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# Model-based design and experimental validation of active vibration control for a stress ribbon bridge using pneumatic muscle actuators

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ABSTRACT

This paper describes the development of an active vibration control system for a light and flexible stress ribbon footbridge. The 13 m span carbon fiber reinforced plastic (CFRP) stress ribbon bridge was built in the laboratory of the Department of Civil and Structural Engineering, Berlin Institute of Technology. Its lightness and flexibility result in high vibration sensitivity. To reduce pedestrian-induced vibrations, very light pneumatic muscle actuators are placed at handrail level, introducing control forces. First, a reduced discretized analytical model is derived for the stress ribbon bridge. To verify the analytical prediction, experiments without feedback control are conducted. Based on this model, a delayed velocity feedback control strategy is designed. To handle the nonlinearities of the muscle actuator, a subsidiary force control is implemented. Then the control performance from numerical simulation is verified by experiments under free vibration. As a result, analytical analyses agree well with experimental results. It is demonstrated that handrail-introduced forces can efficiently control the first mode response.

## 1. Introduction

Stress ribbon bridges are among the most elegant and lightest bridges. Due to their static and dynamic characteristics, they have been mainly designed for pedestrian traffic rather than for road or rail traffic [1,2]. The suspension cable and the bridge deck are combined into one stiffening element, which is anchored in the abutments. Usually, the cables are made of steel cables or steel plates. To show the potential of high-strength carbon fiber reinforced plastics (CFRPs), a 13 m span stress ribbon bridge with CFRP ribbons was built in the laboratory of the Department of Civil and Structural Engineering, Berlin Institute of Technology (TU Berlin); see Fig. 1. This composite material allows considerably smaller cross sections compared to steel. The bridge's tensile force under dead and live load is carried by only 6 ribbons with a cross section of $\approx 1.1$ mm $\times$ 50 mm each. The combination of low extensional stiffness using CFRP for the ribbons and a lightweight bridge deck leads to considerable dynamic responses caused by pedestrian loads [3,4].

Generally, to keep vibrations within acceptable limits, several conceptual design approaches such as increasing the stiffness or increasing the dead load/traffic load ratio have been applied in practice. Sometimes, additional passive dampers have been installed to reduce high vibrations [5–8].

An alternative potential approach to ensure the structural serviceability respectively comfort criteria of footbridges is to use active vibration control (AVC). In particular, this is necessary for extremely light structures, where system properties such as the mass and stiffness become time-variant with changing pedestrian traffic. Then the natural frequencies start to depend on live loads and some passive damping techniques can no longer operate optimally.

In civil engineering structures, active vibration control has been achieved and implemented by active mass dampers (AMDs) or hybrid mass dampers (HMDs) in towers, tall buildings, and pylons of cable-stayed bridges. Controllable fluids such as electro-rheological (ER) and magneto-rheological (MR) ones have been used as semi-active dampers to control wind-induced cable vibrations and buildings under earthquake excitations [9–11]. Studies on the active control of cable vibrations have been conducted in [12–14]. By axial support movements, sag-induced forces can be applied which change the cable tension and control the in-plane vibrations. Experimental studies have confirmed this control strategy, limited to the symmetric modes and efficient only for the first in-plane mode.

The applied concept of active vibration control for the stress ribbon bridge is to control the symmetric modes as well as the asymmetric modes. The natural frequencies of the CFRP

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