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FACILITY FOR TESTING OF MAGNETORHEOLOGICAL DAMPING SYSTEMS FOR CABLE VIBRATIONS[****]

SUMMARY

The paper presents the laboratory facility developed for testing of cable vibrations. The facility was engineered as a part of the research project covering vibration control of cables by the use of magnetorheological (MR) dampers. Potential applications of MR dampers in vibration control of cables are explored. The main emphasis is on mechanical structure, MR damping system, measurement and control equipment. Various experiments were conducted to test the facility and measurement system.

Keywords*: magnetorheological dampers, cable vibrations, vibrations damping*

STANOWISKO DO BADAŃ MAGNETOREOLOGICZNYCH UKŁADÓW TŁUMIENIA DRGAŃ LIN

W artykule przedstawiono stanowisko laboratoryjne do badań układów tłumienia drgań lin. Stanowisko opracowano w ramach projektu badawczego dotyczącego sterowania drganiami lin z zastosowaniem tłumików magnetoreologicznych (MR). Opisano możliwości wykorzystania tłumików MR w tym zakresie. Przedstawiono strukturę mechaniczną, układ tłumienia MR, układ wzbudzania drgań oraz oprzyrządowanie pomiarowo-sterujące stanowiska. Zamieszczono wyniki testów stanowiska badawczego i układu kontrolno-pomiarowego.

Słowa kluczowe*: tłumiki magnetoreologiczne, drgania lin, tłumienie drgań*

1. INTRODUCTION

Long stay cables, such as those used in cable-stayed bridges are exposed to changeable weather conditions. The results of wind action are being several unwanted phenomena, the most dangerous is cable galloping. For instance, for ice-covered cable the amplitude of vibration can be 50 times larger than cable diameter. Several mitigation techniques have been proposed to solve this problem. One of the modern is semi-active system using magnetorheological (MR) dampers. This kind of dampers are very efficient due to the fact that they can operate as passive dampers [6, 8] or can be controlled using various control strategies [2, 3, 9].

In real supporting structures cables are usually inclined, however, in many experiments conducted under laboratory conditions supports of cables are placed on the same level and MR dampers are mounted transverse to the cables at the points near one of supports. Results of experiments are reported in the literature of the subject [8, 10].

The aim of the venture presented in this study was to create an environment to do research into the practical applications of MR dampers to mitigate cables vibrations. The existing facility, designed for testing of cables used in overhead transmission lines, has been utilized to realize this goal. The venture required us to do some modifications to elements of the supports and tensioning system and first of all the special experimental setup with the measurement and control system.

This paper presents the essential adaptations of the existing facility and the new design of the experimental setup to realize the authors research program concerning the application of MR damper for cable vibrations mitigation. The adequacy of the developed experimental setup was proofed in the series of functional tests.

2. POTENTIAL OF MAGNETORHEOLOGICAL DAMPERS FOR CABLE VIBRATION CONTROL

Cables have very low internal damping. Therefore special dampers are mounted to protect the engineering structure with cables against different types of vibrations. The dampers may be passive with viscous properties or semi-active with MR fluid. Other controllable dampers are not able to provide such great ratio of the maximum force to the minimum force (particularly at low velocities), such quick retuning, such fast response-time and such wide operating temperature range with no significant deterioration of the performance.

The application of MR dampers to cable-stayed bridges subjected to wind-rain excitations has been investigated through many analytical and experimental studies. It was demonstrated that MR dampers installed at the cables are effective and convenient for cable-vibrations control and countermeasures, enabling to suppress vibrations, both in- and out- of plain.

To illustrate the application of MR dampers for vibration suppression we show the schematic diagram of MR dampers implementation at a cable-stayed bridge in Figure 1.

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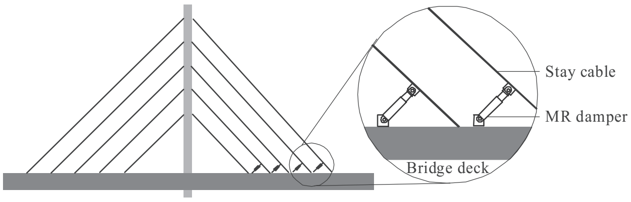

Fig. 1. Diagram of MR dampers implementation at cable-stayed bridge

The first full-scale implementation of MR dampers was accomplished in 2002 at the Dongting Lake Bridge in China (the bridge was completed in 1999) [1]. The reason why such installation of MR damping system was installed at the bridge was that rain-wind induced vibration. The peak-to-peak amplitude of cable vibration exceeded 0.8 m. The encountered 2nd and 3rd modes caused the galloping both in-plane and out-of-plane. The amplitude of in-plane vibration was always larger than in out-plane vibration. The vibration was responsible for cracks on connections between cable and bridge deck.

3. FACILITY DESCRIPTION

The facility is placed in the underground tunnel between two buildings. The tunnel is made of reinforced concrete plates and steel frame. It is 40 m long, 2.3 m wide and 2.4 m high. The mechanical strength of the tunnel against the static and dynamic loadings is significantly greater than loadings encountered during experiments. The tunnel is not directly connected to the overall building structure.

The facility was originally designed for testing of cables used in overhead transmission lines [14]. The supports and stretch system was established to cable parameters most frequently used in transmission lines – the maximum tension 50 kN, the maximum diameter of the cable 50 mm. The series experiments concerning the damping property of cables were performed [7, 14].

The facility can be adapted to experiments with the other type of cables. If the parameters of the cables are similar to those established in the project guidelines, the experiments can be realized directly. In other case the principle of dynamical similarity can be used to select the appropriate model of the cable.

In order to perform the experiments with cable – MR damper system, the facility was adapted to the actual working conditions. Since the MR damper requires the control devices, the hardware and software equipment were designed and built.

3.1. Mechanical structure

Main parts of the facility are two support blocks, two handles mounted on the blocks and the stretch system. The schematic diagram of the facility is shown in Figure 2.

The test part of the cable is bounded by two special handles. It is 30 m long and its two fixed points are 1 m above the floor. The handle consists of replaceable clamping elements (in the shape of two parts of cylinder) and two external plates jointed by bolts. Clamping elements have to be the right size for cable diameter. The handles are mounted on the support concrete blocks. The block diameters are 1.1 m × 1.5 m × 0.7 m and mass is equal to 2500 kg. Thanks the large mass of the blocks the energy transfer from the cable to the floor through the handles is neglected. The handles limit the test segment of the cable but they are not used to stretch the cable. In order to stretch the cable the special stretch system was built. The system consists of two parts. On the front side there is a vertical beam clamped to the floor and to the ceiling. On the cable, near the beam, there is a pre-tensioning system in the form of adjusting screw. The main tensioning system is placed on the rear side and is designed as a single-arm lever. The appropriate weight is placed on the platform hanged at the end of the lever. The cable is attached to the stretch system using original anchor clamps which are mounted to the cable ends using special hydraulic press. The tension of the cable is measured by means of dynamometer placed on the cable near the pre-tensioning system.

3.2. MR damping system

The RD-1097-01 damper (Fig. 3) manufactured by Lord Co. is installed transverse to the cable (Figs. 5 and 6). The technical specification of the RD-1097-01 damper is provided in Table 1 [12].

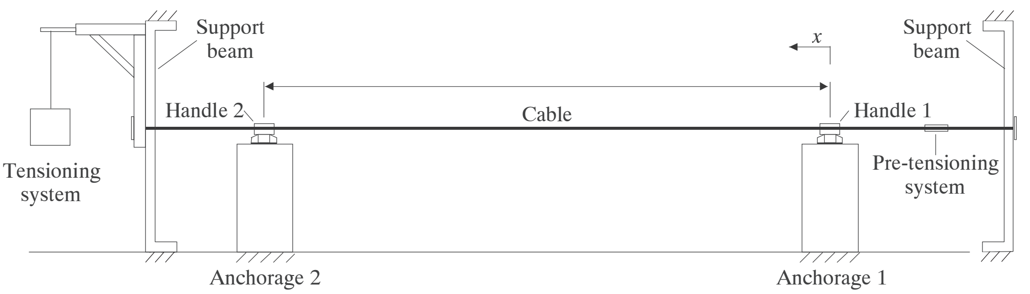

Fig. 2. Diagram of the facility mechanical structure

Fig. 3. Photograph of the RD-1097-01 damper

Table 1

Specification of the RD-1097-01 damper

Extended length	253 mm
Compressed length	195 mm
Body diameter	32 mm
Weight	0.48 kg
Stroke	± 25 mm
Input voltage	12 V DC
Input current continuous	< 0.5 A
Input current intermittent	< 1.0 A
Coil resistance (25°C)	20 Ω
Force (peak to peak)	100 N (51 mm/s, 1 A) 9 N (200 mm/s, 0 A)
Operating temperature	< 70°C
Response time*	< 25 ms
Durability**	2 million cycles

[*] Time to reach 90% of max. level during a 0 A to 1 A (dependent on amplifier and power supply).

[**] ±13 mm, 2 Hz, input current varying between 0 A and 0.5 A.

The damper is fixed in a specially designed guiding mechanism with traveling system incorporated (Fig. 4). A traveling system is provided that allows for selecting the fixing point from the range (1, 3) m from the anchorage 1.

Force generated by the damper enables the effective damping of cable vibrations. The damper force can be adjusted according to the analogue output signal from the specially designed power controller [5].

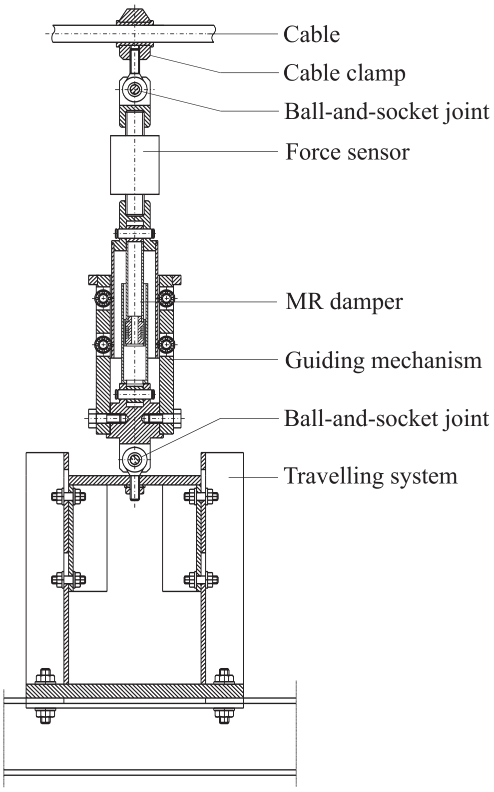

Fig. 4. Structure of the guiding mechanism

3.3. Measurement and control equipment

The diagram of the experimental setup is shown in Figure 5 and the photograph of the cable in Figures 6, 7, 8.

The developed measurement and control system was based on a PC with RT-DAC4 multi I/O board [13] installed and supported by software of Windows XP and MATLAB 0.7 with Simulink and RTW/RTWT.

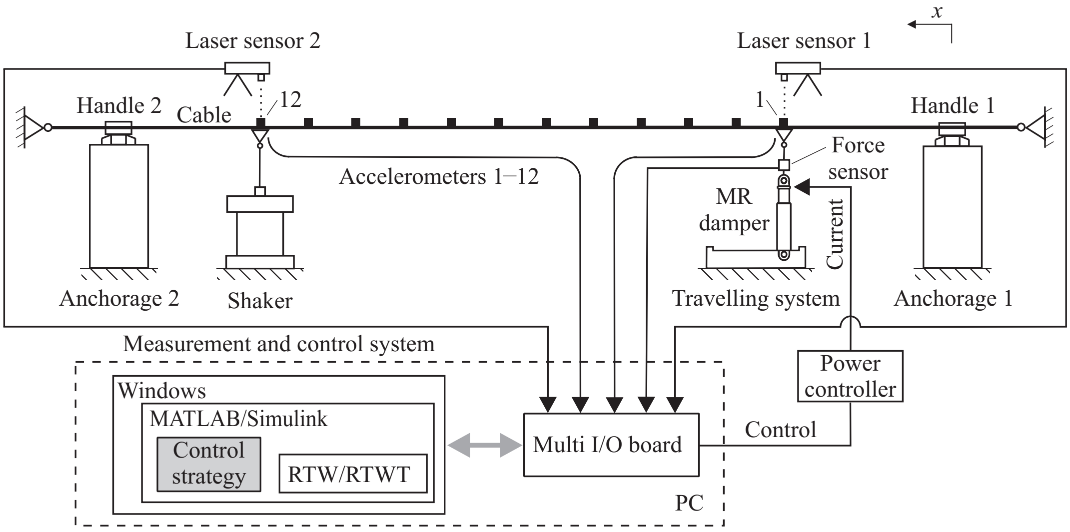

Fig. 5. Diagram of the experimental setup

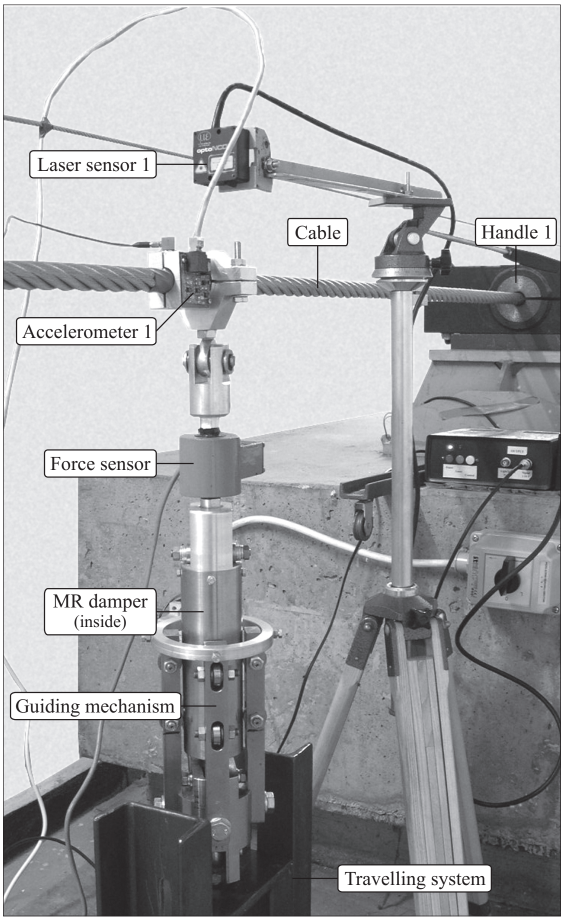

Fig. 6. Photograph of the experimental setup from the side of anchorage 1

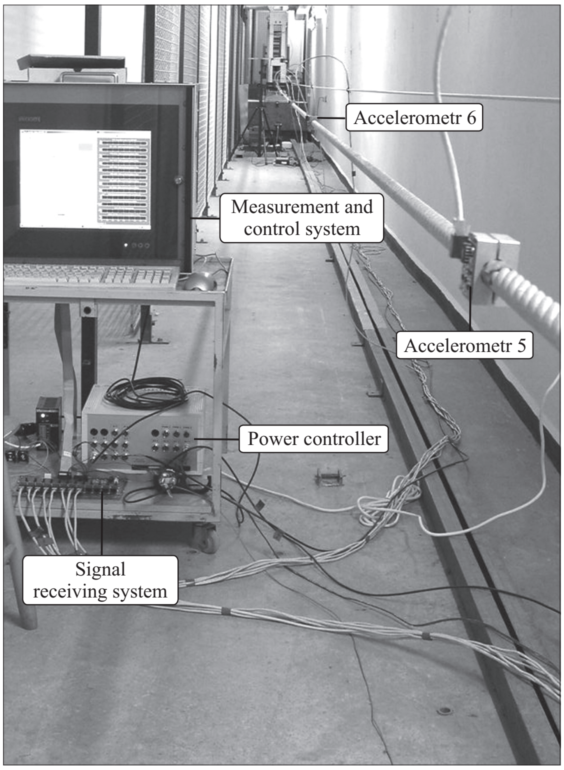

Fig. 7. Photograph of the experimental setup from the side of anchorage 2

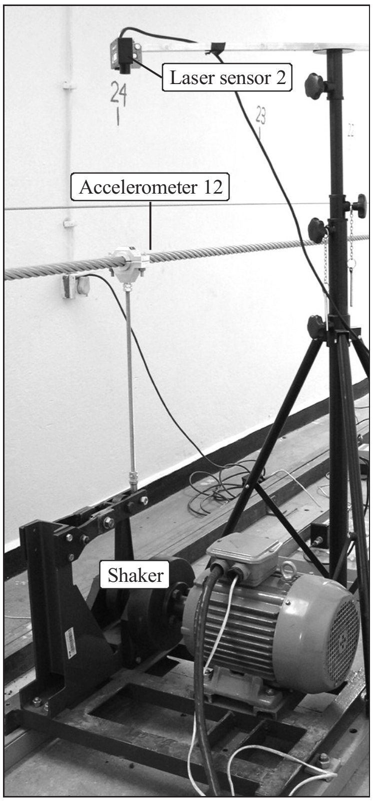

Fig. 8. Photograph of the shaker equipment

The measuring system comprises a force sensor measuring damper force acting along the damper axis, laser sensors measuring transverse cable displacements (at the point the damper is fixed and any other point) and accelerometers measuring transverse cable accelerations at maximally 12 locations.

Force measurements are taken with a sensor MEGATRON, series K1100 (the measurement range 1 kN).

Cable accelerations are measured with dual-axis accelerometers Analog Devices ADXL320, with the measurement range ±5 times of gravitational acceleration. These transducers are fabricated in the MEMS technology. They have low power demand and small dimensions (4 mm × 4 mm × 1.45 mm). The bandwidth might be selected by the user, in the range (0.5, 2500) Hz [11]. In measurements of cable vibrations the bandwidth is set to be 50 Hz.

On account of the actual configuration of measurement points a dedicated data transmission system was designed and engineered [4], comprising a system of signal emitters and receiver. These units are implemented as integrated sensor circuits with intermediate systems. Communication between the emitter and receiver is realized via a communication cable UTP category 5. The system enables signal transmission from measurement points at some distance from the data acquisition and control system. The maximum distance of signal transmission in the laboratory facility was 20 m.

The measurement system utilizing an accelerometer ADXL3210 might be directly integrated with the data acquisition system. However, scattering of the measurement points prompted the authors to use the differential system of analogue signal transmission between the measurement points and the computer. The data transmission system was utilized to ensure the quality of measurement signals.

The data transmission system comprises 12 emitters integrated with dual-axial accelerometers and conditioning systems and 12-channel differential transmission receiver adjusted to receive two measuring signals in one receiving channel. Accelerometers and the remaining emitter units are power-supplied via a communication cable directly from the receiver system. The operation of the data transmission system is based on two specialized integrated circuits (Analog Devices), a AD8132 differential driver and a AD8130 differential receiver [11].

In Figure 9 we present a single driver integrated with an acceleration transducer. The driver is fixed on a cable with a visible electronic board fabricated by the surface assembly method, an accelerometer ADXL320 and a communication cable connected to the socket RJ45 in the driver. The board dimensions are 50 mm × 50 mm.

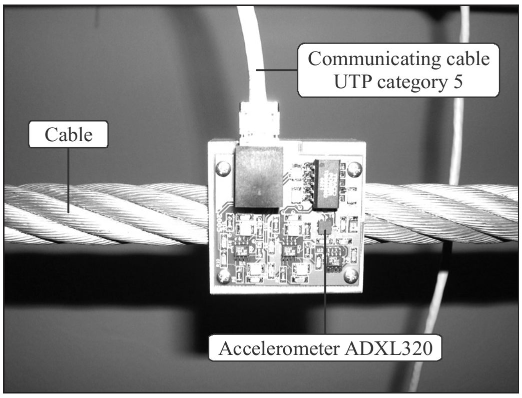

Fig. 9. Photograph of the accelerometer mounted on the cable

A simplified diagram of a single emitter is shown in Figure 10. The emitter utilizes an Analog Devices AD8132 system. The emitter's ancillary systems include the adjustment of voltage signals from an accelerometer to the level required by a differential driver. It is worthwhile to mention that application of these two systems allow for transmission of two signals from the dual axial acceleration transducer ADXL320 (both in-plane and out of plane accelerations).

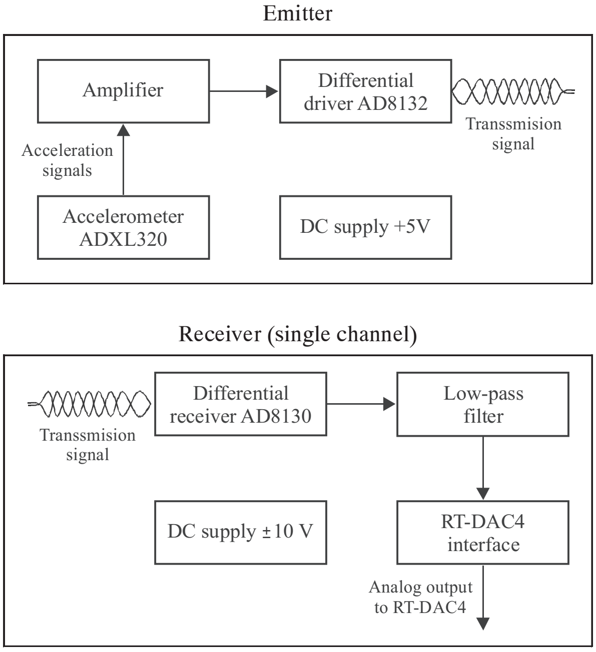

Fig. 10. Block diagram of the communication system

In Figure 11 we present the receiver. It comprises 12 receiving channels. The photo shows a single channel section and the selection switch allowing us to select one of the two measurement signals which might be connected to one channel (in this case the two signals from the acceleration transducer ADXL320). Figure 11 shows the socket RJ45 of 12 reception channels used to connect communication cables. Designated analogue outputs are used for direct connection to the input of the multi I/O board RT-DAC4.

A simplified diagram of a single channel in a receiver is shown in Figure 10. Each channel is implemented using an Analog Devices differential-to-single-ended amplifier AD8130, interacting with the differential driver AD8132.

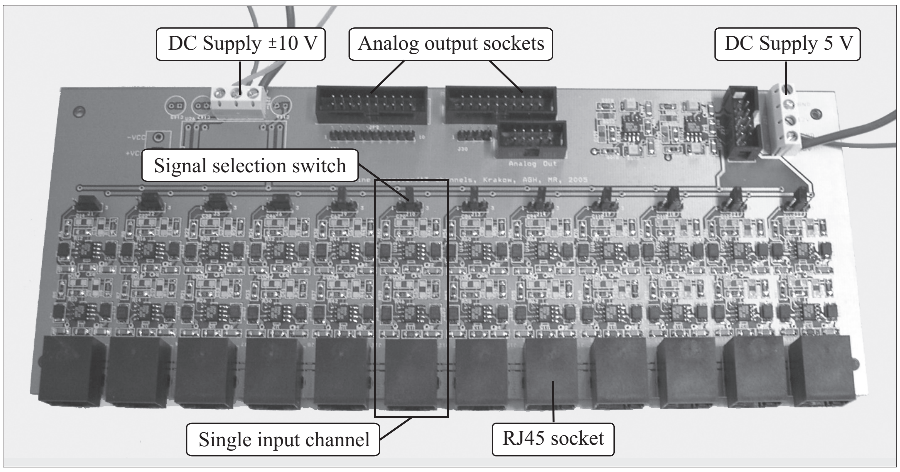

Fig. 11. Receiving system

The receiver's ancillary systems comprise a low-pass filter for the receiver signals (optionally) and the system adjusting voltage output signals to the card RT-DAC4. System parameters were chosen such that for a differential input signal from the range (0, ±1.25) V we obtain a single-ended signal with the value (0, 7.5) V.

The receiver requires the voltage supply of ±10 V and provides the supply to the accelerometers.

4. FUNCTIONAL TESTING

The existing facility has been adjusted to experiments with cables protected by the RD-1097-1 MR damper. In order to test the mecha-nical part of the facility and the experimental setup the special series of measurements must be performed. These measurements should ensure that the main experiment conditions are fulfilled. As a first step the accuracy of mechanical structure setting was checked. Then the testing measurements of free and forced vibrations are conducted.

4.1. Structure setting

In order to achieve the satisfactory accuracy of the results, the cable has to be precisely set in the experimental setup. The main parameter is the tension of the cable. Taking into account the relaxation phenomenon the tension should be checked before each series of experiments. In order to set the tension the external parts of handle must be unscrewed. Then the tension can be checked and appropriate correction can be done.

The experiments have relevance to phenomena of the energy dissipation. MR damper is used in this system as the energy absorbing element. In order to do the precision measurement of the energy it is very important to disable the energy transfer from the cable to the building construction through the handles. Thanks the large mass of the blocks this transfer is very small and can be neglected. The acceleration levels at the points placed on handles are checked and they are below the values that can be measured.

4.2. Free vibration

In the first stage we investigated free vibration of the cable-MR damper system. We measured displacements and accelerations of the cable with no MR damper and with MR damper attached. The displacements were measured by means of laser sensors and the accelerations with accelerometers.

Selected results of measurements conducted for the cable with no damper are provided in Figures 12, 13. They present the first mode and the second mode of the cable vibration respectively measured at point x_m= 22.5 m.

Figure 12 shows time histories of displacement. In the first time interval the cable was excited by hand, then the cable executed the free vibrations. The moment at which the free vibrations were started is indicated in the graph. The vibrations were damped by the internal processes in the cable and reaction between air and moving cable. As mentioned before, the cable has very low internal damping. The dimensionless coefficient of modal damping is equal to 1.300×10^{-3} for the first mode and 0.7×10^{-3} for the second mode.

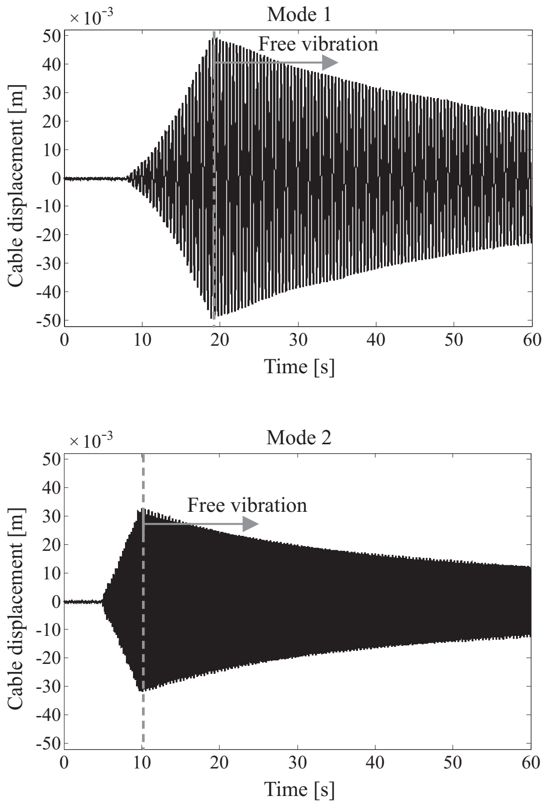

Fig. 12. Cable displacement measured at point x_m = 22.5 m

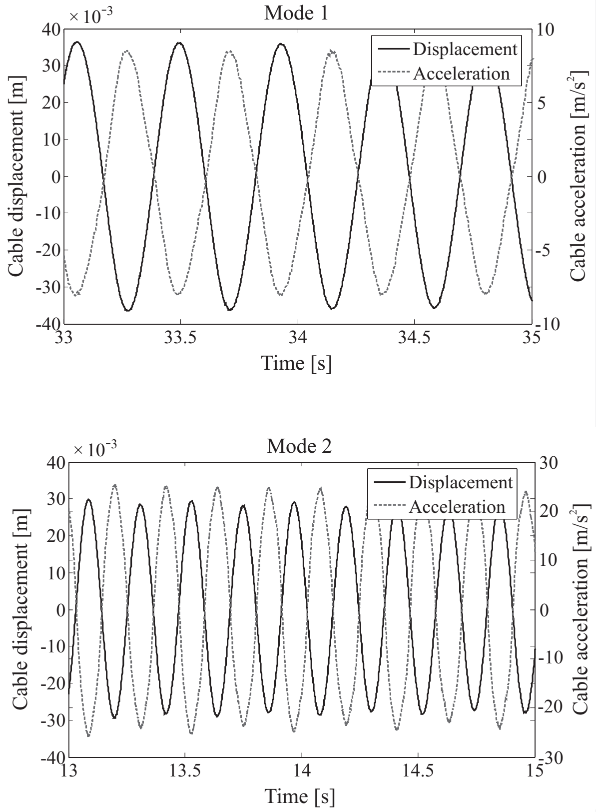

Fig. 13. Cable displacement and acceleration measured at point x_m= 22.5 m

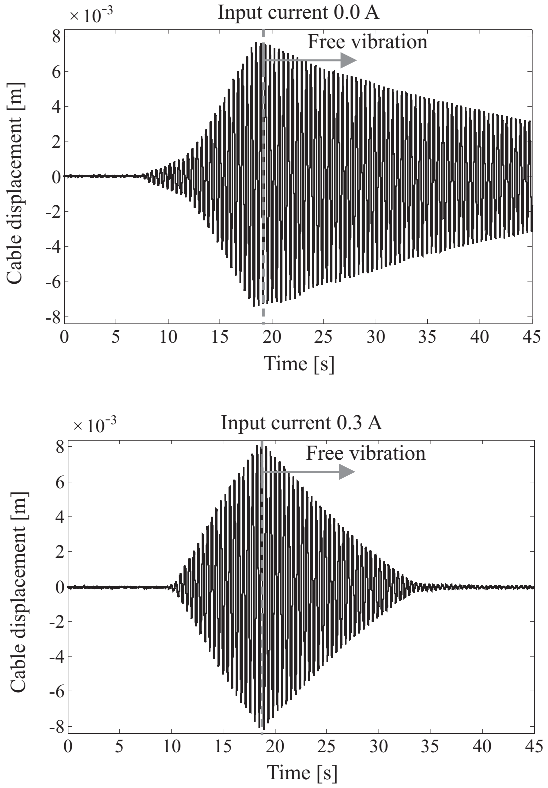

Fig. 14. Cable displacement measured at damper location x_d= 1.1 m

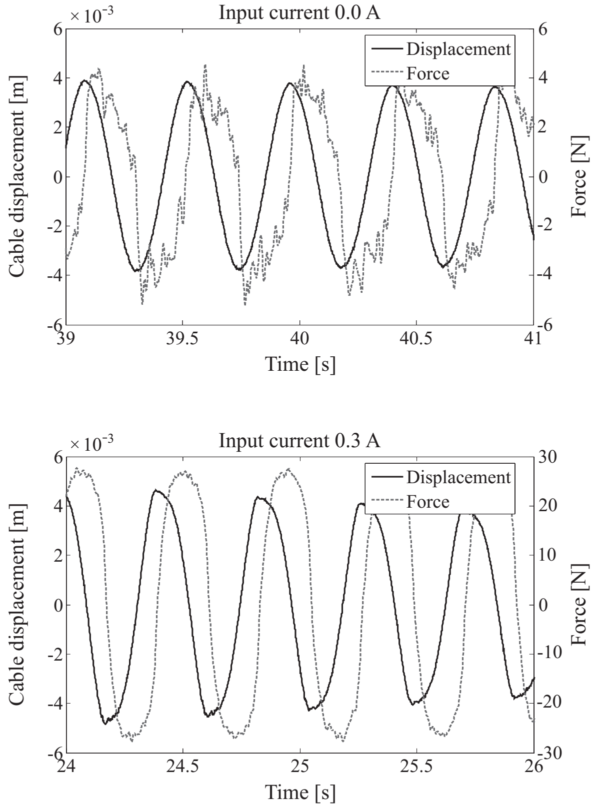

Fig. 15. Cable displacement measured at damper location x_d= 1.1 m and MR damper force

In Figure 13 we show time histories of displacement and acceleration measured at point x_m= 22.5 m. It is readily apparent that the displacement and the acceleration are in opposite phases.

In the second stage we conducted measurement for the cable with MR damper. We measured displacements, accelerations and MR damper force. By applying the input current of 0.0 A and 0.3 A we set two different levels of MR damper force. The cable motion was excited again by hand. The cable executed the vibrations with the first mode. It is apparent that the modes of vibrations with and with no MR damper are not the same but they are very similar. Selected results of measurements are presented in Figures 14 and 15.

In Figure 14 we show time histories of displacement measured at point x_d= 1.1 m. The dimensionless coefficient of modal damping depends on the vibration amplitude. It is evident that the modal damping for the first mode of cable with MR damper are significantly greater than the adequate modal damping of cable with no damper. In Figure 15 we show the cable displacement measured at the point where the damper was attached and the measured damper force acting on the cable. The phase shift between the force and the displacement is about 0.5π (the same signs of force and displacement in Figure 15 means that the force and the displacement take the same direction). The latter ones was confirmed by existing models of MR dampers.

4.3. Forced vibration

In the case of forced vibration measurements, the cable was excited by the use of the shaker described in section 3 (Fig. 8). The frequency was adjusted by means of the frequency inverter. The excitation frequency was 2.644 Hz. This value was close to the first natural frequency of the cable with damper. Selected results of measurements are provided in Figure 16.

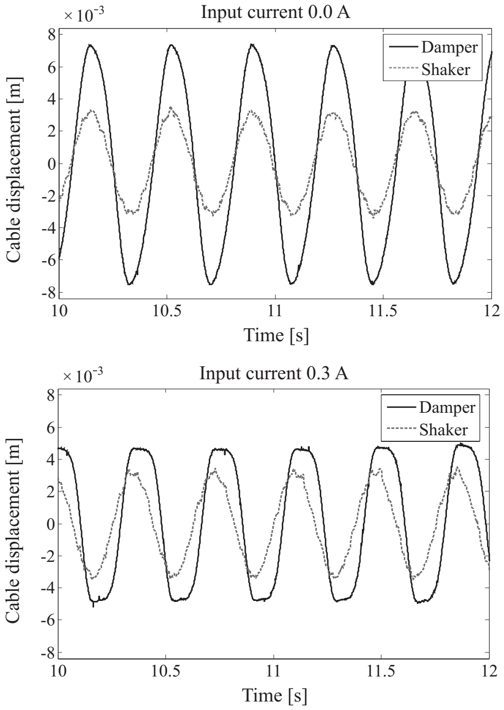

Fig. 16. Cable displacement at damper location (x_d = 1.1 m) and shaker location (x_s = 25 m)

When analyzing the plots, a small phase shift between the displacement at shaker location (excitation) and the displacement at damper location could be observed. This phase shift increased with the increase of input current. As the input current increased, the amplitude of the displacement at the damper location decreased. The displacements were periodic functions of time but not exactly sine functions. The deviation was particularly visible when analyzing the displacement at the damper location for higher input currents.

5. SUMMARY

The papers presents the laboratory facility engineered for testing of MR damping systems for cable vibrations. The existing facility was employed for testing of cables. The necessary modifications in the mechanical structure of that facility were introduced. A new measurement – control system was designed. The MR damping system for cable vibration was developed by the use of RD-1097-01 damper of Lord Co.

The functional tests of the facility were conducted. The tests included: facility structure setting, free and force vibration tests. Experimental results have proofed the usefulness of the facility for MR damping system testing.

Current research is now focused on the development of control strategies for MR damper in the considered system.

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