Modelling and Control of Magnetorheological Damper: Real-time implementation and experimental verification - DTU Orbit (20/07/2019)

Modelling and Control of Magnetorheological Damper: Real-time implementation and experimental verification

This thesis considers two main issues concerning the application of a rotary type magnetorheological (MR) damper for damping of flexible structures. The first is the modelling and identification of the damper property, while the second is the formulation of effective control strategies. The MR damper is identified by both the standard parametric Bouc-Wen model and the non-parametric neural network model from an experimental data set generated by dynamic tests of the MR damper mounted on a hydraulic testing machine. The forward model represents the direct dynamics of the MR damper where velocity and current are used as input and the force as output. The inverse model represents the inverse dynamics of the MR damper where the absolute velocity and absolute force are used as input and the damper current as output. For the inverse model the current output of the network must always be positive, and it is found that the modelling error of the inverse model is significantly reduced when the corresponding input is given in terms of the absolute values of velocity and damper force. This is a new contribution to the inverse modelling techniques for the control of MR dampers. Another new contribution to the modelling of an MR damper is the use of experimental measurement data of a rotary MR damper that requires appropriate filtering.

The semi-systematic optimisation procedure proposed in the thesis derives an effective neural network structure, where only velocity and damper force are essential input parameters for the MR damper modelling. Thus, for proper training, the quality of the velocity data is very important. However, direct velocity measurement is not easy. From the displacement data or the acceleration data, velocity can be determined by using simple differentiation or integration, respectively, but these processes add undesirable noise to the velocity. Instead the Kinematic Kalman Filter (KKF) is an effective means for estimation of velocity. The KKF does not directly depend on the system or structural model, as it is the case for the conventional Kalman filter. The KKF fuses the displacement and the acceleration data to get an accurate and robust estimate of the velocity. The simplicity of the network and the application of velocity in terms of KKF is a novel contribution of the thesis to the generation of a training set for neural network modelling of MR dampers.

The development of the control strategies for the MR damper focuses on the introduction of apparent negative stiffness, which basically leads to an increased local motion of the damper and thereby to increased energy dissipation and damping. Optimal viscous damping (VD) is chosen as the benchmark control strategy, used as reference case for assessment of the proposed control methods with negative stiffness. Viscous damping with negative stiffness (VDNS) initially illustrates the effectiveness of the negative stiffness component in structural damping. In a linear control setting negative stiffness requires active control forces, which are not realizable by the purely dissipative MR damper. Thus, these active components are simply clipped in the final control implementation. Since MR dampers behave almost as a friction damper improved damping performance can be obtained by a suitable combination of pure friction and negative damper stiffness. This is realized by amplitude dependent friction damping with negative stiffness (FDNS), where the force level of the friction component is adaptively changed to secure the optimal balance between friction energy dissipation and apparent negative stiffness. This type of control model for semi-active dampers is rate-independent and conveniently described in terms of the desired shape of the associated hysteresis loop or force-displacement trajectory. The final method considered for control of the rotary MR damper is a model reference neural network controller (MRNNC). This novel control approach is designed and trained based on a desired reference damper model, in which case the amplitude dependent friction damping with negative stiffness (FDNS). The idea is to train the neural network of the controller by data derived explicitly from the desired shape of the force-displacement loop at pure harmonic motion. In this idealized representation the optimal relations between friction force level, negative stiffness and response amplitude may often be given explicitly by e.g. maximizing the damping ratio of the targeted vibration mode. Consequently the idea behind this trained neural network is that the optimal properties of the desired hysteresis loop formulation can be extrapolated to more general and non-harmonic response patterns, e.g. narrow-band stochastic response due to wind, wave, traffic or even earthquake excitation.

Numerical and experimental simulations have been conducted to examine the performance of the proposed control strategies. Force tracking by using an inverse neural network of the MR damper is improved by a low-pass filter to reduce the noise in the desired current and a simple switch that truncates negative values of the desired current. The performance of the collocated control schemes for the rotary type semi-active MR damper are initially verified by closed loop dynamic experiments conducted on a 5-storey shear frame structure exposed to harmonic base excitation. The MR damper is mounted on the structure so that it operates on the relative motion between the ground base and the first floor of the shear frame. The shear frame structural model is initially experimentally identified, where mass and stiffness of the model is determined by an inverse modal analysis based on the natural frequencies obtained experimentally. The damping matrix is subsequently determined from the estimated damping ratio obtained by free decay tests. The results in the thesis demonstrate that introducing apparent negative stiffness to the control of the MR damper significantly decreases both the top floor displacement and acceleration amplitudes of the shear frame structure. The structural damping ratios obtained from the response curves of the experiments correspond well to the expected values. This indicates that the mean stiffness and mean energy dissipation of the control forces are predicted fairly accurate.

A final numerical investigation is based on a classic benchmark problem for earthquake protection of a multi storey building. The seismic response of the base-isolated benchmark building with an MR damper installed between the ground and the base is illustrated, and the effectiveness of negative stiffness of the control strategies is verified numerically. Similarly, the response of another wind excited benchmark building installed with MR dampers is demonstrated and the performance shows satisfactory result.

The main contributions to this thesis are the novel modelling approach to the direct and the inverse dynamics of a rotary MR damper from experimental data, the development of model based semi-active control strategies for the MR damper,
the effective introduction of negative stiffness in the control of semi-active dampers and the demonstration of effectiveness and closed loop implementation of the control techniques on both a shear frame structure and a numerical benchmark problem.

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