Tunable Pendulum Actuator for Vibration Attenuation

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Abstract:
The passive behaviour of the unique pendulum actuator design presented here is similar to that of a tuned mass damper making it particularly suitable for vibration attenuation in structures afflicted by a disturbance with a pronounced fundamental frequency. Through the use of a high-force active material such as a piezoelectric ceramic or magnetostrictive alloy at the core of the device, the resulting system anti-resonance is tunable to a varying disturbance frequency over a wide range, simply by changing the driving signal offset. Actively driving the transducer material with an appropriately phase-shifted control signal increases the attenuation effect. This paper illustrates the passive and active vibration attenuation potential of the novel tunable pendulum.

Keywords: vibration attenuation, adaptronics, pendulum actuator

Introduction

The task of structural vibration attenuation is increasingly being approached with the development of active system solutions, exceeding passive systems in terms of bandwidth and attenuation performance. A tuned mass damper is a typical passive solution suitable for attenuating a predominant tonal vibration disturbance, but it augments the vibration level over a wide frequency band above its resonance. By incorporating active materials, the device acquires broadband attenuation capability, and the frequency of predominant attenuation can be shifted [5-7].
The pendulum actuator introduced in [1] makes use of a special kinematic condition to increase the displacement of the seismic mass, thereby imparting the tuned mass damper with a high force-to-mass ratio. The device acquires adaptive properties through the use of high-force electromechanically transductive materials such as piezoelectrics or magnetoelastics implemented at the core of the pendulum actuator; simply setting the operating point of the transducer element enables the fundamental frequency of the device to be tuned or adapted to a changing set of operating conditions. An appropriate dynamic control signal enables the device to generate harmonic forces or – when implemented within a closed control loop – to affect vibration attenuation in structures afflicted by a dominant disturbance frequency.
This paper will elaborate on the passive structural vibration attenuation capability of a pendulum actuator making use of magnetostrictive material. Despite its nonlinear kinematics, the pendulum damper exhibits a pronounced anti-resonance when attached to a vibrating structure. Simulation and experimental results will illustrate the harmonic nature of the device and explore its tunability. A shift from 44 Hz to 56 Hz is achieved by varying the operating point of the active material. An outlook to future developments will be given by presenting an example demonstrating the vibration attenuation potential of the pendulum actuator in active control. In one case, manual adjustment of the driving signal to the pendulum actuator results in an approximately 19 dB reduction in acceleration of the vibrating structure.

Actuator and experimental set-up

The novel pendulum actuator concept introduced in [1] makes use of a singularity to double the displacement range of the mass used to generate dynamic forces. The seismic mass m_2, comprised in the example of a magnetostrictive pendulum actuator of the backing plates, the driving coils and the magnetostrictive element, oscillates about the reference position at which the suspension arms of length l are parallel to the working force F of the active element (see Figure 1).

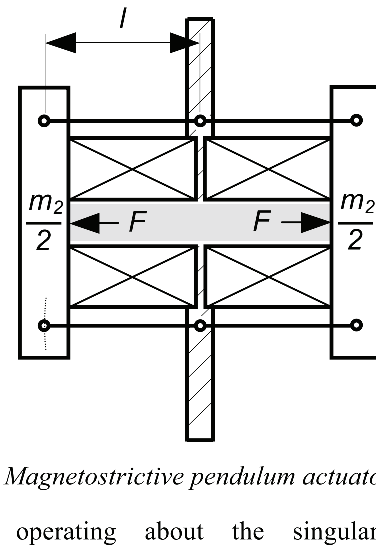

Fig. 1: *Magnetostrictive pendulum actuator*

While operating about the singularity point decreases the device's linearity and consequently its suitability for broadband control, the resulting displacement amplification results in a high force-to-mass ratio. The dynamic force is particularly strong when the device is in resonance, the frequency f of which can be approximated by

$$f = \frac{1}{2\pi}\sqrt{\frac{F}{m_2 \cdot l}}\,. \qquad (1)$$

Equation (1) describes the dependence of the resonant frequency of the pendulum actuator on the internal preload force F, the key for implementing the pendulum actuator as an adaptive device.

When mounted on a vibrating structure, the pendulum actuator fulfils the function of an auxiliary mass damper, whereby the frequency of anti-resonance in the combined dynamic system (see Figure 2) corresponds with the resonant frequency of the pendulum actuator.

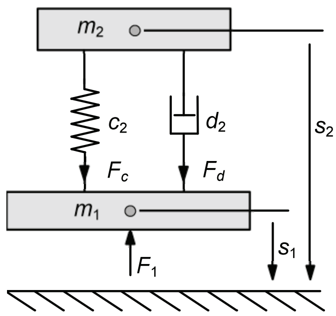

Fig. 2: Disturbed structural mass m_1 with passive auxiliary mass damper of mass m_2

This paper reports experimental results demonstrating the vibration attenuation potential of the pendulum actuator implemented as a tunable auxiliary mass damper as well as when operated actively.

Measurement results

Experiments were carried out on the pendulum actuator in order to investigate its tunability in terms of frequency as well as to demonstrate its vibration attenuation potential when implemented as an active device.

Frequency tuning

The degree to which the resonant frequency of the pendulum actuator – and consequently the anti-resonant frequency when the device is attached as an auxiliary mass damper to the test mass – can be adapted was investigated in dependence of the driving current offset by plotting the Bode diagram for a swept sinusoidal disturbance force F_1 (see Figure 3). The reference signal for the magnitude and phase responses is the driving current of the disturbance shaker, which is proportional to the resulting disturbance force F_1.

The effect of implementing the pendulum actuator as an auxiliary mass damper is quantifiable by comparing the frequency response values with those resulting for the case when no auxiliary mass damper is attached ('reference' in Figure 4).

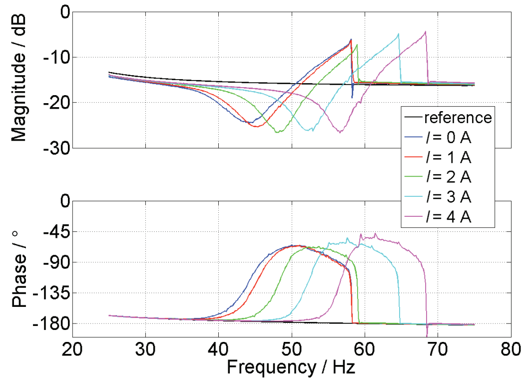

Fig. 3: *Tuning the frequency of maximal vibration attenuation by adjusting the driving current offset*

The frequency of maximum vibration attenuation is approximately 44 Hz when the device is implemented in a purely passive fashion, i.e. without applying a driving current offset. The semi-active operating mode makes use of the relationship between the current offset and the frequency of maximum vibration attenuation (see Figure 4) for tuning the device to a given predominant disturbance frequency F_1. For offset currents in the range of 0 A to 4 A the frequency of maximum vibration attenuation is shifted with a nearly linear relationship from 44 Hz to 56 Hz. The relatively low slope value corresponding to a driving current between 0 A and 1 A may be attributed to the typical non-linear relationship between driving current and magnetostrictive displacement in the active rod.

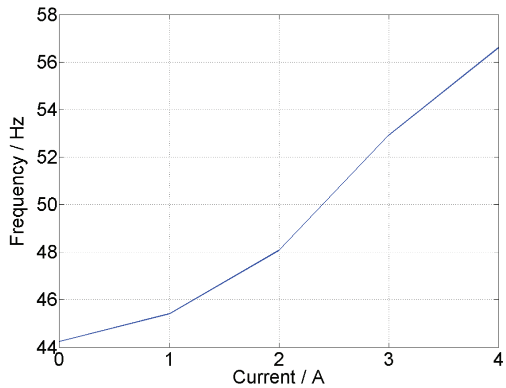

Fig. 4: *Relationship between the tuned damping frequency and the driving current offset*

Demonstration of attenuation potential

An experiment was constructed to demonstrate the vibration attenuation potential of the magneto-strictive pendulum actuator by means of tuning as well as in active operation. A sinusoidal disturbance force with an amplitude of approximately 16 N acts on the test mass at a frequency of 49.4 Hz resulting in an acceleration amplitude of about 2.3 m/s^2 (see ‘reference’ curve in Figure 5). Upon mounting the magnetostrictive pendulum actuator the root-mean-square value of acceleration is reduced by 3.0 dB (‘passive’, see Table 1). This, however, does not correspond with the optimally tuned condition.

Table 1: *Levels of test mass acceleration for different operating conditions*

	Acceleration:	m/s^2 (RMS)	dB
	Reference	1.58	0
With pendulum actuator	**Passive**	1.11	-3.0
	Tuned	0.54	-9.4
	Active	0.18	-18.9

Increasing the coil current offset to $I = 2.1$ A shifts the frequency of optimal damping to match the disturbance frequency, thereby resulting in a vibration attenuation of 9.4 dB with respect to the reference condition. To achieve an even greater attenuation of vibrations, a dynamic driving current signal can be added to the current offset. In accordance with the operating principle of the pendulum device, the frequency of the dynamic driving signal should be twice that of the mechanical disturbance (see [1]). A sinusoidal current with a frequency of 98.8 Hz and an amplitude of 2.1 A was added to the existing offset. The phase of the control signal was adjusted manually until reaching a minimum value of acceleration corresponding to a vibration level 18.9 dB lower than the one measured on the test mass before the pendulum actuator was mounted.

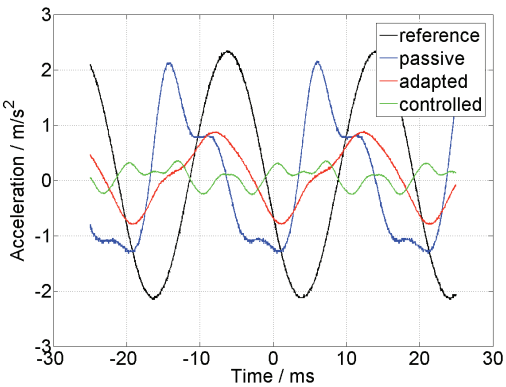

Fig. 5: *Acceleration of the disturbed test mass before and after tuning the magnetostrictive pendulum actuator as well as in active operation.*

This type of experiment could be repeated for other current offsets, whereby the amplitude of the dynamic component of the current signal is bounded on the lower side by 0 A – to avoid introducing additional non-linearities from the magnetostrictive material – and by the maximum driving current on the upper side. Consequently, an offset current in the middle of this range will generally offer the greatest control authority when implementing the device in the active mode of vibration attenuation, presuming of course that the RMS value of the driving current respects the thermal dimensioning of the coil.

Summary and outlook

A magnetostrictive pendulum actuator was tested experimentally in terms of its passive vibration attenuation behaviour, and its active attenuation potential was explored. Operating as a passive auxiliary mass damper, structural vibrations are attenuated in the region of frequency around the device resonance. Experimentally obtained transfer functions show that adding an offset to the electrical driving signal – coil current as in this case involving a magnetostrictive element or operating voltage in case a piezoelectric element is used – increases the mechanical preload *F* within the pendulum device, thereby affecting an upward shift in the anti-resonant frequency. In the experimental set-up, this frequency, which corresponds to the maximum vibration attenuation of 9.4 dB with respect to the reference system condition, was shifted from 44 Hz to 56 Hz. The simple quasi-static approach to shifting the anti-resonance of the system predestines the device for use in adaptronic applications such as the attenuation of vibrations in aircraft structures in which the frequency of tonal disturbances are shifting with changing flight conditions.

To demonstrate the active capability of the pendulum actuator, a sinusoid was added to the electrical driving signal offset. By applying a driving signal frequency twice as great as that of the disturbance and manually adjusting the phase, a steady overall attenuation of approximately 19 dB was achieved, almost 16 dB greater than the attenuation achieved by the device operating passively.

Future work on the pendulum actuator at LPA will involve 1) investigating the use of a piezoelectric element (see Figure 6) instead of a magnetostrictive one, and 2) developing adaptive control methods for implementing the device as a force generator as well as for use in active vibration attenuation.

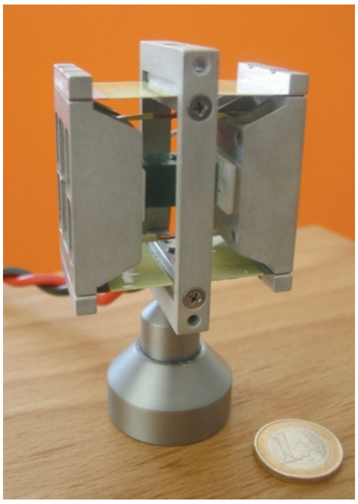

Fig. 6: *Piezoelectric pendulum actuator*

Acknowledgements

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