Apart from offering other advantageous features, hydraulic actuators are first choice if heavy loads have to be moved, lifted, or controlled. This paper presents exemplarily two applications for hydraulic systems which can help to solve problems caused by dynamic excitations and illustrate the potentials offered by electro-hydraulic control systems: On a large-scale cable-stayed bridge mock-up semi-active electro-hydraulic actuators were implemented and tested. The results impressively demonstrate the damping effect that can be achieved in conjunction with the control strategy selected. In a second large-scale mock-up, hydraulic cup-spring actuators were used to uncouple the carriageway for rail-bound vehicles from foundations (vibration isolation). These developments were carried out during CaSCo, a research project within FP 5 funded by the EC.

Keywords: hydraulic actuator, semi active damping, vibration isolation

1 Introduction

Hydraulic actuators do not only allow the generation of large forces, but are - thanks to modern control technology and sensors - also capable of assuming control tasks such as closed-loop velocity controlling or highly precise positioning of heavy loads. Advanced electro-hydraulic control systems with integrated sensorics offer further features like monitoring functions, error detection and observation of live loads. This opens up hydraulic solution approaches for many problems in the field of civil engineering.

An example of this is vibration damping of cable-stayed structures. Modern cable-stayed bridges are characterized by their slim and increasingly flexible design, which is, however, extremely susceptible to vibrations. Wind and traffic can induce dangerous oscillations both in the deck and in the cables, which results not only in the requirement of increased servicing, but also reduces the availability (closing of the bridge in the case of extreme oscillations). Electro-hydraulic damping equipment can be arranged at the point of coupling between the stay cable and bridge deck, which results in a very high damping effect.

Another field of application for hydraulic actuators is the isolation of oscillations.

Vibrations induced by rail-bound vehicles are transmitted almost unabatedly into the carriageway, from where they propagate into adjacent structures and buildings and can sometimes cause severe vibration and resonance (clinking of glasses, etc.). This reduces home comfort and is unacceptable to adjacent high-quality production plants, theaters, etc.

Solutions to this problem on the basis of spring-mass systems with mechanical springs or elastomers are available, but do not allow parameters (damping, stiffness) to be changed after the installation.

An innovative solution approach with hydraulic actuators offers the possibility of changing both, the stiffness (and thus the natural frequency) and the degree of damping. A decisive feature of this solution is that unlike with conventionally designed spring-mass systems the damping component does not affect the isolation efficacy.

2 Electro-hydraulic system solutions

2.1 Semi-Aktive Hydraulic Actuator to mitigate Vibrations of Flexible Structures

2.1.1 Control Strategy and Implementation
The control strategy provides the arrangement of hydraulic dampers in the anchoring point between the deck and the rope or between the pylon and the cable [1]. They are located directly in the flow of forces and must therefore absorb the entire rope load.

The elasticity of the cable results in a spring/actuator series connection. The idealized model (c.f. Figure 2) shows the technical layout of the cable-stayed bridge with actuator.

The control law for achieving the damping effect is based on integral force feedback. A force sensor is arranged in the coupling point of the actuator with the cable (collocated actuator-sensor pair), which senses the effective force. After filtration (high-pass filter), the dynamic force component obtained is fed back. The control positions the actuator in proportion to the integral of this force. Equivalently, a closed-loop velocity control of the actuator is directly proportional to the dynamic force. The actuator has to respond to altering (dynamic) forces with velocity in the direction in which the dynamic force acts. This means that the actuator is more or less driven by the induced oscillation energy. With a suitable design concept of the hydraulic actuator, the energy consumption can be significantly reduced when compared with an active system.

With the closed-loop control concept described here, the semi-active actuator itself behaves like a viscous damper (structurally stable characteristics).

2.1.2 Design and Description of the Functional mechanism

As mentioned before, the hydraulic actuator carries the total load of the deck (in the order of some hundreds of tons). The static force component is largely constant and just varies according to the differing traffic load. The dynamic changes in force that occur as a result of vibration movements is by a factor of about 10 lower, and only these have to be supported during the damping movement. For this reason, the hydraulic concept of the actuator provides an area, onto which pressure can act and which takes up the very large static load. The required pressure is made available by a hydraulic accumulator. A smaller area of the actuator that is rated for these lower dynamic forces performs the damping movement.

To realize damping, the cylinder is controlled by means of a hydraulic variable displacement unit (axial piston pump / motor). Whereas with a passive damping mechanism, the vibration energy is converted into heat across a throttle, with this electro-hydraulic concept, this energy is converted into mechanical energy in the axial piston unit and fed to the connected electric motor. The motor is supported on the electrical mains and can therefore feed in energy, at the best. However, this is useful only in the case of a remarkable amount of vibration energy, for, on the one hand, the components used are not completely loss-free, and on the other hand, a small amount of hydraulic control energy is required for adjusting the displacement units.

The hydraulic circuit is tailored to the load situation respectively pressure situation within the hydraulic cylinder: The drive torques of both hydraulic units are retro-acting and are equal in the steady-state mean. When vibrations occur the electric motor is needed to control the required movement.

The overall system of the electro-hydraulic damper is designed as a compact unit consisting of a force-generating hydraulic cylinder, the hydraulic displacement units and connected electric motor.

The size of the actuator is determined by the load to be absorbed and the permissible hydraulic pressure. The stroke required for the damping function is relatively low. If an admissible dynamic force of 1/10 of the static load is assumed, the stroke is less than 1/1000 of the length of the stay cable [2].
Apart from the actual control tasks for realizing the damping function, the digital control allows further functions to be performed such as

- Automatic start-up of the system
- Safety and monitoring functions
- Automatic adjustment to static load changes

With the help of integrated sensors and modern communication technology, monitoring and diagnosis functions can also be remote controlled.

### 2.1.3 Tests on a large-scale mock-up

An experimental examination of semi-active damping system was carried out on a large-scale mock-up of a cable-stayed bridge. The object under examination was a 30 m long cable-stayed cantilever beam. The conditions correspond to a bridge currently under construction. Four pairs of stay cables carry the deck. Both, first bending and first torsion mode are in the range of 1.1 Hz [3]. The actuators are arranged on the longest pairs of cables.

#### Figure 4: Actuator unit implemented in cable-stayed bridge mock-up

The structure is excited by means of an electro-hydraulic shaker (bandwidth noise 0.6 – 1.3 Hz). The reduction in the vibration in the frequency range examined is very impressive (see Fig. 5) and confirms the effectiveness of the semi-active damping concept.

#### Figure 5: Displacement of the free bridge edge in response to a random excitation

### 2.2 Vibration Isolation System

Systems intended for vibration isolation are typically based on spring-mass systems (mss). To this end, the mass of the concrete slab is supported on spring elements (see Fig. 6).

#### Figure 6: Vibration isolation system

In order to achieve the desired isolation effect, the natural frequency of the mss must be remarkably lower than the excitation frequency. An ideal system (without any damping) reaches an amplitude attenuation of 40 dB/decade above the resonance frequency so that these vibrations have no longer any effect in the foundations.

#### 2.2.1 Design and Description of the Functional mechanism

An innovative approach for a hydraulic spring element (see Fig. 7) combines the hydraulic or hydro-pneumatic with the mechanical spring effect.

#### Figure 7: Hydraulic cup spring actuator

An actuator that is built from crosswise packed cup springs takes up the hydraulic fluid. It can be seen from the schematic circuit diagram (Fig. 6) that the mechanical and the hydraulic springs are connected in parallel. By installing a hydraulic throttle, an adjustable damper is obtained that is connected downstream of the hydraulic spring (compressibility of the fluid). An advantage of this circuit is that resonance overshoots can be significantly reduced, while the damping feature does not affect attenuation of amplitude (see Fig. 8).

This hydraulic spring element offers the essential benefit that the natural frequency of the mss can be varied at a later point in time. The stiffness can simply be changed by adding/removing capacities.
The system described here can be operated passively or semi-actively (with an electrically adjustable throttle). Monitoring and diagnosis functions can also be implemented with additional sensors (temperature, pressure, position, etc.).

Moreover, this element can also be employed as active actuator, e.g. for leveling functions.

2.2.2 Tests on a large-scale mock-up

An experimental examination of the hydraulic spring element was carried out on a large-scale mock-up of a mass-spring-system. The object under examination was concrete slab with the dimensions: Length 12.8 meter, width 3.8 meters, thickness 0.60 meters. The mock-up corresponds to a block of the mass-spring-system installed in the Zammer Tunnel - Austria in its dimensions. The total weight without additional load amounts to 73 tons (see Fig. 9).

The slab was prepared with 6 holes and an anchoring system at each bearing point in order to be able to lift up the system with six hydraulic actuators. In this way it was easy to change the bearings for testing.

During the second part of the testing campaign two additional 20 tons concrete masses were put on the slab simulating the static weight of a train.

The structure is excited by means of an electro-hydraulic shaker fixed in the centre of the system, taking care to fix the adding oil pipes to external structures in order to avoid additional damping.

Input for the exciter were random noise and records taken on real mass-spring-systems. The data of field measurements (static and dynamic) in the Zammer Tunnel were used as data basis. Random noise is useful for modal analysis, while the train signal gives an idea of the behavior under realistic load pattern. Sinusoidal excitation and sweep sine tests were also performed in order to understand the frequency dependence of the cup-spring elements properly.

The sensor setup consists of 7 displacement sensors located along both sides of the slab, 6 load cells were fixed under the bearings and 5 accelerometers put on the system and the ground recorded the performance of the devices.

Additionally a systematic testing campaign was carried out using conventional devices. Several manufacturers of rubber and steel bearings supplied their products for comparative tests. In this way the excellent behavior of the cup-spring-isolators could be proven.

Nevertheless there is space for further improvements. Therefore a second testing campaign on another large-scale mock-up, the Rohrbach Bridge, will be carried out this summer.

3 Conclusions

Hydraulic actuators are the right choice for a multitude of tasks in the field of civil engineering. For example, the susceptibility to vibration of cable supported structures can be significantly reduced with the help of semi-active actuators, which are arranged in the coupling point between the rope and the structure, in conjunction with a suitable control strategy. This was demonstrated on a large-scale mock-up of a cable-stayed bridge. When compared with active concepts, the energy requirement is much lower.

In another application, hydraulic spring elements were developed for the isolating the vibration on rail carriageways, which allow damping effects without impairing the isolation effect. Another essential advantage of these hydraulic spring elements is the possibility of re-adjusting the natural frequency.

4 References

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