Reduction of compressor vibrations by means of an active tuned vibration absorber

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Introduction

Electric locomotives of trains and trams are usually equipped with HVAC (heating, ventilation, and air conditioning) units that are placed on top of the locomotive's roof. These units are used to air-condition the driver's cab of the train or tram and consist of two heat exchangers, a compressor, a condenser fan, and a ventilation fan (see Fig. 1). These components cause vibrations and noise, often at an annoying level, both on the inside and on the outside of the locomotive.

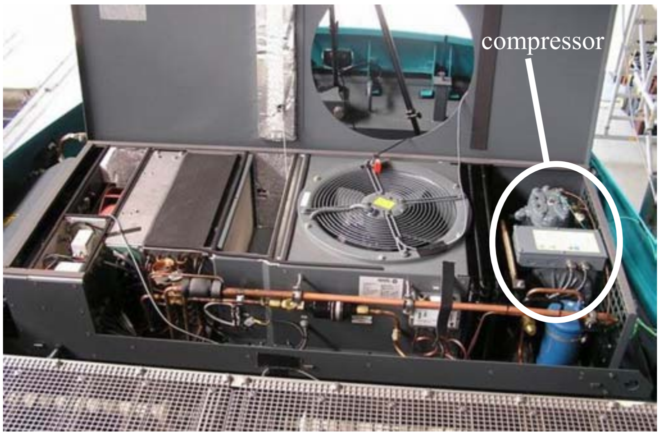

Fig. 1: General view of the HVAC unit mounted on top of a tram roof.

Annoying noise inside the driver's cab

The manufacturer of the HVAC unit performed noise and vibration measurements both inside the driver's cab of a tram and at the unit itself. It was possible to significantly reduce particularly annoying tonal noise in the 50 Hz and 100 Hz one-third octave bands inside the driver's cab simply by lifting up the compressor a couple of millimeters by means of a crane. This indicates that the compressor mounted in the HVAC unit on the roof of the tram is the main vibration source that causes the annoying noise levels inside the driver's cab. Therefore, some experiments were performed that demonstrated the potential of active vibration control measures [1]. Based on these preliminary results active tuned vibration absorbers were designed that reduce the vibrations caused by the compressor [2].

Design of the active tuned vibration absorbers

The design of the active tuned vibration absorber was inspired by a paper by Konstanzer et al. [3]. Figure 2 shows a schematic view of the active tuned vibration absorbers mounted beneath the compressor. The vibration absorbers consist of two discrete masses attached to the ends of two cantilevered beams and are tuned to 50 Hz, which is very close to the frequency of the highest vibration level of the compressor.

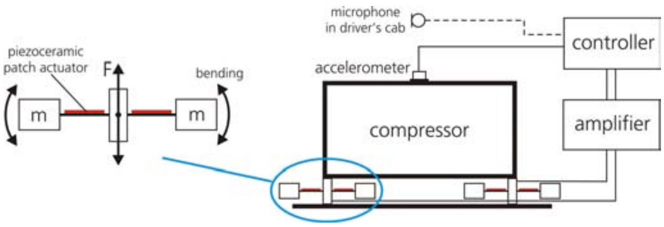

Fig. 2: Schematic view of the active tuned vibration absorbers mounted beneath the compressor.

This fundamental frequency can be varied within a certain range by an acceleration feedback control system using the acceleration of the discrete masses as input to the voltage signal applied to the piezoelectric patch actuators attached to the cantilevered beams, thus virtually adapting the mass of the passive absorber. In addition, the acceleration at the mounting point can be used as the input to another control system such that the absorber behaves as a vibration compensator at higher frequencies, using the inertia of the masses at the end of the cantilevered beams to generate a force at the mounting points.

Testing and validation

The vibration absorbers were dimensioned, and their behavior was validated by means of finite element simulations and measurements performed at a preliminary prototype. The total mass of each absorber is 1.7 kg. The final design, which is quite simple and very robust, can be seen in Fig. 3. The absorber mounts rigidly connect the compressor feet to the HVAC unit's housing, which is an important safety issue.

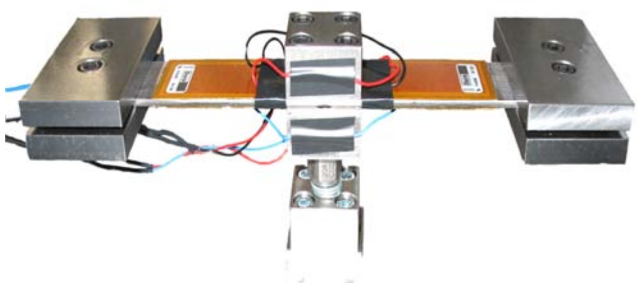

Fig. 3: Prototype of an active tuned vibration absorber.

The fundamental frequency of the vibration absorbers can be varied in the range –12 Hz/+3 Hz by applying an appropriate voltage signal to the patch actuators. In the higher frequency range beyond the fundamental frequency up to about 200 Hz the vibration absorbers can act as vibration compensators and can generate forces of approximately 11 N each.

Figure 4 shows the active tuned vibration absorbers mounted beneath the compressor. Due to the limited number of available control channels only three instead of four absorbers could be used. Likewise, the voltage signal was applied only to the two piezo patches on top of the cantilevered beams and not to the ones beneath. The acceleration of only one of the two masses of each absorber was fed back as a voltage signal to both piezo patches instead of applying an individual voltage signal to each of the two patches. The six discrete masses of the three vibration absorbers have a total mass of 3.5 kg, which is approximately 10% of the compressor's mass.

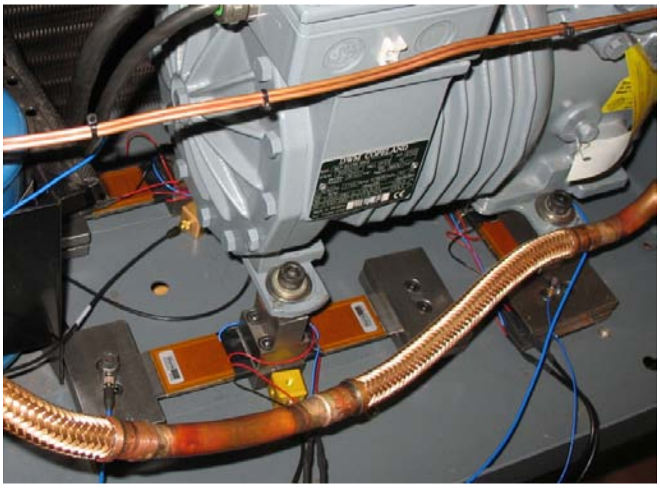

Fig. 4: Active tuned vibration absorbers mounted beneath the compressor.

Measurement results

The acceleration levels of the HVAC unit's housing directly beneath the compressor are depicted in Fig. 5. The blue and red lines show the acceleration levels with the controller being switched off and on, respectively. Two effects can be seen: At 48 Hz the acceleration levels are reduced by 15 dB by means of the passive vibration absorber whose fundamental frequency is actively tuned to match exactly the frequency of the highest peak.

At 119 Hz and 191 Hz the vibration absorbers act as vibration compensators, thus reducing the acceleration levels by 10 dB. At these frequencies an appropriate anti-phase sinusoidal voltage signal is applied to the piezo actuators. The required amplitudes and phase shifts are determined automatically by a digital control system. The peaks at 119 Hz and 191 Hz were chosen arbitrarily in order to demonstrate the potential of the compensator effect – other or more peaks could be reduced as well.

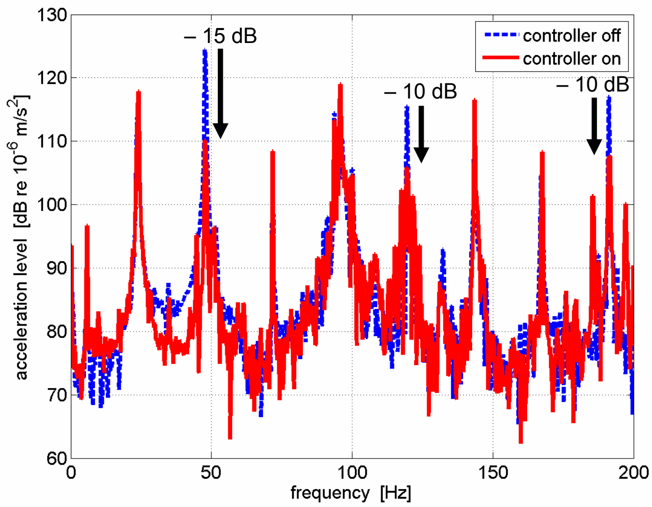

Fig. 5: Significant reduction of the acceleration level beneath the compressor at 48 Hz and other frequencies.

Future work

The effectiveness of the active tuned vibration absorbers should be verified by sound pressure measurements in-situ in the driver's cab of the tram while the tram is in operation. The efficiency of the vibration absorbers can be increased by applying control signals to all four piezo patches of each absorber and by using an individual acceleration feedback control signal for each of the two cantilevered beams of each absorber. The adaptation of the fundamental frequency should happen automatically such that the mutual influence of several absorbers can be compensated automatically as well. It would also be advantageous to use low-voltage actuators and miniaturized control hardware.

Acknowledgments

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References

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