# Active vibration isolation of high precision machines

**Article** *in* Diamond Light Source Proceedings · October 2011

DOI: 10.1017/S2044820110000134 · Source: OAI

# Active vibration isolation of high precision machines

Collette, C (CERN) *et al*

21 January 2011

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no. 227579.

This work is part of EuCARD Work Package **9: Technology for normal conducting higher energy linear accelerators**.

*Diamond Light Source Proceedings*, Vol 1, e1, page 1 of 5
MEDSI-6 2010

doi:10.1017/S2044820110000134

Contributed paper

# Active vibration isolation of high precision machines

C. COLLETTE†, S. JANSSENS, K. ARTOOS AND
C. HAUVILLER
European Organization for Nuclear Research CH-1211 Geneva 23, Switzerland

(Received 15 June 2010; accepted 26 August 2010)

This paper provides a review of active control strategies used to isolate high-precisionmachines (e.g. telescopes, particle colliders, interferometers, lithography machines or atomic force microscopes) from external disturbances. The objective of this review is to provide tools to develop the best strategy for a given application. Firstly, the main strategies are presented and compared, using single degree of freedom models. Secondly, the case of huge structures constituted of a large number of elements, like particle colliders or segmented telescopes, is considered.

## 1. Introduction

Ultra-high-precision machines are used increasingly in various fields of engineering. They become more sensitive to vibration as the precision increases and their size increases. In addition to this, large precision structures are made of a very large number of components, sometimes thousands (e.g. segments of a telescope), which makes them more complex and more difficult to control; a few examples are given in figure 1.

There is an emblematic example of the clean rooms of the science park in Taiwan, which were no longer able to operate after the inauguration of the high-speed train line which was passing next to the park, because of the vibrations transmitted through the ground. It is fair to say that extreme precision machines are always associated with vibration problems, and the problem culminates when these structures are extremely large as giant telescopes, interferometers and particle accelerators. Vibration alleviation is often obtained in two steps: (i) stability enhancement by vibration isolation, vibration damping and disturbance rejection, and (ii) precision pointing and positioning. The details of the control strategy depends on specific features of the machine involved (Table 1).

This paper is organized as follows. Section 2 reviews the basic concept used for active vibration isolation. Section 3 discusses the case of huge structures, constituted of a large number of elements, like particle colliders or segmented telescopes.

---

† Email address for correspondence: christophe.collette@cern.ch

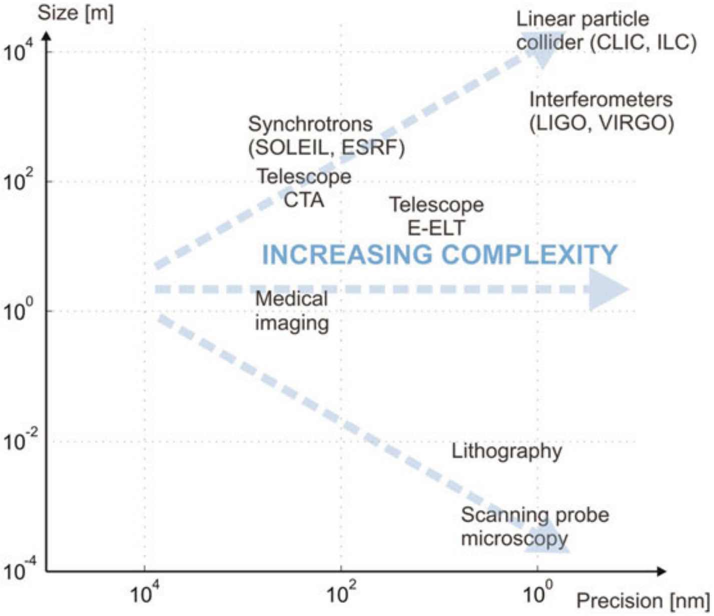

FIGURE 1. Size versus precision for some precision engineering applications.

## 2. Single degree of freedom

For a passive suspension, the typical transmissibility $T_{\mathrm{wx}}(f)$ between the ground and the payload is shown by the solid line in figure 2. It is equal to 1 at low frequency, shows an overshoot at the resonance of the payload on the support stiffness, and then decreases with a slope comprised between power –1 and –2 at higher frequency. A drastic reduction of the amplitude of the overshoot can be obtained without degradation of the roll-off at high frequency in two ways: either passively by increasing the passive damping in the suspension and a relaxation isolator (see Preumont (2006) for an electromagnetic realization) or actively using the well-known skyhook strategy (Karnopp, Crosby & Harwood 1974). However, an improvement of the passive isolation (transmissibility lower than 1) can only be obtained by decreasing the resonance of the payload (e.g. at 2 Hz in figure 2). Although it is increasingly difficult to achieve for low frequencies, it also leads to an increased susceptibility to disturbance forces directly applied on the payload. This is the main reason why efficient low-frequency seismic isolation can only be obtained actively.

Figure 3 shows three classical strategies used for active isolation. Strategies (a) and (b) are based on the use of an inertial reference, fixed on the payload

| | Stability | Positioning |
|---|---|---|
| Particle collider | Active stabilization | Quadrupole alignment/final focus |
| Telescope | Active optics | Adaptive optics |
| Interferometer | Active isolation and damping | Delay lines |
| Lithography | Active isolation and damping | Nano-positioning |

TABLE 1. Active control in precision engineering applications.

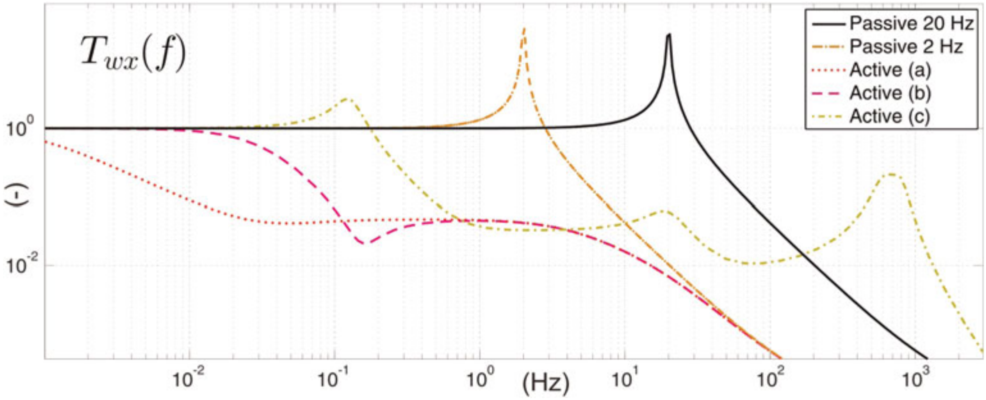

FIGURE 2. Typical transmissibilities $T_{wx}(f)$ between the ground and the payload for various passive and active isolation strategies.

(Saulson 1894; Nelson 1991; Collette *et al.*, 2010) or directly on the ground (Vervoordeldonk Ruijl & Rijs 2004; Vervoordeldonk & Stoutjesdijk 2006; Kar-Leung Miu 2008).

This inertial reference is an oscillator with an extremely low resonance frequency, as in a seismometer. A capacitive sensor is used to measure the motion of the payload with respect to the reference. An important advantage of strategy (*b*) over (*a*) is that it is robust to external force. Strategy (*c*) consists of a small intermediate mass mounted on a stiff piezoelectric actuator, and in series with a rubber part (Schubert, Beard & von Flotow 1994; Schubert *et al.* 1997). A geophone measures the velocity of the intermediate mass and a capacitive sensor measures the relative displacement between the small mass and the payload. Typical transmissibilities obtained with these strategies are also shown in figure 2.

## 3. Segmented structures

The strategies discussed in the previous section are dedicated to mitigate the transmission of ground vibrations to a payload. When the payload has several degrees of freedom, independent (decentralized) controllers can be applied in each active mount (e.g. Schubert, Beard & von Flotow 1994, Schubert *et al.* 1997). However, when the structure is composed of many different elements, it is not

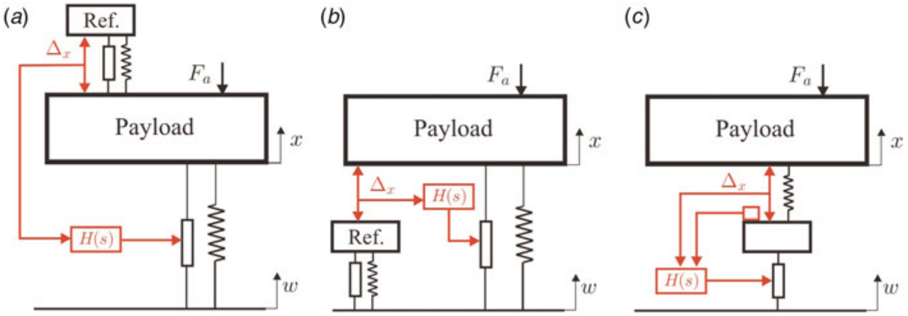

FIGURE 3. Three classical active isolation strategies.

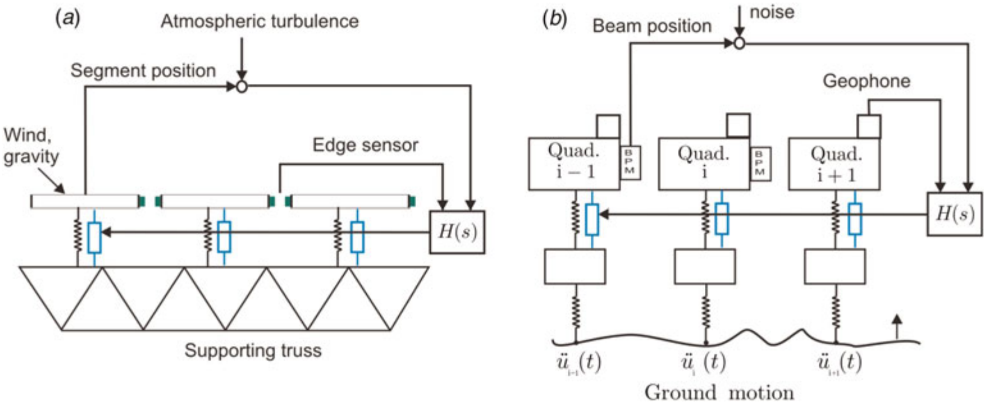

FIGURE 4. (*a*) Active optics flow for the large segmented mirror of a telescope (adapted from Bastaits *et al.* (2009)); (*b*) beam-based feedback flow for the alignment of a particle collider.

only important to stabilize each of them, but even more important to ensure the relative stability between each other. Figure 4 shows a schematic view of the controller used for (*a*) the *active optics* for the primary mirror of a telescope and (*b*) the *beam-based feedback* for a particle collider.

In both cases, there exists a linear relationship between the set of sensors (edge sensors or beam position monitors) and actuators (position actuators or corrector magnets). The matrix relating these two vectors is called the *Jacobian*, or the *transfer matrix*. The correction is then based on the inversion of this matrix. For this purpose, a powerful technique is to use a singular value decomposition (Chanan *et al.* 2004; Buflone 2008). It has the main advantage to provide the possibility to use a scalar controller to each singular modes (e.g. a proportional integral derivative regulator), to consider only the modes with the highest singular values and can be efficiently applied to a rectangular matrix.

## 4. Conclusion

In this paper, the main strategies used in the active vibration isolation of high-precision machines have been presented and briefly compared. The strategies have been discussed using single-degree-of-freedom models. Then, the case of multi-segmented structures has been considered, emphasizing some similarities between the control of the primary mirror of a telescope and the control of a beam of a linear particle collider.

## Acknowledgement

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement No. 227579.

## REFERENCES

BASTAITS, R., RODRIGUES, G., MOKRANI, B. & PREUMONT, A. 2009 Active optics of large segmented mirrors: dynamics and control. *J. Guid. Control Dyn.* **32**, 1795–1803.

Buflone, D. 2008 Overview of fast beam position feedback systems. In *Proceedings of EPAC*, Genoa, Italy 1021–1025.

Chanan, G., MacMartin, D. G., Nelson, J. & Mast, T. 2004 Control and alignment of segmented-mirror telescopes: matrices, modes, and error propagation. *Appl. Opt.* **43**, 1223–1232.

Collette, C., Artoos, K., Kuzmin, A., Janssens, S., Sylte, M., Guinchard, M. & Hauviller, C. 2010 Active quadrupole stabilization for future linear particle colliders. *Nucl. Instrum. Methods Phys. Res. A*, **621**, 71–78

Kar-Leung Miu, K. 2008 A low cost, DC-coupled active vibration system. PhD thesis, Massachusetts Institute of Technology, September 2008.

Karnopp, D., Crosby, M. J. & Harwood, R. A. 1974 Vibration control using semi-active force generators. *J. Engng Ind.* **96**, 619–626.

Nelson, P. G. 1991 An active vibration isolation system for inertial reference and precision measurement. *Rev. Sci. Instrum.* **62**, 2069–2075.

Preumont, A. 2006 *Mechatronics: Dynamics of Electromechanical and Piezoelectric Systems*, Springer, Dordrecht, The Netherlands ISBN 1-4020-4695-2.

Saulson, P. R. 1894 Vibration isolation for broadband gravitational wave antennas. *Rev. Sci. Instrum.* **55**, 1315–1320.

Beard, A. M., Schubert, D. W. & von Flotow, A. H. 1994 A practical product implementation of an active/passive vibration isolation. *SPIE*, **2264**, 38.

Schubert, D. W., Beard, A. M., Shedd, S. F., Earles Jr., M. R. & von Flotow, A. H. 1997 Stiff actuator active vibration isolation system. *Tech Rep.* Patent Number: 5,823,307, United States Patent.

Vervoordeldonk, M. J., Ruijl, T. A. M. & Rijs, R. M. G. 2004 Development of a novel active isolation concept. ASPE Spring Topical Meeting.

Vervoordeldonk, M. J. & Stoutjesdijk, H. 2006 Recent developments, a novel active isolation concept. In *6th Euspen International Conference*, (ed. H. Zervos) Baden bei Wien.