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Damping of stay cable with passive-on magnetorheological dampers: a full-scale test

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Abstract

Damping of a full-scale cable with a pair of passive–on magnetorheological (MR) dampers was tested. A cable 215.58 m long with a first mode frequency of 0.658 Hz was tensioned horizontally in a cable prefabrication factory. Two MR dampers were attached to the cable at an angle to each other, in the plane perpendicular to the cable axis at a position 5 m along the cable from its anchorage point. The applied voltage levels were 0 V, 3 V, 6 V and 9 V, respectively. The cable was excited manually to a certain amplitude level for the first three modes of vertical vibration. The free decay curves of the cable were then recorded. The damping of the cable was calculated from the measured anti-node vibration amplitude. The damping of the free cable was also tested for reference. It was found that the damping of the cable was still low when MR dampers were not strengthened by voltage. However, the damping of the cable increased greatly compared to the free cable case when the MR dampers were voltage-strengthened. The damping of the cable with MR dampers strongly depends on the applied voltage level and the vibration amplitude. There is an optimal damping value when the MR dampers are voltage-strengthened. The dependence of the optimum damping on applied voltage level, vibration amplitude and vibration mode was analyzed further.

Keywords: *Full-scale cable, MR damper, Damping, Voltage, Amplitude.*

1. Introduction

As the crucial members of cable-stayed bridges, stay cables commonly exhibit excessive and unanticipated vibrations, especially on rainy days with wind. Studies have shown that when such undesirable phenomena occur, the damping of the stay cables is typically low, rendering them susceptible to multiple types of excitation [1]. Recognizing the severe danger posed by cable vibrations, researchers have investigated many ways to solve this problem. The MR damper has attracted particular attention due to its semi-active controllability, which gives it an advantage over other types of passive dampers [2-8]. The MR damper force can be controlled by applied voltage, thus providing a convenient means of modulating the magnitude of cable damping. As the force-velocity relationship of MR damping is a highly nonlinear function of input voltage [9], the damping of cables with MR dampers would be far different from that predicted via the linear design method of Pacheco et al. [10]. Some studies have stated that the maximum (optimal) damping value of cable with nonlinear dampers would depend not only on the vibration mode, but also on the vibration amplitude [11-13]. Although there have been tests carried out on the damping of full-scale cable or model cable incorporated with passive-on MR dampers [14-16], there have been no detailed full-scale tests of stay cable with MR dampers, due to test facility limitations. There is an urgent need for further studies on the voltage, amplitude and mode dependence of full-scale cable damping with MR dampers, as a guide to the formulation of design guidelines for cable vibration mitigation, as well as to design a practical semi-active multi-switch control strategy.

In this study, we carried out a full-scale cable vibration-damping test using a pair of passive-on MR dampers. The length of the stay cable reached 215.58 m, with a first mode frequency of 0.658 Hz. The cable vibration displacement, the acceleration and the damper force were measured. The dependence of the MR damping of the cable on voltage level, vibration amplitude and mode number was then analyzed based on the test results.

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2. Experimental setup and test method

2.1. Full-scale cable

The full-scale cable was tensioned horizontally in the cable manufacturing factory located near Jianyin, Jiangsu Province, China (Fig. 1). The parameters of the stay cable were chosen to match a real stay cable from a cable-stayed bridge in China. The stay cable was PPWS type with indented aerodynamic countermeasures in its surface. The length of the cable reached 215.58 m, with a first mode frequency of 0.658 Hz (Table 1). The vibration frequency of the free cable was calculated from the following formula:

$$f_n = \frac{n}{2L}\sqrt{\frac{T}{m}} \tag{1}$$

where f_n is the cable vibration frequency of the n^{th} mode, n is the mode number, L is the cable length, T is the cable tension force and m is the cable mass per unit length.

2.2. The tested MR damper

The tested MR damper was a linear-stroke-type damper (Fig. 2). The extended length of the MR damper was 208 mm with a stroke of ∓2.5cm, and the outer diameter of the damper was 41.4 mm. The resistance of the damper was about 5 Ohms at an ambient temperature of 25° C, and the maximum applied voltage was 12 V. The damper force varied with the applied voltage level. Two MR dampers were attached to the cable at l_1=5 m from the cable anchorage at an angle of 45° to each other, in the plane perpendicular to the cable axis (Fig. 2). The damper installation length ratio was l_1/L=2.32%, which is within the range (about 2%-4%) commonly accepted by engineering professionals. During the test, a storage battery with a control unit was also connected to the MR dampers to supply different voltage levels.

2.3. Instrumentation

A force transducer was connected in series with each MR damper and fixed at the damper supporter (Fig. 2). Six displacement meters were oriented vertically and located at the damper location, L/8, L/2, L/4, 3/4L, and 7/8L (Fig. 1). Five vertically oriented accelerometers were placed near the damper location, and at L/8, L/2, L/4, and 3/4L. One transversely oriented accelerometer was located at 7/8L. The measured displacement and force data were fed through a DA converter and recorded by an HP notebook. The acceleration data were recorded by another computer. The sampling frequency was set at 50 Hz. One channel of acceleration data at L/4 was also connected to an HP digital analyzer to monitor the cable vibration frequency online.

Table 1 Parameters of the full-scale cable

Length (m)	Mass (ton)	Tension force (kN)	Cable type (PWS)	Diameter (mm)	f_1 (Hz)
215.58	10.61	3955.80	Φ7×151	113	0.658

2.4. Testing method

The stay cable was excited manually during the test. The cable was released when its vertical vibration amplitude reached a certain value. Then the free decay curve of the vertical vibration was recorded. Data relating to the decay of the cable's free vibration were filtered to eliminate the influence of other modes. From the filtered free-vibration decay curves, the logarithmic decrement of the cable could be estimated by using the following formula:

$$\delta_i = \frac{1}{j}\ln\left(\frac{A_{i-j/2}}{A_{i+j/2}}\right) \tag{2}$$

where $A_{i-j/2}$ and $A_{i+j/2}$ are the double amplitudes of the $(i\text{-}j/2)^{th}$ and the $(i+j/2)^{th}$ period of oscillation, respectively; δ_i and denotes the logarithmic decrement corresponding to A_i, i.e. the double amplitude of i^{th} period. As the damping value of the cable before/after damper installation is very small, the following formula applies:

$$\xi_i \approx \frac{1}{2\pi}\delta_i \tag{3}$$

where ξ_i is the corresponding modal damping ratio.

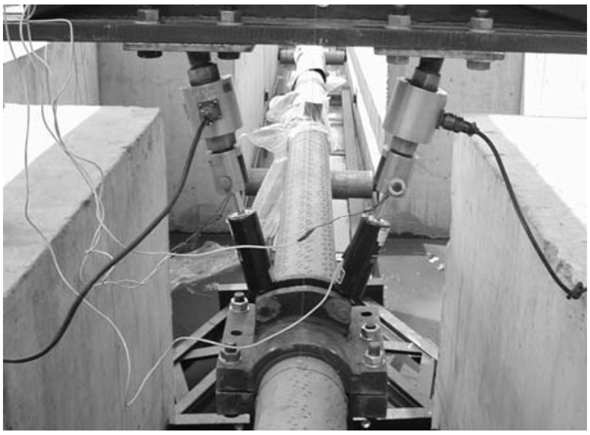

Fig. 2 MR dampers and force transducers

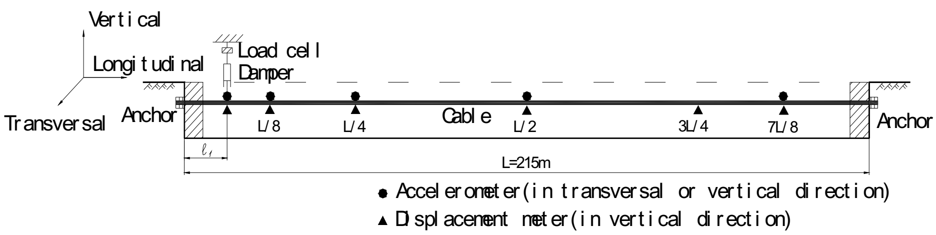

Fig. 1 Experimental setup

From the data recorded by the force transducers and the displacement meters, the vertical damper force and the vertical vibration velocity at the damper location could also be derived:

$$F_V = \left(F_{d1} + F_{d2}\right)\cos\frac{\alpha}{2} \tag{4}$$

where F_V is the vertical damper force; F_{d1} and F_{d2} are the measured forces of the two MR dampers; and α is the angle between the two MR dampers in the vertical plane perpendicular to the cable axis.

The damper vertical velocity was derived from the damper vertical displacement by the following equation:

$$v_k = \left(d_{k+1} - d_{k-1}\right) f_s/2 \tag{5}$$

where v_k is the damper vertical velocity, d_k is the damper vertical displacement at the sampling time k, and f_s is the sampling frequency.

3. Experimental scheme and test results

The damping of the free cable was tested first for reference. Then the two MR dampers were attached to the cable for the test. The voltages applied to the MR dampers were 0.0 V (voltage is not applied), 3.0 V (low voltage level), 6.0 V (medium voltage level) and 9.0 V (high voltage level), respectively. For each applied voltage, the first three modes of the cable's vertical vibration were tested. Each test case was run twice to check the repeatability of the experimental data; it was found that the results of repeated runs agreed very well.

A primary focus was put on the displacement data in the analysis of cable damping, as acceleration data tend to exaggerate higher mode cable vibration. Considering that the anti-node vibration amplitude has often been applied and reported in cable vibration mitigation, and also that the anti-node amplitude is the maximum cable amplitude response and can be easily understood by engineering professionals, the anti-node vibration amplitude was used in the paper. This might influence the test conclusions, as the vibration amplitude at the damper location and at the anti-node are not related sinusoidally for a cable with dampers [11]. The data corresponding to anti-node amplitudes smaller than 10 mm were discarded in this study due to the influence of transverse cable vibration that was discovered during the test.

3.1. Test of full-scale free cable

The internal damping of the free cable was found to be very small. The mean logarithmic decrement value of the first mode of vibration for the free cable was only 0.0049, and the logarithmic decrement value of the second and the third modes were 0.0032 and 0.0036 (Table 2). In fact, the damping value of the free cable is well below the minimum damping requirement (about 0.03 in logarithmic decrement value) [1] for vibration mitigation. The tested frequency of the free cable was also measured and it was found to be very close to the theoretically predicted value (Table 2).

Table 2 Measured frequencies and mean logarithmic decrement of the free cable

Mode number	1st	2nd	3rd
Frequency (Hz) (error)	0.655 (-0.46%)	1.299 (-1.31%)	1.946 (-1.44%)
Logarithmic decrement	0.0049	0.0032	0.0036

3.2. Test of full-scale cable with MR dampers

3.2.1. Cable vibration decay

Fig. 3(a) displays the decay curve of the first vibration mode at *L*/2 with the MR dampers in place, but without voltage strengthening. Fig. 3(b) displays the decay curve with the MR dampers at 9.0 V; in this case the second vibration mode dominated, with the anti-node located at *L*/4. Comparing Fig. 3(a) with Fig. 3(b), it is clear that voltage strengthening of the MR dampers has a strong influence on the amplitude envelopes of the free decay curves. The decay curve envelopes of cable vibration with the MR dampers at 9.0 V were far from being exponential, which indicates that the mechanical behavior of the system becomes nonlinear when the MR dampers are voltage-strengthened.

3.2.2. MR damper behavior

Fig. 4 shows one loop of the vertical damper force vs. the vertical velocity curve in the second mode of vibration, with

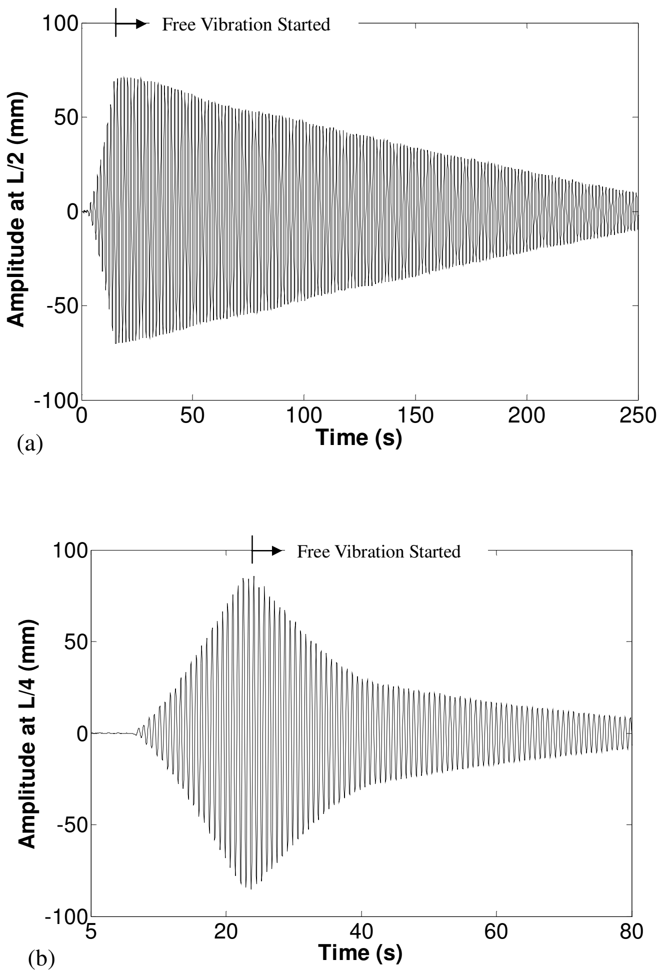

Fig. 3 Decay curve of the cable attached with MR dampers: (a) no voltage strengthening, first mode; (b) 9.0V, second mode

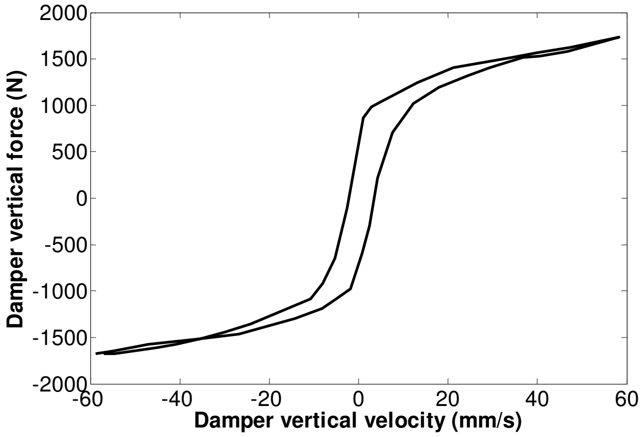

Fig. 4 Vertical force vs. vertical velocity of MR dampers: 3.0 V, second mode

MR dampers strengthened by 3.0 V. It can be seen that the damper force vs. velocity relationship is highly nonlinear, further highlighting the nonlinear mechanical behavior of the damped system.

3.2.3. Frequency of cable vibration with MR dampers

Table 3 lists the frequency of the cable with MR dampers. The frequency of the cable-MR damper system was found to be slightly higher than the frequency of the free cable. However, for engineering applications the difference could reasonably be neglected, as the frequency increment is only about 1%.

4. Damping dependence on voltage level, amplitude and mode number

Fig. 5 displays the curves of the logarithmic decrement value at the corresponding double amplitude for each tested case. It can be concluded that cable damping is greatly improved when the MR dampers are voltage strengthened. Fig. 5 also shows that the curves for different applied voltage levels were different from each other, which means the test cable damping was strongly dependent on the applied voltage level.

4.1. Damping dependence on applied voltage level

It could be clearly observed that the curves for the logarithmic decrement vs. the corresponding double amplitude of the MR-damped cable without voltage strengthening (Fig. 5(a)) were different from those with voltage strengthening

Table 3 Frequency of the cable with MR dampers

Voltage level	1st mode Frequency (Hz)	2nd mode Frequency (Hz)	3rd mode Frequency (Hz)
0V	0.662	1.305	1.960
3V	0.664	1.305	1.957
6V	0.662	1.309	1.943
9V	0.664	1.312	1.945

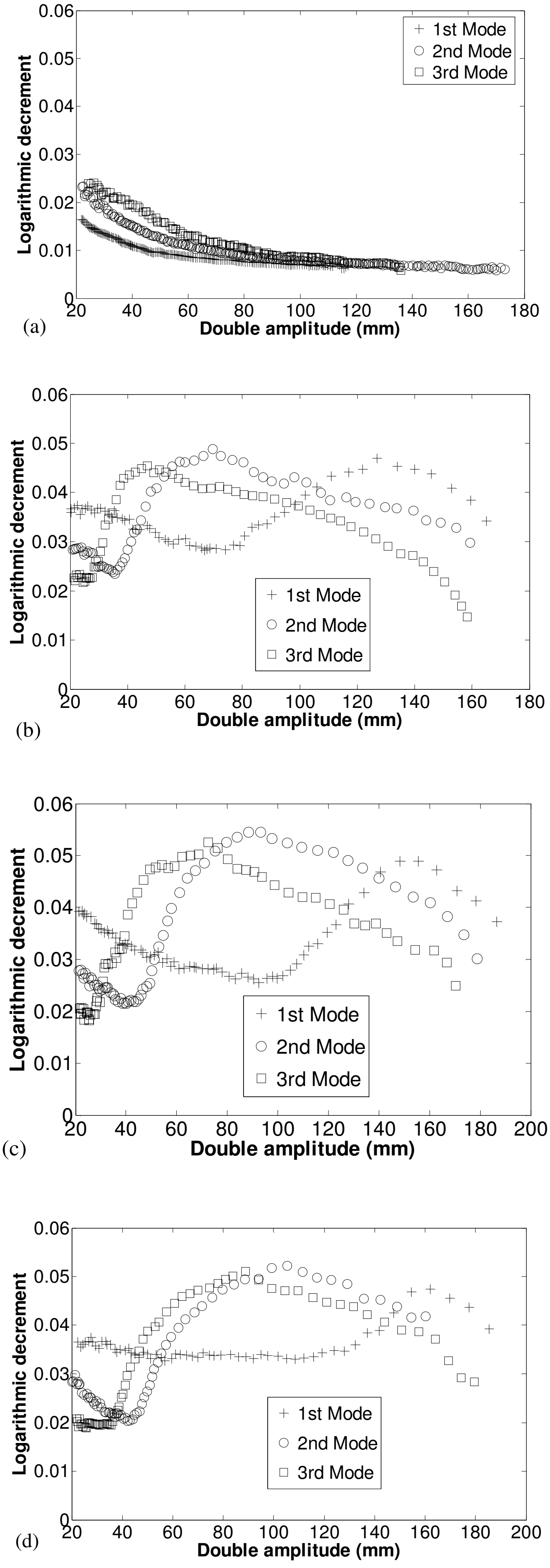

Fig. 5 Damping of the cable with MR dampers: (a) 0V, (b) 3.0V, (c) 6.0V, (d) 9.0V

(Fig. 5(b), (c), (d)). The damping of the MR-damped cable without voltage strengthening was much lower than the damping of the other cases. The maximum logarithmic decrement value was smaller than 0.03 for the cases of MR damping without voltage strengthening. Given that 0.03 is considered to be a lower limit for vibration mitigation for cables with attached viscous dampers, these results suggest that, in engineering practice, it would be desirable to supply a voltage to the MR dampers used for cable vibration mitigation.

For the cases of low, medium and high applied-voltage levels, the logarithmic decrement value depended strongly on the vibration amplitude (Fig. 5(b), (c), (d)). There was an optimal (maximum) damping value, and this optimal damping value would be of great interest for further optimization of passive MR damping and the multi-switch control strategy [3]. It was found that the optimum damping values only varied slightly between different cases (Table 4). However, the anti-node amplitude corresponding to optimal damping increased as the applied voltage increased (Table 5) for the tested cases of the same vibration mode number.

Based on the above test results, it can be concluded that there was an optimal damping value when the MR dampers were voltage strengthened. The maximum damping values were almost the same for different test cases. However, the amplitude corresponding to optimal damping for each test case varied greatly, as discussed below.

4.2. Damping dependence on amplitude

The damping vs. amplitude curves for the cases of no voltage strengthening (Fig. 5(a)) decreased monotonically as the cable vibration amplitude increased. This pattern was very different from the curves of the other test cases (Fig. 5(b), (c) and (d)). The observed damping value became smaller as the amplitude became larger, which might be due to the influence of the small ceiling and the connection friction force of the MR dampers.

For the cases of low, medium and high voltage levels, it can be seen from Fig. 5(b), (c) and (d) that the relationships between damping and amplitude were similar in all three cases: the measured logarithmic decrement value first decreased as the amplitude increased, then reached a minimum value and began to grow again, eventually reaching a maximum value and then once again decreasing with increasing amplitude. The calculated minimum logarithmic decrement value was between 0.020-0.030, and the maximum was between 0.046-0.055 (Table 4). The amplitude at which the logarithmic decrement was maximized differed for each test case (Table 5). It can be concluded that the maximum damping of the cable with MR dampers at constant applied voltage is strongly dependent on the vibration amplitude. When designing MR dampers for cable vibration mitigation, it is important to determinate an optimum damper force value corresponding to the cable amplitude in order to provide maximum damping. However, it is also apparent that the amplitude corresponding to optimum damping not only depends on the applied voltage level, but also on the vibration mode number.

Table 4 Measured optimal damping of the cable with MR dampers

Voltage level	1st mode optimal damping	2nd mode optimal damping	3rd mode optimal damping
3V	0.047	0.049	0.046
6V	0.049	0.055	0.053
9V	0.046	0.052	0.051

Table 5 Measured double anti-node cable amplitude corresponding to the optimal damping

Voltage level	1st mode amplitude (mm)	2nd mode amplitude (mm)	3rd mode amplitude (mm)
3V	127	70	47
6V	148	88	72
9V	162	99	89

4.3. Damping dependence on vibration mode

When voltage was not applied, it can be seen in Fig. 5(a) that damping increased slightly with the vibration mode number. This was due to the fact that the higher modes need a smaller damping force for optimal dissipation of vibrational energy; the damper force for the case of no voltage strengthening was too small, as stated earlier. For the cases of low, medium and high voltages, the corresponding amplitude to the optimal damping decreased as the mode number increased (Table 5).

5. Conclusions

Free vibration damping tests were conducted on a full-scale cable with a pair of MR dampers. The performance of the MR dampers was tested at applied voltages of 0 V, 3 V, 6 V and 9 V, respectively. The damping of the cable with and without the MR dampers was evaluated for the first three modes of cable vibration. The anti-node amplitude was measured as the key variable for analysis. Based on the test results, the following conclusions can be drawn:

1. The damping of the free cable was very small, with a mean logarithmic decrement value smaller than 0.0049 for the first mode of vibration; and the logarithmic decrement value of the second and the third modes were 0.0032 and 0.0036.

2. The damping of the cable with MR dampers but without applied voltage was still small, with a logarithmic decrement value less than 0.03. However, when voltages of 3.0 V, 6.0 V and 9.0 V were applied, the damping of the cable was greatly increased. The frequency of the cable-MR damper system was found to be slightly higher than the frequency of the free cable.

3. It was also found the mechanical behavior of the MR-damped cable becomes nonlinear when the MR dampers are voltage-strengthened. The damping value of the cable with MR dampers was found not only to be strongly dependent on the applied voltage level, but also on the vibration amplitude and mode number. Optimal damping conditions were identified for the cases of constant voltage applied to the MR dampers, and these optimal damping values only changed slightly from case to case.

4. The test results also showed that the shapes of the damping vs. amplitude curves for the cable with voltage-strengthened MR dampers were qualitatively similar to each other. These results suggest that a simple design formulation might exist for the damping of cables with passive MR dampers for practical parameter optimization or a multi-switch control strategy.

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