizontal tilting effect.

(1) The tilt of the payload is measured by three vertical motion sensors. By integrating the low frequency acceleration signal twice and estimating the coupling to the horizontal sensors, the tilting effect can be compensated.

(2) The tilting of the horizontal sensor around its sensitive axis can be prevented by attaching the sensor with only five DoF to the payload. The remaining DoF can be attached to the frame through a flexure mechanism. This flexure mechanism can be designed such that it contributes minimally to the stiffness between frame and payload, and has internal resonances above the band width of interest.

3 Performance test results

A plot of the measured transmissibility of the Hummingbird in open and closed loop is shown in Figure 2. The system was configured for the numerical compensation solution. The reduction of ground vibrations in vertical direction is 40 dB at 1 Hz, with a band width of 45 Hz. The reduction in horizontal direction is 30 dB at 1 Hz, with a band width of 20 Hz. The main limitation on the horizontal band width is the spurious frequency of the horizontal sensor. Due to the imperfection of the numerical compensation, the system showed some oscillation around 0.1 Hz.

In the mechanical compensation configuration, comparable reduction and band widths were achieved. In this case, the horizontal band width was limited also by resonance frequencies of the frame that appeared in the vibration sensor. This configuration showed no low frequency oscillation whatsoever.

Both configurations showed the above presented reduction of ground vibrations on a floor that had lower background vibrations than VC-E [1].

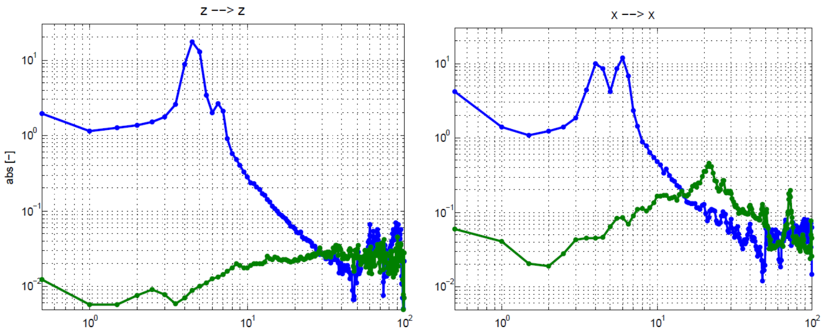

Figure 1: Left: transmissibility reduction in vertical direction. Right: transmissibility reduction in one horizontal direction.

4 Conclusions

The Hummingbird provides significant reduction of ground vibrations and force disturbances between 1 and 50 Hz, which is currently unprecedented in commercial vibration isolation systems. Through optimal use of a newly developed vibration sensor and innovative solutions to the horizontal tilting problem, the reduction factor of 30 dB in all directions is achieved.

In horizontal direction, the band width of the reduction is still limited. A solution is currently being studied in detail.

References:

[1] Generic criteria for vibration sensitive equipment, Gordon CG, Proc. SPIE Optomech. Eng. Vib. Control, 3786, 22-33 (1999).