Active Vibration Isolation for highly Sensitive Measurement Equipment

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Highly sensitive measurement equipment, e.g. atomic force microscopes, suffer from building vibration. To counteract the vibration, active isolation systems are best suited, since these units achieve a very low remaining vibration level, especially for low frequency disturbances without the resonance behavior of a passive isolation system. By using a velocity feedback controller, a so-called skyhook damper can be created, which uses the absolute velocity of the isolated payload as control input. After some signal conditioning the input signal is amplified and used to drive electro-dynamic actuators. Finally the actuator generates a force to minimize the motion of the isolated device.

Indroduction

Todays key technologies require best suited environmental conditions, such as clean room laboratories. Especially the production, manipulation and testing of very small items is a major task in a variety of industrial applications. In the semi conductor industrie so-called wafer inspection systems are used to scan the wafer structure with a resolution of several nanometers. In the field of bio technology cell manipulation has to be carried out with a precision in the scale of microns. Material scientists investigate the molecular structure of new materials by using scanning electron microscopes (SEM). All these applications are limited in their performance by the presence of mechanical vibrations.

Unfortunately mechanical vibrations are a physical phenomenon which can never be eliminated. These vibrations are generated by natural sources, e.g. wind and seismic activities, and artificial sources, e.g. traffic and plants. They travel through different pathes from the source to the location of the sensitive equipment.

The technical solution for this problem is called vibration isolation. The sensitive device is connected to an isolated stage whereas the stage has an elastic link to the structural environment. This setup creates a spring-mass-system with a typical low pass characteristic. For excitation frequencies above the eigenfrequency of the spring-mass system the remaining vibration amplitude on the isolated stage is smaller than the excitation amplitude.

The principle of vibration isolation by using a spring-mass-system is well known and successfully applied to a lot of different sensitive devices. Nevertheless this passive isolation approach has a major drawback which will be discussed in the following sections.

Building Vibration

From the engineering point of view buildings are mechanical structures assembled by plates, shells, beams and rods. As every mechanical structure buildings are vibrating due to the presence of vibration sources.

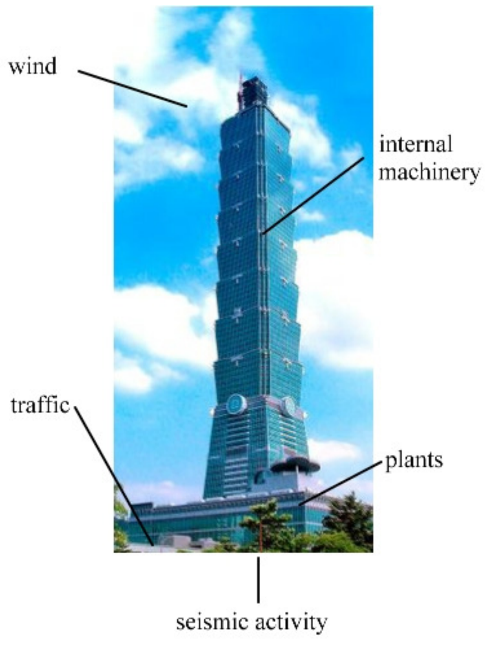

Fig.1 Taipei 101 Skyscraper with Excitation Sources

In Fig.1 the Taipei 101 skyscraper with a height of 508m is depicted with typical excitation sources. These sources generate different types of vibrations.

Wind excitation causes a low frequency tilting of the building with high vibration amplitudes (up to 500µm/s) in the horizontal direction. Especially the upper floors are affected by wind excitation.

Internal machinery, e.g. elevators and air condition systems may generate local vibrations. Local vibrations are limited to a substructure of the building, e.g. a single floor. The related amplitudes are high in the near field of these sources (up to 200µm/s), but they are decreasing rapidly with the distance. The excitation frequencies are very different, depending of the type of internal machinery but as a general rule they are more focused to higher values (10Hz and higher).

Plants and heavy traffic in the surrounding area result to building vibration of small to mid size amplitudes (typical values are 5 – 100µm/s). The related excitation frequencies are typically in the range of 5 to 100Hz.

Seismic excitation causes vibration over the entire building in vertical and horizontal direction. The corresponding excitation frequency is very low (0.5 – 10Hz) whereas the amplitudes are varying from small to extrem large values.

Passive Vibration Isolation

The passive isolation system can be described by a parallel arrangement of a spring (spring constant *c*) and a damper (damper constant *d*) which supports the mass *M* (see. Fig.2).

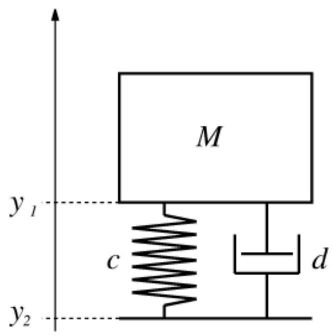

Fig.2 Ideal Passive Isolation Element

The excitation (building vibration at the floor) is defined by

$$\ddot{y}_2(t) = a_2 e^{i\omega t} \tag{1}$$

with a_2 as the excitation amplitude and ω as the circular excitation frequency. The system response is given by

$$\ddot{y}_1(t) = a_1 e^{i\omega t} \quad . \tag{2}$$

Formulating the equation of motion

$$M\ddot{y}_1 = -c(y_2 - y_1) - d(\dot{y}_2 - \dot{y}_1) \ , \tag{3}$$

applying the defined excitation and response and using some algebraic conversions the so-called transmission can be specified as

$$\frac{a_1}{a_2} = \frac{1 + i\delta\omega}{\left(1 - \frac{M\omega^2}{c}\right) + i\delta\omega} \ . \tag{4}$$

In the resonance of the passive system the circular excitation frequency ω equals the circular eigenfrequency ω_0 and the transmission gets

$$\frac{a_1}{a_2} = \frac{1 + i\delta\omega_0}{i\delta\omega_0} \ . \tag{5}$$

Therefore in the case of resonance the transmission is limited by the viscous damping. Nevertheless even by the assumption of infinite viscous daming the transmission can not be reduced below the value of 1. On the other side high viscous damping leads to less isolation for excitation frequencies above the resonance since the value of the numerator is increasing with the frequency. In practice the viscous damping as to be adjusted to achieve acceptable amplification within the resonance and desired isolation for higher frequencies.

Active Vibration Isolation

For the active vibration isolation system the viscous damper is replaced by an actuator (see Fig.3). Following the concept of sky-hook damping (see Ref.1,9,12) the actuator force is proportional to the absolute velocity of the mass M and the equation of motion can be rewritten as

$$M\ddot{y}_1 = -c(y_2 - y_1) - k\dot{y}_1 \ . \tag{6}$$

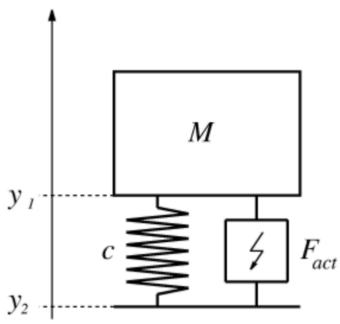

Fig.3 Ideal Active Isolation Element

The transmission of the active system gets

$$\frac{a_1}{a_2} = \frac{1}{\left(1 - \frac{M\omega^2}{c}\right) + ik\omega} \ . \tag{7}$$

In contrast to the passive system the transmission of the active isolation stage within the resonance

$$\frac{a_1}{a_2} = \frac{1}{ik\omega_0} \quad (8)$$

can be reduced below the value of 1 since the damping term is not affecting the numerator. For the same reason the isolation at high frequencies is not influenced by the sky-hook damping.

Comparison of Passive and Active Isolation

Regarding the equations for the transmission it has been pointed out that passive isolation always exhibits an amplification within the resonance and the isolation for higher frequencies decreases because of the viscous damping. In Fig. 4 the transmission of both isolation concepts are plotted. For this plot the eigenfrequency has been set to 5Hz which is a very common value for passive isolation systems. Unfortunately the excitation from the building often occurs at the same frequency range. For this reason the remaining amplitude on top of the passive isolation system is higher than the amplitude on the floor of the building.

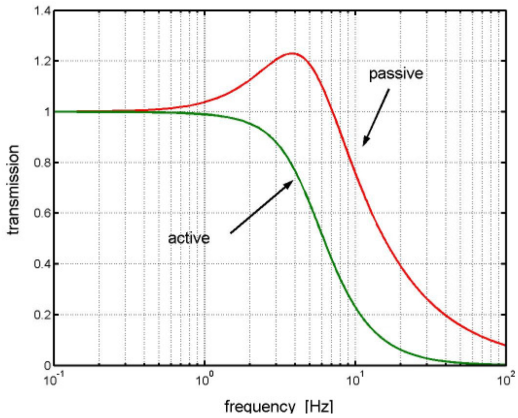

Fig.4 Theoretical Transmission of Passive and Active Isolation Systems

For further illustration of the discussed drawback of passive isolation in Fig, 5 the measured vibration amplitude is shown.

In this example the main excitation is caused by internal machinery and traffic and results to a peak at 10Hz and 21Hz. The used passive isolation table reduces these peaks significantly by a factor of approximately 20. Nevertheless the low excitation amplitude of 3 to 4µm/s within the range from 2 to 5Hz is amplified by the resonance of the passive system to a maximum of 50µm/s.

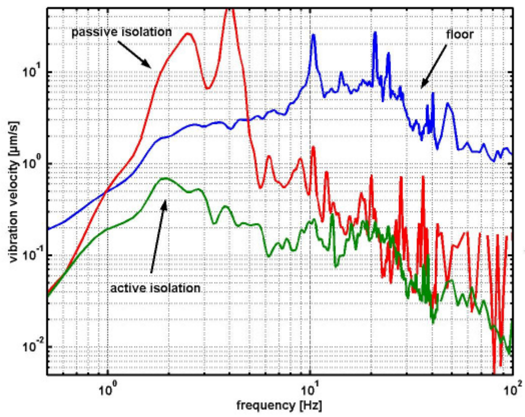

Fig.5 Measured Vibration Velocity

The active system reduces the floor vibration over the complete frequency range. The remaining vibration at the main excitation peaks is below 0.3µm/s which indicates a transmission of –40dB.

Another advantage of an active isolation system compared to a passive stage is the short settling time. The red curve of the plot in Fig.4 demonstrates the importance of a low eigenfrequency for passive systems since the isolation effect takes place for frequencies above the resonance. The low eigenfrequency combined with low damping leads to a long time constant. In Fig.6 the settling time after an impact is compared for the active and the passive system. In case of the active system the vibration decays within 0.3s whereas the passive system vibrates for almost 2s.

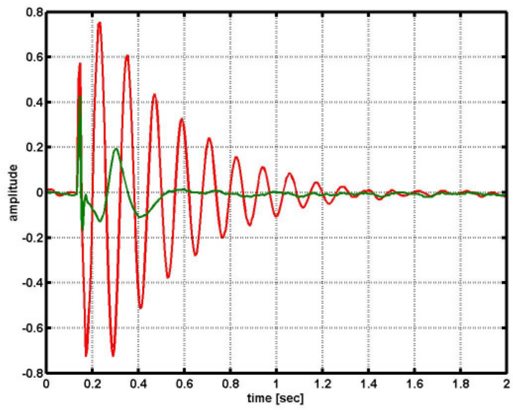

Fig.6 Settling Time of Passive and Active Isolation Systems

Active System

Since the active system is based on the sky-hook concept the absolute velocity is required to drive the actuator. Accelerometers with an intertial mass *m* can be used for this task because of their capability to sense the absolute acceleration.

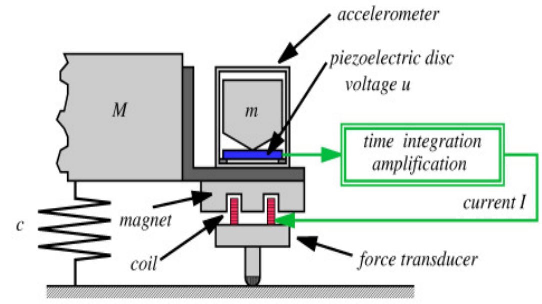

Fig.7 Sensor-Actuator-Unit with Feedback Loop

In Fig.7 a sensor-actuator-unit is depicted. The signal of the accelerometer is generated by a piezo electric disc and then feed in an electronic circuit. This circuit is designed to perform a time integration and to amplify the input signal. The output of the electronics is a current which is proportional to the ablsolute velocity. The feed-back loop is closed by the electro dynamic voice coil actuator, which generates the compensation force in order to counteract the motion of the isolated device.

The described sensor-actuator-unit works in a single direction. For the control of all six degrees of freedom of a rigid body at least six of these units are required.

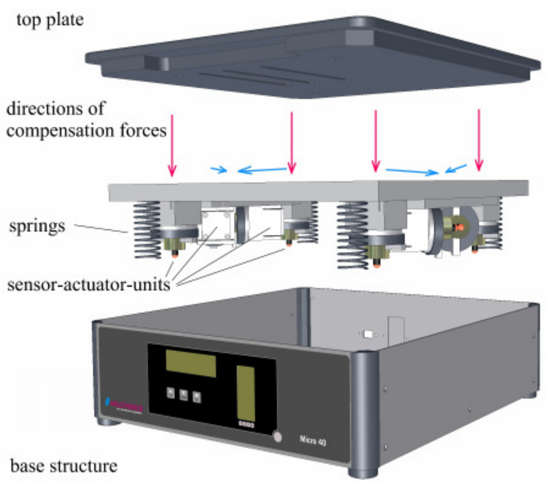

Fig.8 Internal Construction of Micro40 Benchtop System

In Fig.8 the so-called Micro40 benchtop system is shown with eight sensor-actuator-units. The directions of the compensation forces are illustrated with arrows. Four sensor-actuator-units have a vertical orientation. These units are used to counteract the vertical movement of the top plate and the rotation about the two in-plane axes. The other four sensor-actuator-units have a horizontal orientation with an angle of 90 degrees to each other. These units prevent the top plate to move in the two horizontal directions and to rotate about the normal axis.

Application Examples

Isolation of Atomic Force Microscope

Atomic force microscopes (AFM) are used for high resolution surface investigations of arbitrary material samples. The probe head of the AFM is suspended by a cantilever. During the measurement the probe head is scanning the surface of the sample and causes a displacement of the cantilever. This displacement is detected with a laser beam and the computer software calculates the image of the analysed surface.

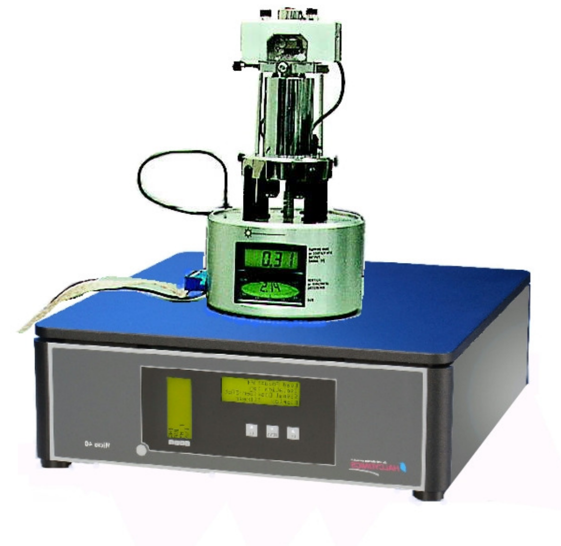

Fig.9 Micro40 with AFM on top

AFM technology resolves surface structure down to the nanometer scale. Even the imaging of a single atom is possible. Because of the resolution and the mechanical construction of the cantilever the AFM requires a very low ambient noise level. To protect the AFM against the building vibration it has to be positioned on top of an isolation stage, as depicted in Fig.9.

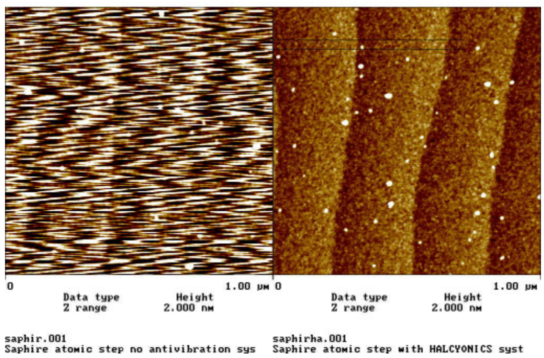

Fig.10 Scan with and without Active Isolation

The scan depicted in Fig.10 illustrates the difference between an isolated and a non isolated AFM. The scan is made with a sapphire sample over an area of 1x1µm. Without active isolation the noise in the resulting image covers the pattern of the surface and a meaningful analyses can not be carried out. By using the active isolation system the pattern can be clearly identified.

Isolation of High Precision Balances

High precision balances are able to weigh samples with an accuracy of one µ-gramme. Often these balances are used within production lines (see Fig.11). Therefore the environmental vibration amplitudes are above the critical range of the operation mode and the accuracy of the measured data decreases.

Furthermore vibration peaks and impacts may cause the balance to be overloaded. To continue the measurement the balance has to be reinitialisated. This procedure takes a couple of minutes and the production line has to be stopped. This may result to other technical problems in the production process within the plant and lead to higher production costs.

The overload can be avoided, if the balance comes to rest within a time interval of approximately 1s. According to Fig.6 the active isolation system reduces the settling time below 1s. This means a continuous production process can be guaranteed.

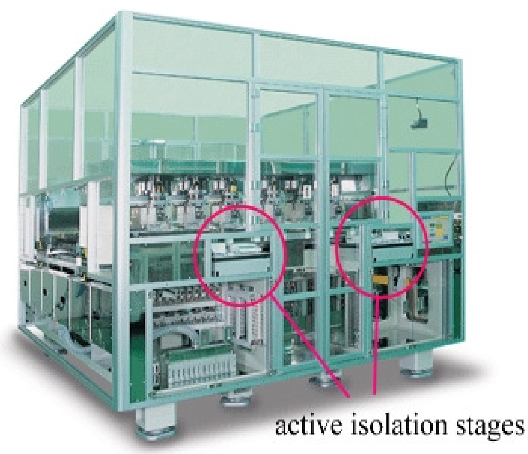

Fig.11 Isolated high precision Balances in Production Line

Summary and Outlook

Vibration isolation of delicate measurement and production equipment from building vibration, will become more important with the development of future nano technology. Because of the nature of building vibration in terms of amplitudes and frequencies, active isolation systems are best suited for this task. They provide significant isolation for low frequencies without any resonance amplification. Direct impacts on the isolated device can be compensated by the actuator forces.

Future trends in the design of active isolation systems will lead to highly integrated and customized solutions. Halcyonics is working in cooperation with several other companies to develop these new systems.

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