6-DoF Active Vibration Isolation without Tilt-Horizontal Coupling

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Abstract

High precision measurement instruments, like electron microscopes, aim for imaging resolutions of 100 picometer (pm) RMS. The maximum relative position between sample and the measurement components should be in the order of 25 pm RMS. To reach this high accuracy the instrument is placed on a vibration isolated platform. The positioning stages in these high end measurement systems typically have a bandwidth in the order of 150 Hz. The maximum allowed vibration levels are estimated to be: $\ddot{x}_{\max} = error \cdot (2\pi f_{BW})^2 \approx 40 \mu m / s^2$ RMS. An active vibration isolation system can be used to reach this performance. The active vibration isolation requires a high bandwidth to reject external noise sources and low noise sensors to limit self excitation. MI-Partners has developed an active vibration isolation system (AVI) with a high bandwidth and low noise components.

1 Reaching high bandwidth in 6-DoF

The developed vibration isolation system uses the sky-hook damping technique to suppress external vibrations. In sky-hook damping, a geophone forms an absolute velocity sensor reference for payload vibrations. An active controller translates these velocity signals into damping force acting on the isolated payload, see Figure 1.

A limiting factor for achieving high error suppression in the horizontal plane is caused by the tilt horizontal coupling in the geophone. At low frequencies the geophone is sensitive to both the linear velocity as well as tilt, due to the influence of gravity forces, see Figure 2. Thus the stability of feedback and performance is endangered by additional dynamics at low frequencies (below 1 Hz). An example of a system suffering from tilt horizontal coupling is shown in Figure 3.

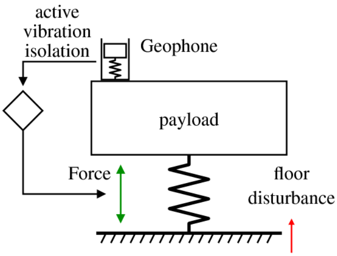
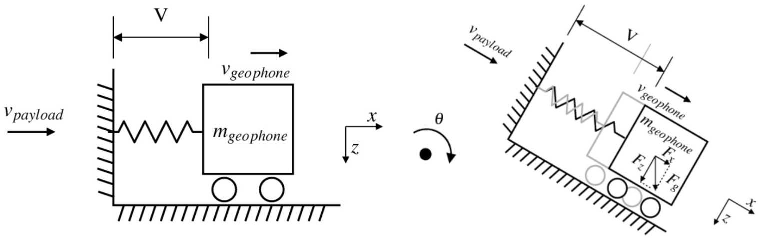


Figure 1: Vibration isolation using sky-hook damping. The geophone forms an absolute velocity signal passed through a controller generating a damping force.



(a) (b)

Figure 2: Horizontal geophone. The difference in velocity between the payload and the mass of the geophone is a measure for the relative velocity of the payload. A voltage, V is induced by a relative displacement of a magnetic field and a coil (a). The geophone is measures tilt through the influence of gravity forces F_g . (b)

The negative influence of tilt horizontal coupling can be reduced by careful sensor and actuator placement or by using a separate tilt sensor for compensating the tilting dynamics in the geophone. The first solution significantly restricts actuator and sensor placement and the second solution leads to more control complexity. MI-partners has taken a different approach to reduce the influence of tilt horizontal coupling.

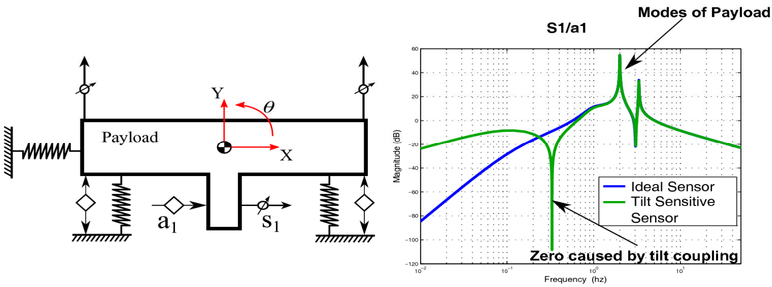


Figure 3: A typical layout of a vibration isolation system (left). The horizontal actuator (a1) and sensor (s1) suffer from tilt horizontal coupling. Open-loop Bode diagram of a sky-hook control loop showing the difference between an ideal sensor and a sensor suffering from tilt coupling (right).

2 Solution to tilt horizontal coupling

The solution developed by MI-Partners to the tilt-horizontal coupling problem is a mechanical Guide which constrains tilting motions of the geophone by connecting these to the fixed world using elastic elements. Figure 4 shows a schematic of this solution. An elastic element constrains the motion of the geophone such that tilting motions are constrained; while the Stinger transfers the horizontal motion of the payload to the geophone assembly. Presently, it has come to the author’s attention that a similar solution was presented in a newly disclosed patent application [2]. The authors were not aware of this publication during the development of the system.

4 System Performance

The geophone assembly was developed and integrated into the AVI system. A closed loop vibration suppression is achieved between 0.3 Hz and 40 Hz, with a 40 dB reduction at 3 Hz! The measured levels in horizontal direction are 37μm/s^2 RMS, while in the vertical direction 24μm/s^2 RMS is achieved. This was measured on a floor with peak accelerations equal to a BBN-D floor [1]. This shows the AVI system is clearly suitable for the most high end precision measurement equipment in horizontal and vertical directions.

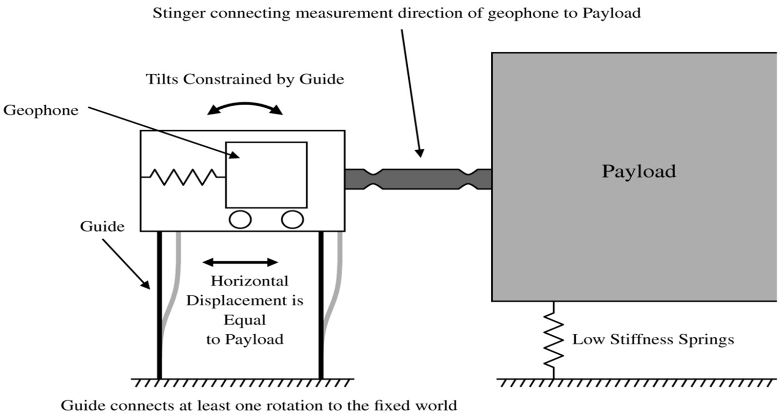


Figure 4: Novel idea for solving issues regarding tilt horizontal coupling. The Guide stiffness allows a horizontal motion of the geophone, while constraining tilting motions. In the measurement direction the geophone is stiffly connected to the payload.

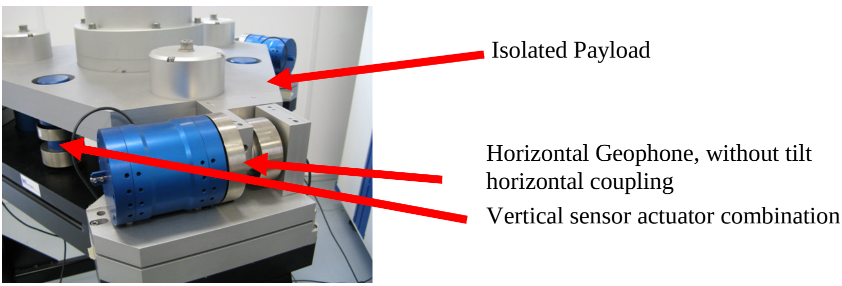


Figure 5: AVI vibration isolation platform with novel horizontal sensors without tilt horizontal coupling

References:

[1] The Mystery of Active Vibration Isolation, *J. van Eijk, D.A.H. Laro, J. Eisinger, W.W.J. Aarden, C.J.M van den Berg,*
Proceedings Euspen 2011

[2] An active vibration isolation and damping system, N. *Rijnveld, T. van den Dool, TNO,* patent nr: WO2010/143959