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OPERATIONAL MODAL ANALYSIS OF THE CABLE-STAYED FOOTBRIDGE

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Abstract

Modern architecture leads to design subtle bridge structures that are more sensitive to increased dynamic loading than the massive ones. This phenomenon can be especially observed on lightweight steel structures such as suspended footbridges. As a result, it is necessary to know precisely its dynamic characteristics, such as natural frequencies, natural shapes and damping of construction. This information can be used for further analysis such as damage detection, system identification, health monitoring, etc. or also for the design of new types of construction. For this purpose, classical modal analysis using trigger load or harmonic vibration exciter in combination with acceleration sensors is used in practice. However, there are many situations where it is not possible to stop the traffic or operation of the bridge. The article presents an experimental measurement of the dynamic parameters of the structure at the operating load using the operational modal analysis.

Keywords:

Footbridge;
Dynamic characteristic;
Natural frequencies;
Natural shapes;
Modal analysis.

1 Introduction

In assessing the current state of bridge structures, it is important to have proper diagnostic methods that are sensitive enough to identify the defects that have arisen. There are many diagnostic methods that are used for this purpose. The basic nature of most of them is primarily based on visual inspection and mechanical tests of materials that are used to build it. Subsequently, static calculations are made in which the obtained information is used [1], [2]. The disadvantage of this approach is that it cannot consider dynamic behaviour of the construction. Another way to get information about the state of structure is to use the experimental or operational modal analysis procedures. In this case, the dynamic parameters are estimated. They can be used for evaluation of dynamic characteristics as well as for determination of the current state of the construction. It can be determined from the calibrated model which has the same dynamic characteristics as the measured one [3], [4].

Operational modal analysis is an alternative to experimental modal analysis, as there is no need to know the source of the excitation. In the case of bridge structure, this is a crucial factor because vibrations from the surrounding environment or operational excitement are often the only one effective source of excitation. Characteristics of these types of load are almost impossible to identify. However, it is possible to assume that it is a white noise that provides excitation throughout the whole observed spectrum. Due to the fact that in the operational modal analysis the input signal is not known, it is difficult to determine the correct shape of the frequency response functions which are used to identify the modal parameters of bridge structures. Several methods have been developed to improve the quality of modal parameter identification methods only from the response functions [5]. One of these, which is also presented in the article, is based on the singular value decomposition of a frequency response function matrix [6]. The first step in this method is to estimate the frequency response function matrix $[G_{yy}]_{n\times n}$ which size $n\times n$ depends on the number of measured points. Its members then represent the functions of power spectral densities that we can obtain with regards to the Wiener-Khintchine theorem by the Fourier transformation of autocorrelation and cross-correlation functions.

They are calculated from the measured output signals. In the next step, a singular value decomposition of the matrix is calculated.

$$[Gyy]_{\mathrm{n\times n}} = [U]_{\mathrm{n\times k}}[\Sigma]_{\mathrm{k\times k}}[V]_{\mathrm{k\times n}}\,. \qquad (1)$$

The diagonal matrix $[\Sigma]_{kxk}$ contains singular values that are determined separately for each frequency. The largest singular value for each frequency represents the value of the power auto spectrum, and the corresponding vector of the matrix $[U]_{nxk}$ represents mode shape for that frequency.

The operational modal analysis has been performed on a steel cable-stayed footbridge, Fig. 1. The footbridge spans the River Hron and connects the city of Žarnovica and the adjacent village of Lukavica. The bridge is primarily intended for pedestrians and passenger cars weighing up to 3.5 tonnes. The vertical alignment of footbridge is in the shape of concave arc with radius R = 800 m. The footbridge works as a cable-stayed bridge system with one steel pylon. The steel pylon of elliptical shape is a distinctive architectural element of the footbridge. The total height of the pylon above the terrain is 22.6 m and on its upper part there are anchors of inclined hangers. The hangers are from steel bars and their arrangement is radial. The upper end of the hangers in the pylon is hinged; the lower anchorage of the hanger is adjustable by steel nut. In addition, there is also the transverse oscillation dumper installed in lower part of the anchorage of the hangers. The superstructure with total length of 106.18 m has two spans with theoretical length 40 m + 65 m and it creates one structural and expansion element. The superstructure has an open cross-section and consists of two major I-shaped girders together with an orthotropic bridge deck. The superstructure has the constant 0.7 m height and 3.9 m width. The steel sheet of bridge deck has thickness 10 mm and it is supported by the L-shaped longitudinal stiffeners at the distance of 400 mm. The crossbeams of the orthotropic bridge deck are twofold. The main cross beams support the bridge deck at the anchorage of steel hangers. Among them there are placed secondary crossbeams at a distance of 2000 mm. The bridge deck is sloped in a one-sided slope of 1 % gradient to the drainage. The pavement on steel bridge deck is made of mastic asphalt and it is placed on waterproofing layer made of polyurethane.

Fig. 1: The steel cable-stayed footbridge in Žarnovica.

2 The numerical model of the footbridge

The numerical spatial model of the suspended footbridge is created in the ADINA system. All bridge structural parts made of steel plates are modelled as finite shell elements of the appropriate thickness according to the design documentation. The truss finite elements are used to define the cables that support the deck. For simplicity of calculation, the concrete slab on the orthotropic deck is not modelled. Its weight is counted and included in the weight of the orthotropic steel deck instead.

Thus, for the whole model only isotropic steel material is used with Young's modulus 210 GPa, Poisson’s ratio 0.27 and density 7850 kg·m^{-3}. In the longitudinal direction, the modelled deck has the same longitudinal slope as the real bridge structure. The spatial model of the footbridge is shown in Fig. 2.

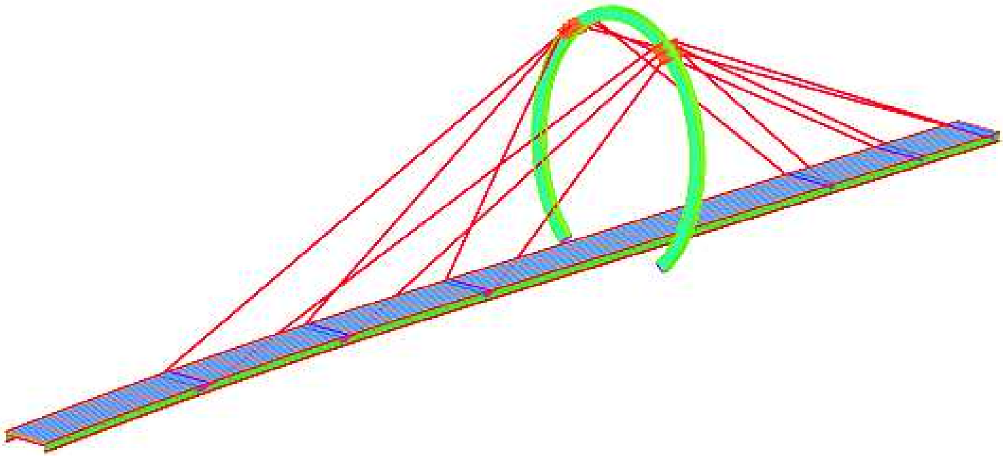

Fig. 2: The numerical spatial model of the suspended footbridge.

The rule-based mesh generator is used to define shell elements with the size 0.15 m. As the bridge structure is defined by many geometric shapes, it is crucial to satisfy the compatibility of the mesh defined on them. The connections of supported steel rods to the main girders as well as to the steel arc are the most sensitive parts as they include reinforcing steel plates. The proper connection between the structural parts in this area is achieved by choosing the right procedures for generation of the finite elements. These details are shown in Fig. 3.

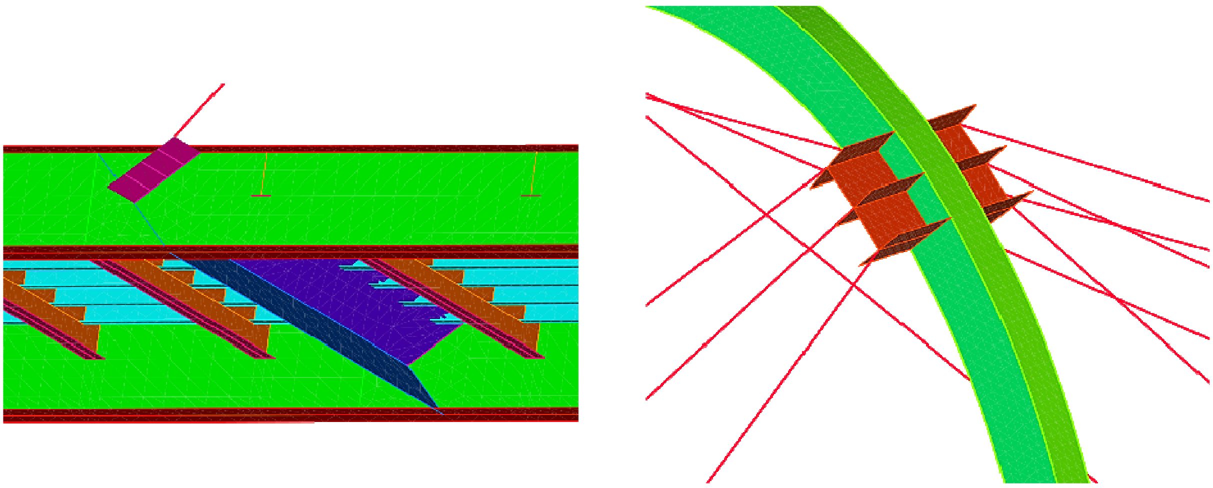

Fig. 3: Details of connections of supported steel rods to main girders and to the steel arc.

The main girders are also supported in the location of middle pillar and abutments. The mechanical behaviour of the modelled supports are defined with respect to the designed ones. The steel arc is supported on both sides. It turned out, that this support has a significant impact on the results so the hinged support has to be defined exactly. It is accomplished by closing the end cross section of the arched structure with rigid reinforcing sheets. Booth sheets have the hinge support at one point in the centre of gravity.

The results of numerical computing are modal shapes and frequencies of the footbridge. They have been used to find out if the results of operational modal analysis are good. First six of them are shown in Fig. 4.

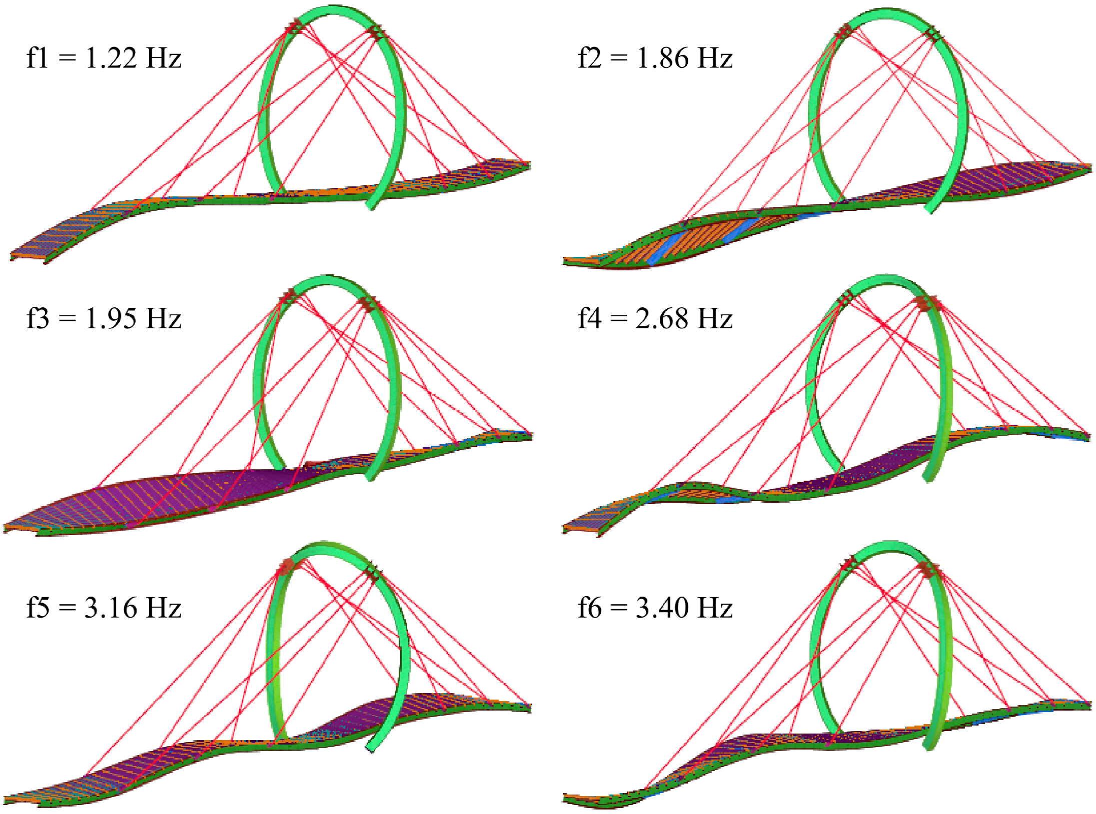

Fig. 4: The mode shapes and natural frequencies calculated from the numerical model.

3 Operational modal analysis of the footbridge

Experimental measurement on the investigated footbridge was performed on March 29, 2017. The main goal of the measurement is to determine natural frequencies and the respective natural shapes of the suspended footbridge. For this purpose, operational modal analysis based on FDD techniques is used. The dynamic responses of the construction in the form of signals of accelerations are the inputs into this analysis. They were measured at the selected points on the construction that are denoted P1-P12. Accelerometers KB12VD are used to measure the desired signals. The scheme on the following picture shows the placement of accelerometers as well as the connection of all applied devices (Fig. 5).

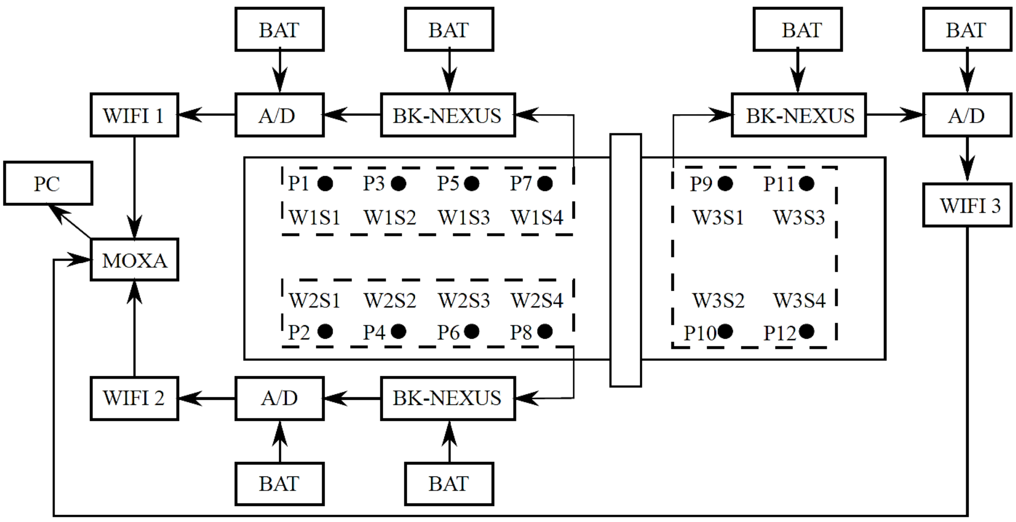

Fig. 5: Block diagram of the measuring set.

As the dimensions of construction are large, the WI-FI interface has been preferred to cable connection for transmitting of the signals from sensors. Keeping the order in the measurement, the sensors were divided into three groups. Then there is not a problem to identify each signal by choosing the group W1-W3 and the sensor number in the groups S1-S4 (W1S1, W1S2,…W3S4). Other devices displayed in the scheme are the BK-NEXUS amplifier of type 2693 from Bruel & Kjaer, A/D converter of type SX-10WG with WI-FI from NI, MOXA wireless AP/BRIDGE/CLIENT of type AWK-3121 connected to the external computer and BAT external battery packs.

Identification of dynamic characteristic based on OMA techniques does not require that the excitation is known precisely. In the presented case, four different loading conditions were used:

- LC1 – moving passenger vehicle up to 3.5 tones,
- LC2 – running of the three persons,
- LC3 – the jumps of the four persons in the selected points on the structure,
- LC4 – the passing crowd.

The difference between the shapes of the measured signals obtained for different loading conditions is showed in Fig. 6.

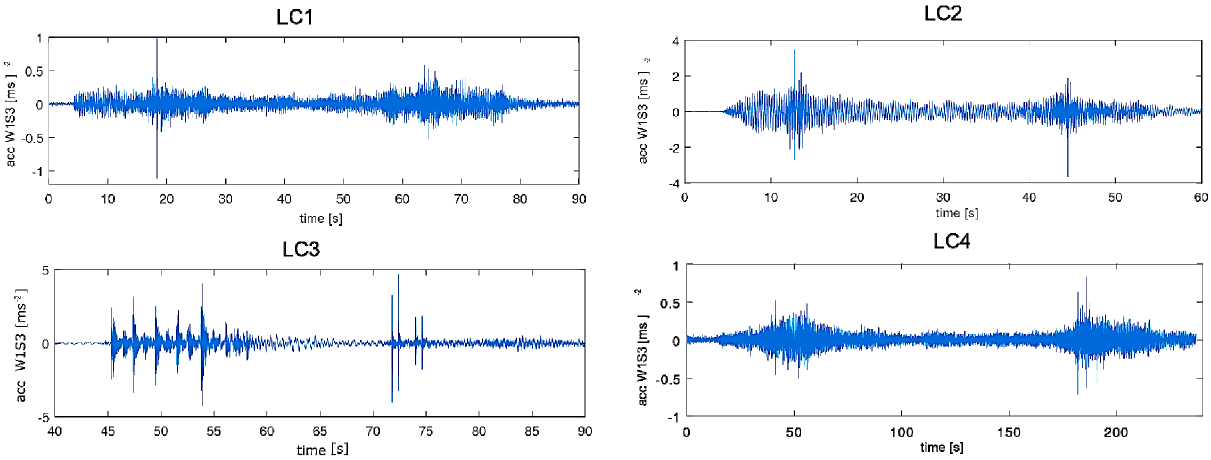

Fig. 6: Signals from the W1S3 sensor for different loading conditions.

The software ARTeMIS Modal ver. 5 (64 bits) from the company Structural Vibration Solutions A/S is used to estimate the natural frequencies and mode shapes. Its calculation core is based on the FDD methodology and the first step is to determine power spectral density matrix (PSD). Natural frequencies and natural shapes are then obtained from the PSD matrix using SVD techniques (Fig. 7).

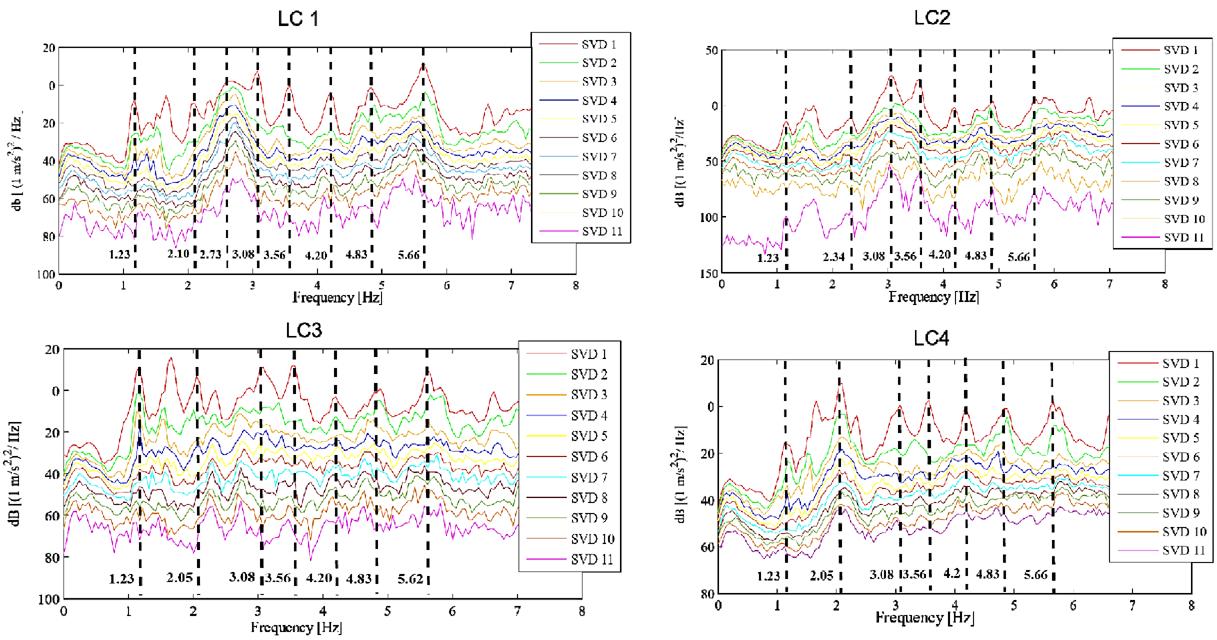

Fig. 7: Estimation of natural frequencies.

In total, the first nine natural frequencies of the construction are identified. The next analysis of natural shapes and its comparison with the shapes calculated from the numerical model shows that the signal from the W1S2 sensor is wrong. The exact reason has not been identified till now, so there are only a few doubts as a wrong mounting of the sensor or stray electrical current. The ARTeMIS software makes it possible to use linear signal interpolation from neighbouring sensors for solving this issue with a sufficient quality. Thanks this, the signal from the sensor W1S2 with a poor quality has not had to be used, so it is not presented in the article. Identified natural shapes are showed in Fig. 8.

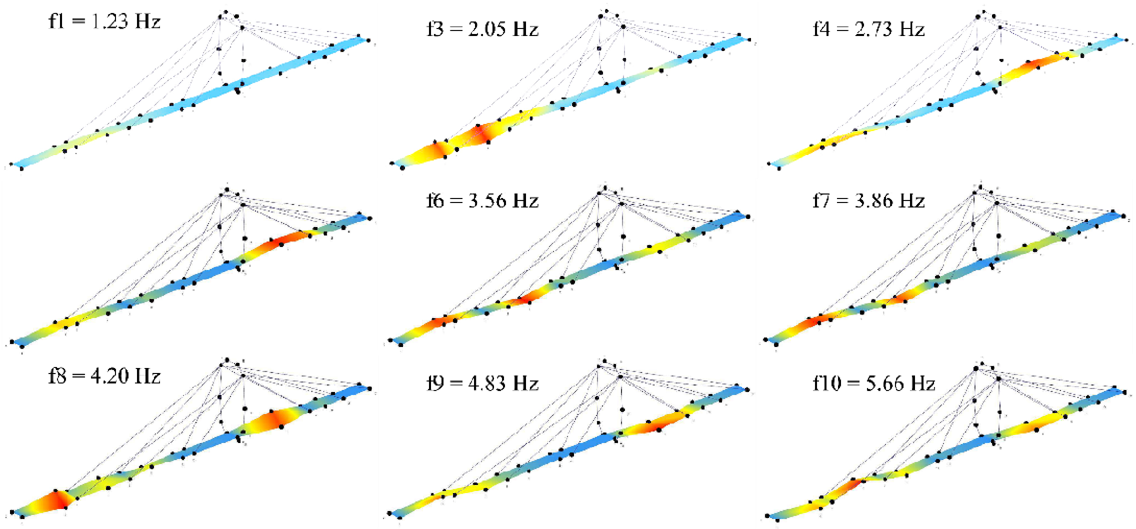

Fig. 8: Natural shapes of construction.

From the measured natural shapes, the first bending shape of the construction with the frequency 1.23 Hz and the first torsional natural shape with a frequency 2.051 Hz were determined. Natural shapes from the frequency of 3.857 (frequency number 7) can no longer be fully accurately displayed due to insufficient number of sensors. Therefore, the results in Fig. 8 are not in accordance with the calculated shapes.

4 Conclusions

The presented estimation of natural frequencies and mode shapes by application of operational modal analysis shows that this technique is appropriate for large constructions such as the suspended footbridge. Even though that one of the sensors measured wrong signals, the results are acceptable.

This mistake can be eliminated by applying of linear interpolation to improve the estimation of modal shapes. The comparison between the estimated dynamic characteristics from the experimental measurement and the calculated characteristics from the numerical model shows small differences. It can be seen especially in the case of natural frequencies of torsional modal shapes and higher natural frequencies. It means that the global stiffness and weight of the construction is properly defined, but some details of the model (stiffness of joints, handrails, material properties etc.) are not taken into account. The next investigation should be done to identify how they can influence the results. In this case, the modal updating techniques seem as a good alternative.

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