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A robust Active Mass Damper control strategy for Vortex-Induced Vibrations mitigation

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SUMMARY:
This paper investigates a sky-hook-based active control strategy for the mitigation of vortex-induced vibrations (VIV) in slender structures. The approach is experimentally validated on a wind tunnel model representative of a high-rise building, equipped with an Active Mass Damper (AMD). The control gain is derived from the aeroelastic characterization of the uncontrolled system, by compensating the maximum negative aerodynamic damping observed during lock-in conditions. Results show that the proposed strategy effectively suppresses VIV at the critical wind speed, leading to a 93% reduction in displacement amplitude and maintaining oscillation levels below the prescribed performance threshold. The method combines a simple and general control law, based solely on structural velocity measurements, with a physically-informed tuning procedure tailored to the VIV mechanism. These findings highlight the potential of sky-hook-based active control as a compact, robust, and easily implementable alternative to traditional passive devices, with possible extension to different types of dynamic loading.

Keywords: Vortex-Induced Vibrations, Active Mass Damper, Sky-Hook, Active control, Wind tunnel tests, Robust control

1. INTRODUCTION

Vortex-induced vibrations (VIV) represent a major serviceability issue for slender and lightly damped civil structures exposed to wind, such as high-rise buildings, bridge towers, and similar vertical cantilever systems. When the vortex shedding frequency approaches the natural frequency of the structure, a lock-in condition may occur, leading to sustained oscillations with potentially large amplitudes (Païdoussis et al., 2010). For civil structures, this phenomenon is particularly critical because their fundamental frequencies are typically low, so VIV may develop under moderate wind velocities that occur frequently during the structure's life. As a result, VIV can affect occupant comfort, operational continuity, fatigue performance, and, in some cases, construction-stage safety. Traditional mitigation strategies are mainly based on passive devices, such as tuned mass dampers (TMDs), or on aerodynamic modifications of the external shape. Although effective in many applications, passive solutions have intrinsic limitations when applied to very slender structures. Their performance depends on proper tuning to the structural properties, while the required auxiliary mass and installation space may become significant, especially near the top of high-rise systems, where the economic and architectural penalties are more severe. In this context, Active Mass Dampers (AMDs) provide an attractive alternative, since they can supply the additional damping required to mitigate VIV with reduced moving mass and greater adaptability. Their effectiveness has been widely demonstrated in the context of long-span bridge towers, where active control systems have become a standard solution for vibration mitigation (Tanida, 2002). More recent applications confirm the relevance of active control strategies also during construction stages, where structural properties continuously evolve, and passive solutions may be inadequate (Son et al., 2023). Among the possible control laws, the sky-hook strategy, also referred to as direct velocity feedback, is especially appealing because it introduces an equivalent viscous damping action directly related to the structural velocity. Its formulation makes it inherently independent of the excitation mechanism, thus suitable for multi-hazard applications. In the case of VIV, the effectiveness of the approach relies on a physically-informed calibration of the control gain, tailored to counteract the negative aerodynamic damping governing the onset of the phenomenon. The design and validation of control strategies for VIV mitigation still rely heavily on experimental investigations, as wind tunnel testing remains the most reliable tool to capture the complex aeroelastic behavior of slender structures (Larose et al., 1993). Based on these premises, this paper investigates a robust AMD control strategy based on the sky-hook concept for the mitigation of VIV in a system representative of a slender high-rise structure. The control gain is calibrated from the experimental characterization of the uncontrolled aeroelastic response. The proposed strategy is then assessed and validated through wind tunnel tests under operative conditions.

2. METHODOLOGY

The investigated system consists of a slender structure representative of a high-rise building, tested in wind tunnel conditions. The model is a prism of aspect ratio $B/D = 3.33$ and height ratio $H/B = 2$, its characteristic cross-wind dimension is $D = 0.3$ m. The structure is modelled as a single-degree-of-freedom system dominated by its first cross-wind bending mode. The modal shape is assumed linear along the height, such that the generalized displacement can be expressed through the top displacement x_H. The structural modal mass is $M_H = 32.75$ kg, the natural frequency is $f_1 \simeq 1.57$ Hz and the structural damping is $\xi_s \simeq 0.6\%$. An AMD is installed at a height $h = 1.73$ m, providing a control force through an inertial actuator. Its mass is $m_{AMD} = 0.407$ kg, which corresponds to a mass ratio $\mu = \frac{\phi_h^2 m_{AMD}}{M_H} = 0.94\%$, where $\phi_h = \frac{h}{H}$ is the modal shape evaluated at the installation height. This mass ratio is typical for civil applications and guarantees the required inertial control force. A picture of the model with the installed AMD is reported in Figure 1a. The coupled dynamics of the structure and the AMD can be expressed as:

$$M_H \ddot{x}_H + r_H \dot{x}_H + k_H x_H = F_{\mathrm{VIV},H} - \phi_h F_C \tag{1}$$

where M_H, r_H, and k_H are the modal mass, damping, and stiffness of the structure, $F_{\mathrm{VIV},H}$ is the aeroelastic force at the top and $F_C = m_{AMD} \ddot{x}_A = m_{AMD} \left(\ddot{x}_{A,r} + \phi_h \ddot{x}_H \right)$ is the AMD control force. The control objective is to counteract the negative aerodynamic damping introduced by vortex-induced excitation by increasing the overall damping of the system. A sky-hook control law is adopted, in which the control force is proportional to the absolute structural velocity at the installation point:

$$F_C = G \dot{x}_h = \phi_h G \dot{x}_H \tag{2}$$

This control action is equivalent to the introduction of an additional viscous damping term, so that the total damping ratio can be expressed as:

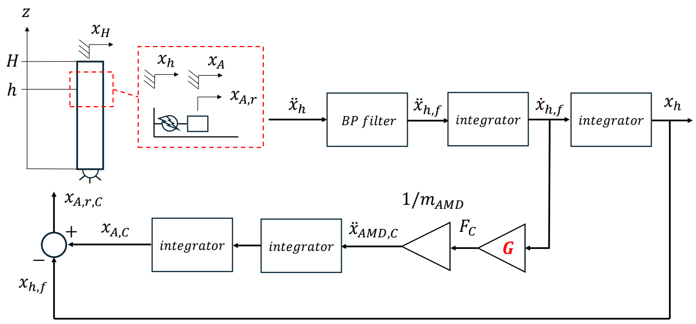
$$\xi_{\mathrm{tot}} = \xi_s + \xi_c = \frac{r_H}{2 M_H \omega_1} + \frac{\phi_h^2 G}{2 M_H \omega_1} \tag{3}$$

where ω_1 is the natural circular frequency of the structure. The gain G is selected based on the experimental characterization of the uncontrolled system.

The control strategy is implemented using acceleration measurements acquired at the AMD installation level. The acceleration signal is filtered and integrated to obtain the structural velocity required by the control law. A sketch of the control algorithm is reported in Figure 1b.

The actuator dynamics are characterized by frequency response functions, which account for amplitude attenuation and phase lag in the control implementation. The overall control loop is implemented in a real-time environment, allowing continuous acquisition, processing, and actuation during wind tunnel tests. Tests have been performed in the Politecnico di Milano wind tunnel atmospheric boundary layer test chamber under smooth-flow conditions ($I_u = 2\%$, $L_u^x = 20$ cm at a reference height of 1 m), representing a severe condition for VIV development.

(a) WT setup with focus on AMD and accelerometers.



(b) Sketch of the Sky-hook control algorithm.

Figure 1. Experimental setup and control logic.

3. RESULTS

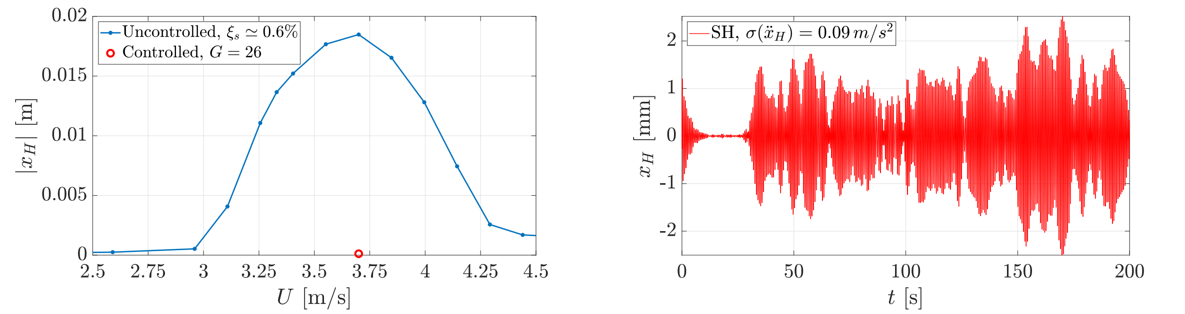
The system was first characterized by evaluating the VIV response at different wind speeds. In Figure 2a the classical bell-shaped plot of the top displacement amplitude versus incoming wind speed is reported. Maximum steady-state oscillations of $x_H = 0.018$ m are measured at $U = 3.7$ m/s in the uncontrolled configuration. This wind speed represents the most critical condition and is therefore used to dimension the control gain. From the build-up tests it is possible to derive the non-linear relationship between total damping and oscillation amplitude. By imposing a threshold on the maximum allowable response in terms of standard deviation of the top acceleration $\sigma(\ddot{x}_H) = 0.1\,\text{m/s}^2$ (Tanida, 2002), the required control damping $\xi_c = 3\%$ is obtained. The maximum negative aerodynamic damping is observed during the first build-up cycles and is taken as the reference to derive the required control gain $G = 26$ according to:

$$G = \xi_c \frac{2 M_H \omega_1}{\phi_h^2}. \tag{4}$$

The controlled system is then tested under the same conditions, showing a significant oscillations reduction $\sigma(x_H) = 0.92\,\text{mm}$, corresponding to a reduction of 93% in displacement amplitude, while maintaining accelerations below the prescribed threshold $\sigma(\ddot{x}_H) = 0.09\,\text{m/s}^2$, effectively preventing the onset of VIV and protecting the structure (Figure 2b). A complete characterization of the VIV phenomenon and of the control calibration procedure, together with a robustness analysis, will be presented in the full paper.

4. CONCLUSIONS

A sky-hook-based control strategy for the mitigation of vortex-induced vibrations has been investigated and experimentally validated on a wind tunnel model representative of a slender high-rise structure. The control gain has been derived from the aeroelastic characterization of



(a) Steady-state top oscillation amplitude versus incoming wind speed.

(b) Top oscillation amplitude of the controlled system at the critical wind speed $U = 3.7$ m/s.

Figure 2. VIV response of the uncontrolled and control system.

the uncontrolled system, by compensating the maximum negative aerodynamic damping observed in lock-in conditions. The proposed approach proved to be highly effective, leading to a 93% reduction of the structural response at the critical wind speed, with oscillation levels kept below the imposed performance threshold and preventing VIV onset. Beyond its effectiveness, the sky-hook strategy stands out for its simplicity of implementation and operation, as it only requires a local measurement of structural acceleration and does not rely on the identification of the external forcing. This makes the control law inherently robust and particularly suitable for real-time applications. Moreover, the formulation based on the structural velocity makes the approach independent of the excitation source, enabling its application to different types of dynamic loading, such as wind or seismic actions. In this context, the physically-informed calibration of the control gain allows tailoring the otherwise general control law to the specific features of the VIV phenomenon, ensuring both adaptability and efficiency. These results highlight the potential of simple yet physically-based active control strategies for VIV mitigation, providing an efficient and compact alternative to traditional passive solutions. Further developments will address a more comprehensive characterization of the phenomenon and a robustness assessment of the control strategy.

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