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CABLE VIBRATION REDUCTION USING AN ATTACHED MR DAMPER

REDUKCE VIBRACE KABELU POMOCÍ MR TLUMIČE

Abstract

The paper addresses vibration reduction of a cable with a transversely attached magnetorheological (MR) damper operating in passive and controlled modes. The model of the cable-MR damper system is presented. The control algorithm for MR damper based on optimal viscous damper emulation is described. Numerical data to demonstrate MR capabilities in cable vibration reduction are provided. The efficacy of an MR damper in reducing cable vibrations is confirmed experimentally.

Abstrakt

Příspěvek se týká problematiky redukce příčných vibrací kabelů s kolmě umístěným magnetorheologickým (MR) tlumičem. Je zde popsán model kabelového - MR tlumiče, dále je popsán řídicí algoritmus pro MR tlumič na bázi emulace optimimálního viskozního tlumiče. V příspěvku jsou prezentována numerická data pro demonstraci možností MR při redukci vibrace kabelu. Úspěšnost redukce těchto vibrací byla potvrzena experimentálním výzkumem.

1 INTRODUCTION

Cables are very useful in various types of supporting structures. They have very low internal damping and therefore tend to develop dangerous vibrations and wave motion. The types of motion differ in the form of energy transfer from the vibration source to the cables.

Various countermeasures such as passive dampers with viscous properties or semi-active dampers, are used to protect cable against vibrations (Krenk 2000, Weber and Feltrin 2003, Wang *et al*. 2005). It was reported that MR dampers are successfully employed in cable-stayed bridges (Duan *et al*. 2003, Weber *et al*. 2005). Unlike viscous dampers, one advantage of MR dampers attached to cables is that they can be tuned to the occurring mode. Such dampers might be employed to effectively damp various cable vibration modes, at some distance from their location and cable anchorage points. MR dampers can operate in the passive mode (under constant current) or in controlled mode (under variable current). In the passive mode the MR damper force depends on the piston velocity in a minor degree only, which seems a major drawback. The capabilities can be fully utilized in controlled mode MR damper by providing an appropriate control algorithm.

The paper considers the problem of cable vibration reduction using an MR damper attached, operating both in passive and controlled modes. The study is organized as follows. Section 1 provides the cable vibration problem, particularly using MR dampers. The cable-MR damper system is described in section 2. Section 3 presents the proposed control system based on the algorithm of optimal viscous damper emulation. Selected results of system behavior in case of free and forced vibrations obtained numerically and experimentally are compiled in sections 4 and 5. The summary is provided in section 6.

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2 MODEL OF THE CABLE-MR DAMPER SYSTEM

The schematic diagram of a cable with an attached MR damper system is shown in Figure 1. The damper is used for control of the cable motion. As damper fixing elements are small sized when compared to the cable diameter, it is assumed that the MR damper acts upon the cable with a concentrated force. This force, related to the damper input current, is an input signal in the cable-MR damper system.

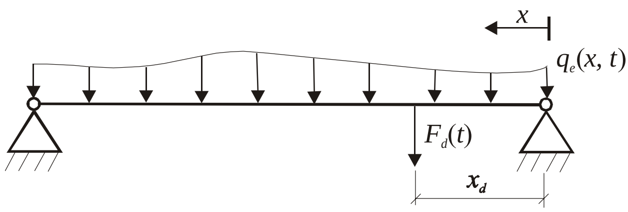


Fig. 1 Schematic diagram of a cable with an attached MR damper

Cable motion, taking into account the control action with the use of an MR damper, is governed by a partial differential equation of the second-order:

$$m_x \frac{\partial^2 w}{\partial t^2} - F_N \frac{\partial^2 w}{\partial x^2} = q_e(x,\ t) + F_d(t)\delta(x - x_d) \tag{1}$$

where: $w\ (x,\ t)$ – transverse displacement of the cable, m_x – mass of the cable per unit length, F_N – cable tension force, $q_e(x,\ t)$ – excitation distributed along the cable, $F_d\,(t)$ – concentrated force acting upon the cable, $\delta(x-x_d)$ – delta function specifying the location of MR damper force at $x = x_d$, x_d – distance of MR damper location from the end.

An effective solution to Eq. (1) in the general case ultises the concept of vibration modes of the cable. In the specific case, associated with steady motion under harmonic excitations, the solution can be determined without resorting to the vibration modes.

The solution to Eq.(1) can be written as:

$$w(x,\ t) = \sum_{i=1}^{\infty} \phi_i(x) q_i(t) \tag{2}$$

where: $\phi_i(x)$ – normalized natural mode, $q_i(t)$ – generalized coordinate.

The model of the cable-MR damper system is shown schematically in Figure 2. The damper used in the system is the RD-1097-01 damper of Lord Co. (http://www.lord.com). The key functional parameters of this damper are: maximal force 100 N (for input current 1 A and piston velocity 51 mm/s), stroke ±25 mm, response time < 25 ms (time required to reach 90% of the steady-state value under the step change of the current level from 0 to 1 A, for 51 mm/s).

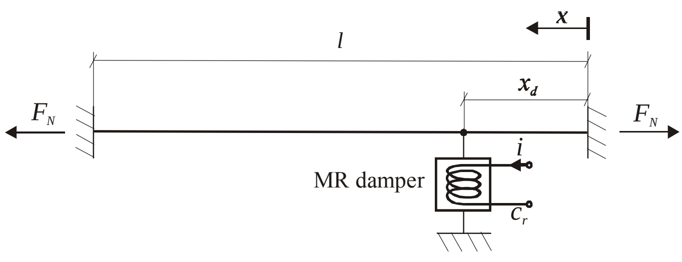


Fig. 2 Model of the cable-MR damper system

The RD-1097-1 damper is modeled by of the Bingham model, the parameters of which were obtained in identification experiments. The Bingham model utilizes a Coulomb friction element f_c placed parallel to the dashpot c_0 (Fig. 3).

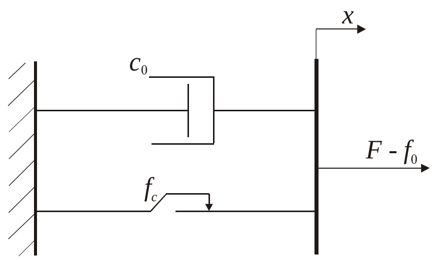


Fig. 3 Bingham model of an MR damper

According to the Bingham model, the damper force F for non-zero piston velocity $\dot{x}$ is given by:

$$F = f_c \operatorname{sgn}(\dot{x}) + c_0 \dot{x} + f_0 \qquad (15)$$

where: f_c – friction force, c_0 – viscous damping coefficient, f_0 – force due to the presence of an accumulator.

3 CONTROL SYSTEM

To illustrate how cable vibrations can be controlled by the use of an attached MR damper the algorithm based on optimal viscous damper emulation is considered (Maślanka *et al.* 2007). This algorithm control is realized in a manner which ensures the effective emulation of the linear force-velocity relationship holding for viscous dampers (unlike dampers operating in the passive mode, where the damping force depends on velocity in a minor degree only). The viscous damping coefficient $c_n^{(opt)}$ to be emulated should be chosen depending on the parameters: l, m_x, F_N, x_d and the observed mode, in accordance with the formula yielding the optimal damping coefficient $c_n^{(opt)}$ (Krenk 2000):

$$c_n^{(opt)} = \frac{1}{n\pi} \frac{l}{x_d} \sqrt{m_x F_N} \qquad (3)$$

Eq. (3) reveals that, for a cable with the given parameters, the value $c_n^{(opt)}$ for each mode will be different. Therefore, a viscous damper optimally selected to handle one mode, would not be able to effectively damp other modes of vibrations. In real of cable vibrations, for example in the case of rain-wind excitations acting on cable-stayed bridges, various modes were observed for similar parameters (Duan *et al.* 2006). For this reason it is difficult to specify a priori the dominant mode of cable vibrations. A diagram of the control system based on the selected algorithm is shown in Fig. 4. This algorithm required feedback from velocity $\dot{x}_d$.

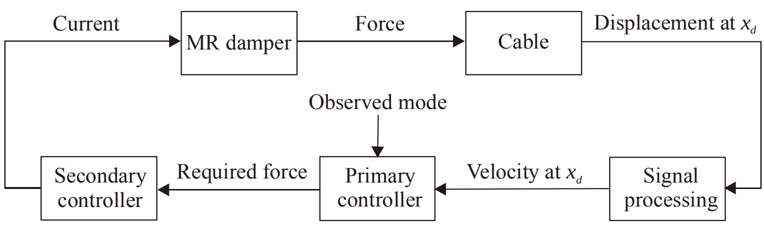


Fig. 4 Diagram of the control system

In real life conditions this velocity might be reconstructed from the acceleration or displacement signals. During the tests this velocity was reconstructed from the measured displacement signal at x_d. The displacement signal was first filtered and then differentiated (signal processing block). Knowing the occurring mode and velocity, one is able to determine the required force to be produced by an MR damper (primary controller block). This force corresponds to that generated by a viscous damper for $c_n^{(opt)}$. This is the preset value for the secondary controller block which represents the inverse model of an MR damper. This model would yield the input current value so that the required force is generated in the MR damper. Underlying the inverse model is the relationship between damping force and velocity and input current. This model takes into account the intrinsic nonlinear and changeable damping nature of an MR damper (Xia 2003, Du *et al*. 2005, Tsang *et al*. 2006). It should be noted that the secondary controller does not require an internal force feedback.

4. SIMULATIONS

The model of the cable-MR damper system (Fig. 2) was studied in MATLAB/Simulink. The following system parameter values were assumed: cable tension, $F_N = 30.93$ kN, mass of the cable per unit length, $m_x = 1.675$ kg/m, cable length, $l = 29.78$ m, and MR damper location at $x_d = 1.1$ m. The parameter values of the identified Bingham model of RD-1097-1 damper were: $f_c = 3.6$ N, $c_0 = 2.1$ N·s/m for input current 0.00 A and $f_c = 23.5$ N, $c_0 = 35$ N·s/m for input current 0.30 A (note that the parameter $f_0 = 0$ N, since the damper has no accumulator).

In the first stage the cable-MR damper system was investigated in the passive mode. In the simulation procedure the cable motion was approximated using the Ritz-Galerkin method. The efficiency of the Ritz-Galerkin method depends on the selected functions $\phi_i(x)$. They are often assumed as modal functions determined for a cable with no damper. In calculations a finite number of modal functions was assumed. One drawback involved in approximation is that the truncated higher order modes contribute significantly to the motion of the point where the damper is attached. In several recent works (Johnson *et al*. 2000, Johnson *et al*. 2003), the set of modal functions is supplemented with a function describing the static displacement of the string under concentrated force applied at the point where the damper is attached. The graph of this function looks like a triangle.

Simulations cover the first seven modes of the cable with no damper (sine function) and triangular function. The sampling frequency was set to be 1 kHz. Displacements were computed at points with 0.25 m spacing along the cable length. Selected simulation data at frequency nearing that of the first mode are shown in Figures 5−6 (free vibrations) and Figures 7−10 (forced vibrations).

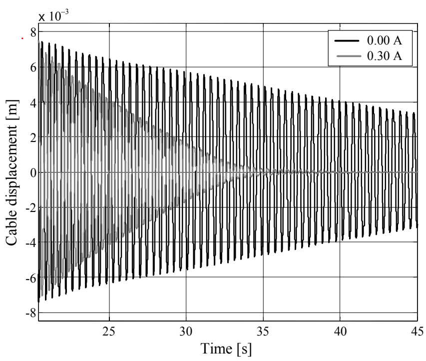


Fig. 5 Cable displacement vs. time at x=xd

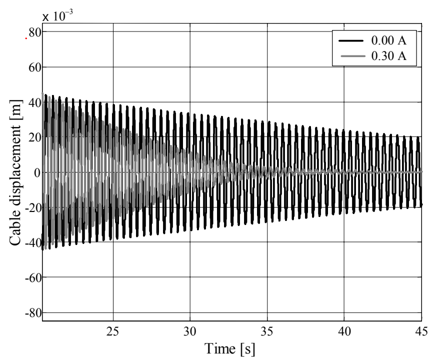
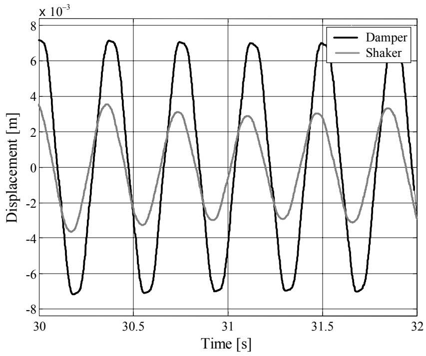


Fig. 6 Cable displacement vs. time at x=xm



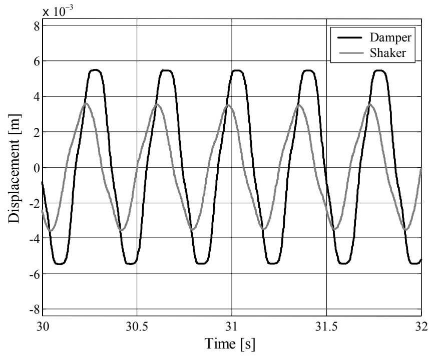
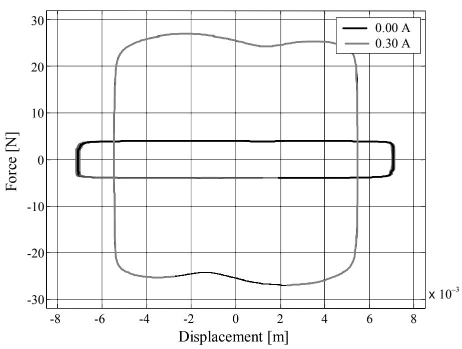


Fig. 7 Cable displacement vs. time at x=xd and at x=xs, input current 0.00 A (zoomed section)

Fig. 8 Cable displacement vs. time at x=xd and at x=xs, input current 0.30 A (zoomed section)

Figures 5 and 6 show cable displacement vs. time at $x = x_d$ (MR damper location) and $x = x_m$ (measurement point assumed to be $x_m = 22.5$ m) for input currents: 0.00 A and 0.30 A. It is observed that higher input currents allowed the vibrations to be damped significantly. Figures 7 and 8 present zoomed sections of cable displacement vs. time at $x{=}x_d$ and at $x{=}x_s$ (shaker location assumed to be $x_s{=}$ 22.5 m) for input currents 0.00 A and 0.30 A. It is seen that cable displacement at x_d has the nature of sine vibrations with the characteristic limitation near the maximal values (Sapiński and Snamina 2007). In addition, a phase shift is observed between cable displacements at x_d and x_s. Figures 9 and 10 show damper force vs. displacement and velocity.



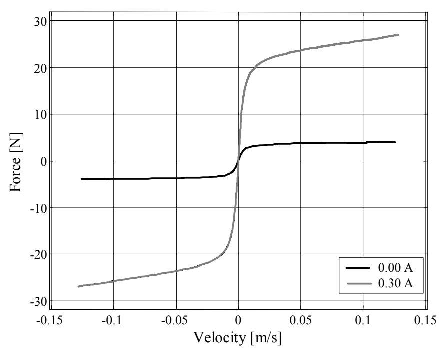


Fig. 9. Damper force vs. cable displacement at x=xd

Fig. 10. Damper force vs. cable velocity at x=xd

5 EXPERIMENTS

Experiments were run in a laboratory setup shown schematically in Figure 11 (Sapiński *et al*. 2006). There is a horizontally suspended steel cable, clamped at the ends. The length of the control section is L = 30 m, cable mass per unit length is m = 1.8 kg/m. The cable is tensioned using a lever mechanism. The maximal tension force approaches 35 kN. The RD-1097-01 damper is attached near one of the cable supports.

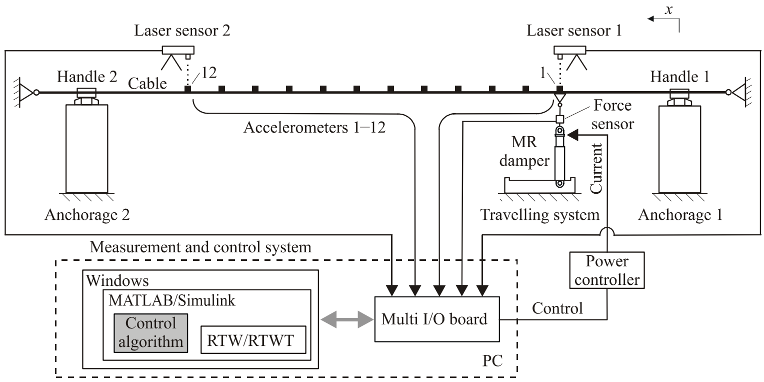


Fig. 11 Schematic diagram of the experimental setup

The measurement and control system comprises a PC, multi I/O board and MATLAB/Simulink. Transverse cable accelerations are measured at maximally 12 locations, there are laser sensors measuring transverse cable displacements at two points, damper force is measured along the damper axis. MR damper is controlled using a power controller operating in the analogue, voltage input-current output mode (Sapiński 2006).

In the first stage the cable-MR damper system in the passive mode was investigated, assuming $x_d = 1.1$ m and $x_m = 22.5$ m. Free vibrations after a cable-MR damper system was excited manually and forced vibrations induced by the shaker were measured. Selected measurement data for the first mode are shown in Figures 12–17 (free vibrations) and in Figures 18–21 (forced vibrations).

A comparison of measurement and simulation data shows a high degree of correspondence in the investigated time intervals. It is clear (see Figs 12 and 13) that the higher the input current the shorter the time of free vibration decay. It is also seen that there is a time instant of about 33 s at which the vibration energy is not dissipated in the damper because it is locked. Under this condition the cable is clamped at the point x_d.

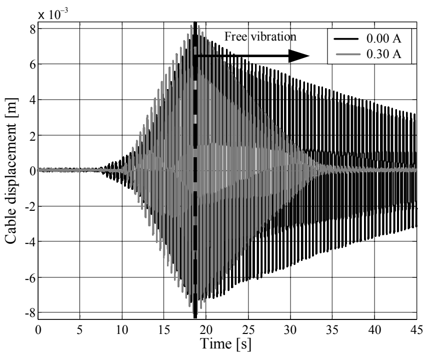


Fig. 12 Cable displacement vs. time at $x = x_d$

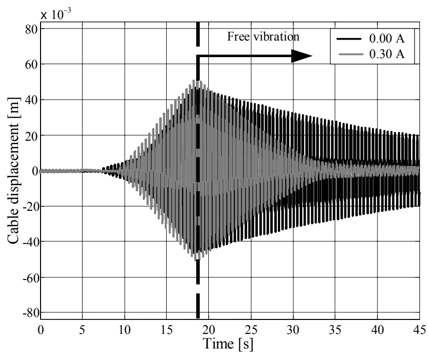


Fig. 13 Cable displacement vs. time at $x = x_m$

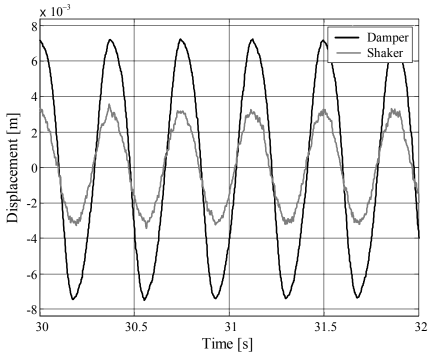


Fig. 14 Cable displacement vs. time at $x=x_d$ and at $x=x_s$, input current 0.00 A (zoomed section)

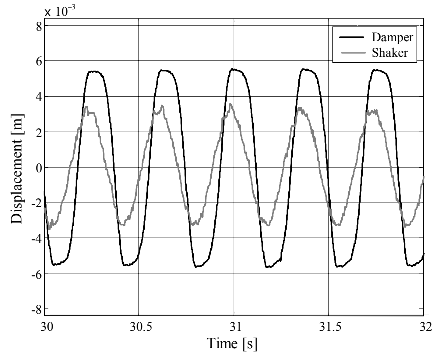


Fig. 15 Cable displacement vs. time at $x=x_d$ and at $x=x_s$, input current 0.30 A (zoomed section)

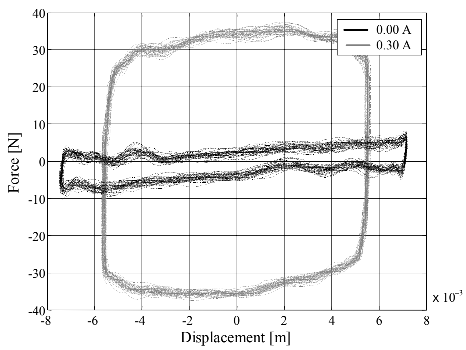


Fig. 16 Damper force vs. cable displacement at $x=x_d$

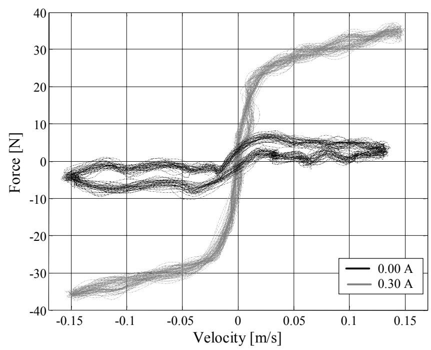


Fig. 17 Damper force vs. cable velocity at $x=x_d$

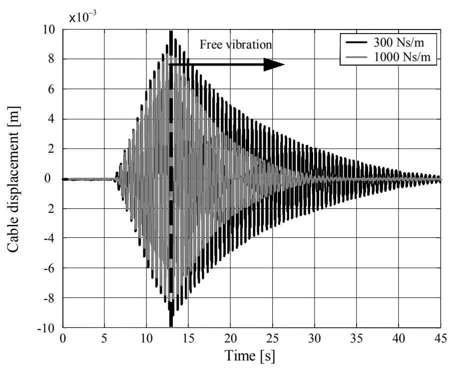


Fig. 18 Cable displacement vs. time at $x=x_d$

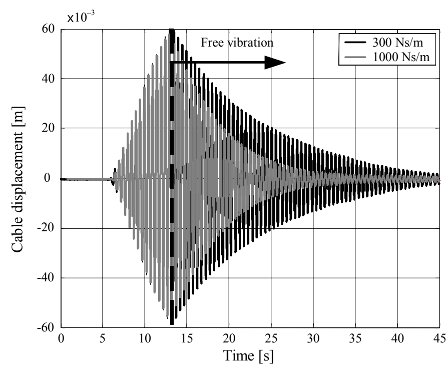


Fig. 19 Cable displacement vs. time at $x=x_m$

In the second stage the cable-MR damper system was investigated in the controlled mode. Free vibrations after a manual excitation of a cable-MR damper system were measured. Selected measurement data for mode one of free vibrations are shown in Figures 16–21. Figures 18–19 present cable displacement vs. time at x_d and x_m (x_m was assumed to be 22.5 m) for values of the damping coefficient: 300 N·s/m and 1000 N·s/m. These values are less than that one obtained from calculations $c_1^{(opt)} = 1961.46$ N·s/m. The $c_1^{(opt)}$ value is the optimal one, however, it is too large to be realized by the RD-1097-1 damper used in the experiments.

The nature of vibrations decay observed in Figures 18 and 19 is typical for viscous dampers. A comparison of the plots in Figure 19 (controlled mode) and Figure 13 (passive mode) shows that the considered algorithm is effective and emulates the viscous damper's operation.

Figures 20 and 21 present damper force vs. displacement and velocity plots at $x=x_d$. Figure 21 shows that the damper force-cable velocity relationship, in accordance with considered algorithm, is nearly linear.

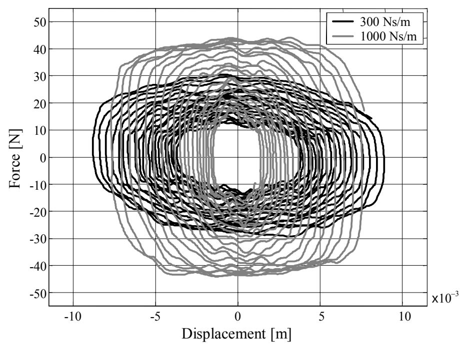


Fig. 20 Damper force vs. cable displacement at $x=x_d$

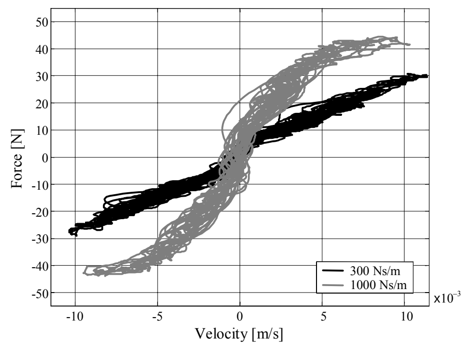


Fig. 21 Damper force vs. cable velocity at $x=x_d$

6 SUMMARY

The paper considers the problem of cable vibration reduction with an attached MR damper. Free and forced vibrations were investigated both for an MR damper operating in passive and controlled modes. In the controlled mode the algorithm was based on optimal viscous damper emulation.

The purpose of this research work was to explore the potential applications of MR dampers operating in the passive mode to the cable vibration control and to find the advantages of the applied control algorithm. The analysis of measurement data indicates that controlled MR damper ensures a nearly constant damping level in a wide range of amplitudes, which is a major benefit of viscous dampers. However, the maximal, theoretically predicted damping levels were impossible to achieve during the experiments. This is associated with limited force range available in RD 1097-1 damper used in the tests.

The algorithm based on optimal viscous damper emulation might be implemented in an alternative manner, as for example by periodic switching of the control current, depending on vibration amplitude.

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