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RECENT ADVANCES IN ACTIVE DAMPING AND VIBRATION CONTROL

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Abstract:
This paper reviews some concepts used for active vibration control and vibration isolation. It is divided into two parts. Part 1 reviews some control strategies based on collocated control systems, which offer promising results for space and civil engineering applications. Part 2 (starting at section 4) is focused on automobile applications.

1. Introduction

The demand for active vibration control devices and systems stems from one of the following needs: (i) increasing performances in precision engineering systems (such as, for example, wafer steppers for the electronic industry, or space interferometric missions), (ii) improving the riding and acoustic comfort of vehicles, (iii) allowing the construction of taller civil engineering structures and longer bridges. So far, there have been very few commercial applications of this technology for various reasons, including limited performances, excessive cost, reliability, and robustness. This latter point is especially important when dealing with time varying systems or with manufacturing tolerances in any mass-production process. Recently, however, a number of decentralized control strategies based on collocated actuator/sensor pairs have been identified as possessing built-in robustness properties and leading to rather simple control algorithms [1]. Two such strategies are described in sections 2 and 3 together with some applications.

Section 4 refers to applications of active vibration control in automotive engineering. In particular, the active compensation of disturbances caused by the engine is discussed. In the design of fuel-efficient vehicles, increasing use is made of new engine concepts in association with lightweight constructions. A conflict of interests arises in the quest for optimum ride comfort. Low-consumption engines may well generate stronger excitation, while weight-reduced structures are often particularly sensitive to vibrations. Therefore new technologies are needed to support assemblies. After years of intensive R&D work, the emerging engine mount systems – that incorporate active components – appear to be precursors of promising solutions edging to the required goal, i.e. low consumption, while retaining low levels of vibration and noise. New developments in the fields of microelectronics and actuators are crucial in this advance. The latter aspect, in particular, will be looked at in more detail below.

2. Active damping

A very interesting control configuration is based on a displacement actuator collocated with a force sensor [2]; the displacement actuator may, for example, be a piezoelectric actuator. This control architecture more or less duplicates a human muscle. It can be shown that if the force sensor is connected to the actuator with a positive integral force feedback, the control system can only extract energy from the vibrating system; this guarantees the stability, but not the performance of the control system. In addition to the simple and reliable control law, the following interesting features have been established:

1. The modal damping is proportional to the fraction of modal strain energy in the active device.
2. Every mode follow the root locus (Figure 1)

$$1 + g\frac{s^2+\omega_i^2}{s^2+\Omega_i^2} = 0 \qquad (1)$$

where the open-loop poles Ω_i are the natural frequencies of the structure, including all passive components, and the open-loop zeros ω_i are the natural frequencies of the structure where the active device has been removed.

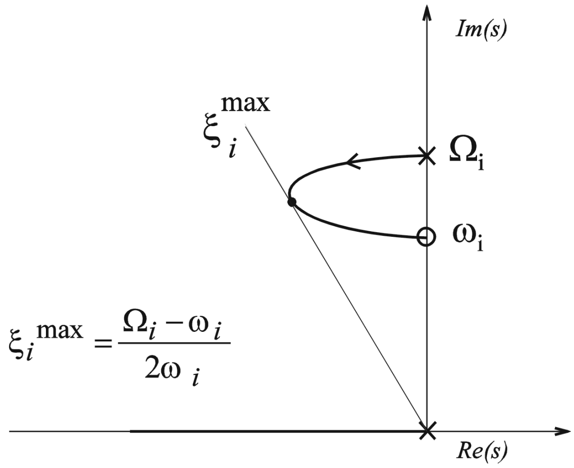

***Fig. 1**: General root locus*

The foregoing features are extremely helpful in the design, and give clear and intuitive information regarding where the active elements should be placed in the structure. They have been found in good agreement with experiments.

This strategy has been applied successfully to representative mock-ups of at least four different types of active damping applications:

(1) Large space structures [2]
(2) Wafer stepper in lithography [3]
(3) Active tendon control of cable structures in space [4-5]
(4) Active tendon control of cable-stayed bridges [6]

In the first three cases, piezoelectric actuators have been used; hydraulic actuators have been used in the fourth one. It is quite remarkable that the active damping of cable structures can be achieved without considering the detailed dynamical response of the cables. The agreement between the predicted and experimental root locus of the cable-stayed bridge were remarkably good [6].

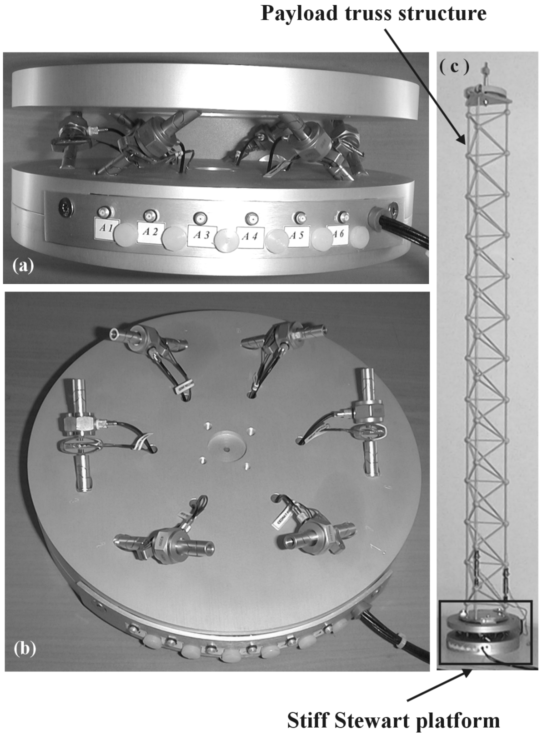

***Fig. 2**: ULB Stiff Stewart platform*

The concept of active strut can be embedded in a 6 d.o.f. Stewart platform to obtain a general purpose interface (Figure 2) which can be used to connect arbitrary substructures (such as various trusses assembled in a large space structure). This system turns out to be extremely efficient as described in another paper at this conference [7].

3. Active isolation

The celebrated "sky-hook" damper [8] aims at combining the –40 dB/decade attenuation rate in the transmissibility with no overshoot below the corner frequency of the isolator. In its classical implementation, the signal from an accelerometer placed on the clean side of the isolator is integrated and fed back into a force generator (typically a voice coil) inside the isolator (Figure 3.a). An alternative implementation of the sky-hook damper consists of sensing the total force transmitted by the isolator, integrating, and feeding back the signal into the force generator (Figure 3.b). For rigid bodies, the two implementations are totally equivalent; however, when the isolator connects two flexible structures, they are no longer equivalent and the stability must be examined. This issue is not important when the flexible modes of the structure are well above the corner frequency of the isolator, but it becomes critical when the flexible modes interfere with the isolation system and the structural damping is small, as expected on future large space structures. In this case, the acceleration feedback implementation (Fig.3.a) may turn out to be unstable, but it can be shown that a single-axis active isolator implemented according to the integral force feedback of Fig.3.b connecting arbitrary flexible structures (Figure 4) has guaranteed closed-loop asymptotic stability [9].

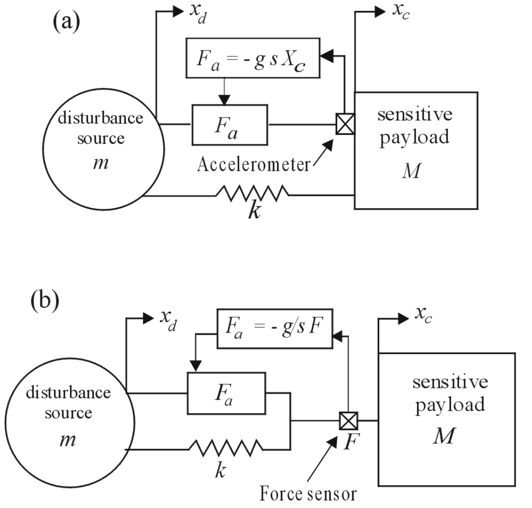

***Fig. 3**: (a):Single-axis soft isolator with acceleration feedback,*
(b): Force feedback isolator

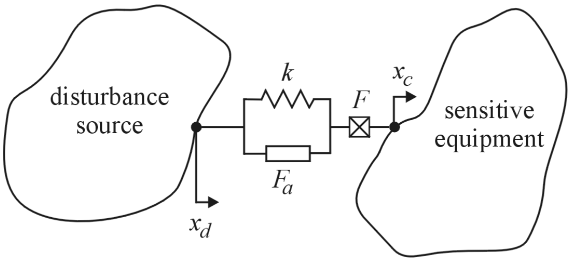

Fig. 4: Two arbitrary structures connected with a single-axis soft isolator with force feedback

As indicated in the previous section, a general purpose six-axis active isolator can be built by fitting six single-axis isolators in the legs of a Stewart platform (Figure 5), every leg being controlled independently by local feedback, in a decentralized manner. Numerous research efforts have been made in this direction [7,10,11,12]. The performance of the isolator depends critically on technological issues such as:

- the flexible hinges at the connection between the legs and the base plates,
- the support of the coil where eddy currents can generate parasitic damping,
- the local modes of the legs which can reduce substantially the attenuation rate of the transmissibility.

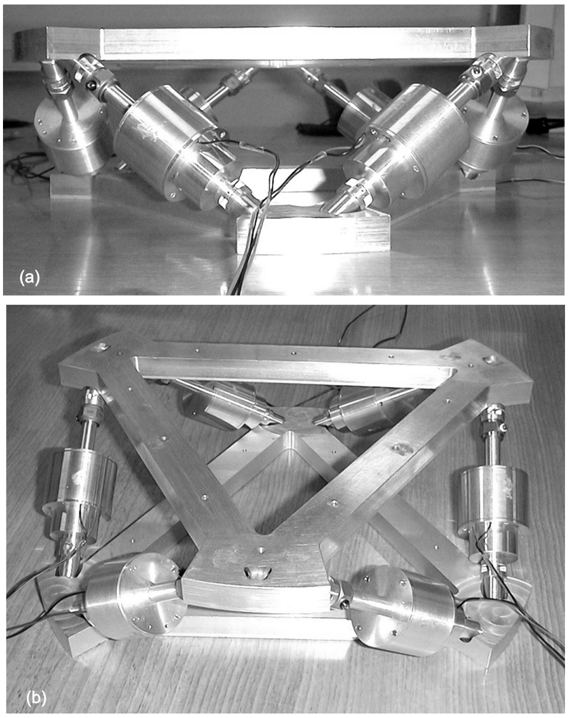

***Fig. 5**: ULB Soft Stewart platform*

4. Automotive applications of active vibration control

Uneven roads, non-uniformity of tires as well as gas forces and inertia forces of the engine are some causes of a number of disturbing vibration phenomena that have a lasting impact on the in-vehicle vibration and noise comfort. Acceptable **N**oise-**V**ibration-**H**arshness performance is usually achieved with passive components to isolate and damp vibration. In addition, for more than a decade there have been intensive efforts, including active measures, to compensate the disturbances occurring over the entire frequency range [13-19]. At the forefront of these investigations were the specific applications intended to damp or even stop the structure-borne noise caused by the engine. Emphasis is given to this application below.

Whereas initially only simple rubber mounts and subsequently rubber/metal parts were used to mount vehicle engines, "self-adaptive" hydromounts are used today even in compact class vehicles, and switchable mounts are used especially in top-of-the-range diesel-powered vehicles. In the latter case, the stiffness and/ or damping characteristic can be adjusted, depending on the driving conditions (e.g. a lower stiffness if the engine is in idling). This can ensure an enhanced ride comfort.
It is likely that even these solutions will not be sufficient to reconcile the steadily increasing expectations of comfort with various other development trends (new engine and engine-mounting concepts, lightweight designs). As fundamental investigations have shown, active systems can make a significant contribution to resolving conflicts of goals.

Regarding their basic way of functioning, active systems for the application discussed here can be divided into three groups:

- Active absorber systems
- Active engine mount systems
- Active structure elements

In all cases the systems mentioned are characterised by the interaction of four basic components in each case:

- Actuators to compensate for forces or travel
- Controllers to regulate the actuators
- Performance boosters to operate the actuators
- Sensors (e.g. acceleration sensors) to record the actual state (input signals for the controller)

The investment required for developing the other system components will vary, depending on the

actuator concept used. This applies in particular to the performance booster.
A regulation concept suitable for targeted application must be installed in the controller. When selecting the concept, the following points must be considered.

- Type of excitation (e.g. periodic or random)
- Type of compensation (e.g. second engine order, multiple engine orders, broad-band)
- Frequency range (e.g. compensation for idling speed or for the overall engine-speed range)

Depending on the system preconditions and requirements, various control concepts can be used [23, 24, 26].

- Feed forward control
- Feed back control
- Combinations of feed forward and feed back control (sometimes referred to as hybrid control)

The most extensive application experience so far has been gained with active absorber systems. Seismic inertia forces are generated using special actuators with the goal of compensating for the dynamic forces introduced into the structure. A particular advantage of this approach is that the actuator can in principle be positioned freely. Regarding compensation effect and/or required space, the actuator can be located at optimum places. The basic configuration of this type of system is shown in Figure 6.

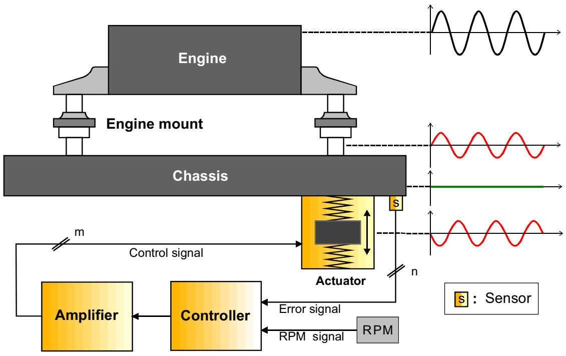

Fig. 6: *Active absorber system principle*

The performance attainable with an active absorber system depends, of course, directly on the capability of the actuators used. Both electrodynamic and electromagnetic driving concepts were examined in great depth, and it was found that a substantially higher power output can be realized with the latter [20, 21]. In this application, the control device and booster have modified the role of the sensor signal to such an extent, that the actuator generates a vibration that has the same amplitude as the disturbance, but is 180° out-of-phase. The demands made on the regulatory and control algorithms are exacting. To ensure a sufficiently large compensation effect, the counter-vibration must be generated in the entire operational range to an accuracy of +/- 5 degrees in the phase and to an accuracy of +/- 0.5 dB in the amplitude.
In a number of our advanced engineering projects with OEM customers it has been shown that active absorber systems can make a substantial contribution to improving in-vehicle comfort [22, 26]. Vibrations caused by the engine can be compensated for (Figure 7), and their intensity can hence be significantly reduced at comfort-relevant points (e.g. seat rail, floor panel, steering wheel). This means that the overall noise level in the passenger cell is lowered. Current development work is aimed at implementing series solutions for hard and software components.

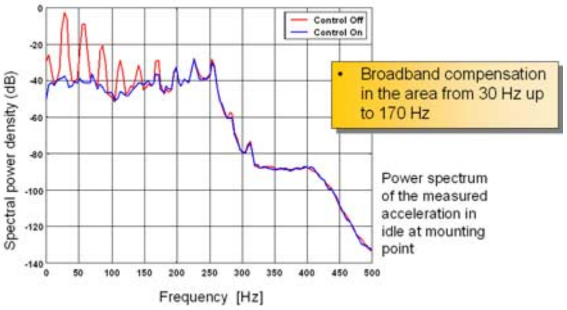

Fig. *7: Vehicle test results*

Active hydromounts represent a considerable development of adaptive mounts and, unlike them, are also controllable over a wide frequency band. With regard to good vehicle acoustics, the usual aim is to reduce the dynamic stiffness to the lowest possible level. As the components under discussion here are located directly in the load-bearing path, they must be able to cope with the effects of all conceivable in-service stressing without getting damaged. A fail-safe backup measure must be ensured in case of a failure of the actuator or the electronic system.
One way of influencing the dynamic characteristic of the hydromount is to act directly on the fluid by means of suitable actuators. This can be accomplished, for example, with electrodynamic or electromagnetic actuators. On the Japanese market the first series applications are already in place.

A quite different approach is to adjust the hydromount characteristic by changing the viscosity of the fluid used. This method is used, for example, for mounts containing electrorheological fluids. Results of laboratory tests confirm the great potential of this technology (Figure 8). Although the quality of the available fluids has been steadily enhanced, there is still a need to improve their long-term stability.

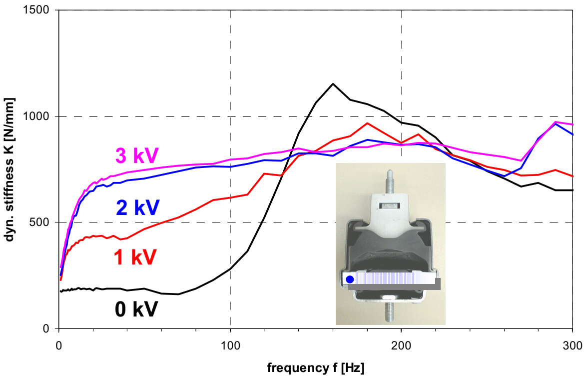

Fig. 8: *Electrorheological engine mount characteristics*

The direct integration of piezoelectric actuators into engine mounts has been systematically researched in the past. Their installation is not practicable because, even if positioning travel enlargers are used, only relatively small travel can be achieved. Much more promising is the use of piezoelectric materials (piezo stack actuators and flat actuators) in combination with structure elements (Figure 9). Test results show that especially higher-frequency structure vibrations of engine brackets, but also of flat components (e.g. vehicle roofs) can be effectively countered [25]. Regarding the development of possible series solutions there is the particular need to develop appropriate manufacturing processes for composite components and to optimise their fatigue resistance.

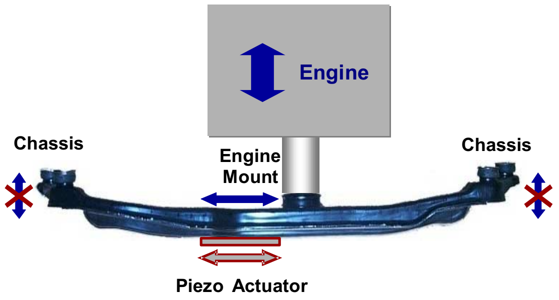

Fig. 9: *"Active"- crossmember*

In summary it can be stated that there is a large range of promising ways of realising active vibration control in automotive series solutions. An integration of these systems into the vehicle development process at the earliest possible time is not only desirable, but essential. A first-rate technical performance can only be ensured when they have been introduced. Furthermore, they pave the way for weight and cost savings, as passive components and structural elements can be simplified or even substituted. In the high-volume automobile market, active technologies can only gain widespread acceptance if the overall package – comprising technical performance, operational reliability and costs – is superior to the existing series solutions. There is keen competition worldwide to attain this goal.

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