

# Experimental Determination of Natural Frequencies of Prestressed Suspension Bridge Model

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**Abstract.** A suspension bridge is the most suitable type for a long-span bridge. Increased kinematic displacements are the major disadvantages of suspension bridges. This problem can be solved by application of prestressed cable truss.

Dynamic approach is one of regulated bridge design parts. Determination of natural frequencies of a physical model of a prestressed suspension bridge is presented in this paper.

Natural frequencies, as mode shapes, of the model depending on a prestressing level were determined. It was shown that a mode shape with one half wave did not appear.

Experiments showed that dynamic characteristics of prestressed suspension bridge could be regulated by changing a prestressing level, which excluded a possibility of resonance appearance.

**Keywords:** cable truss, prestressing level, physical model, acceleration sensor.

## I. INTRODUCTION

Suspension bridges are structures, where the deck is continuously supported by stretched catenary cable [1]. Suspension bridges are the most important and attractive structures possessing a number of technical, economical and aesthetic advantages [2].

At the present moment, a suspension bridge is the most suitable type of structure for very long-span bridges. Suspension bridges represent 20 or more of the longest span bridges in the world. The bridge with the longest centre span of 1991 m is Akashi Kaikyō Bridge, Japan [3]. Such long spans can be achieved because main load carrying cables are subjected to tension, and distribution of normal stresses is close to uniform [4].

Increased deformability is one of the basic disadvantages of suspension bridges [5]. Increased deformability is conditioned by appearance of elastic and kinematic displacements. The elastic displacements are caused by large tensile inner forces. Elastic displacements are maximal at the centre of span in the case of symmetrical load application. Kinematic displacements are caused by initial parabolic shape change, resulting from non-symmetrical or local loads (Fig. 1) [6], [7]. These displacements are not related to cable elastic characteristics. Serviceability limit state dominates for suspension cable structures.

Elastic displacements can be reduced by applying low strength steel structural profiles, reinforced concrete and by increasing elastic modulus and cable camber [8].

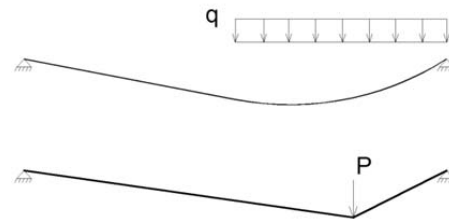


Fig. 1. Initial shape change under the action of non-symmetrical load.

The problem of increased kinematic displacements can be solved by increasing the relation of dead weight to imposed load, which is achieved by adding of cantledge [9]. However, this method causes the increase in material consumption. Stiffness of suspended structure can also be improved by increasing girder stiffness and main cable camber, by connecting a main cable and girder at the centre of span, by applying diagonal suspenders or inclined additional cables, two chain systems or stiff chains, and stress ribbons [10], [11]. Nevertheless, these systems are also characterized with material consumption, and system stiffness is not sufficient in many cases.

Usage of prestressed cable truss is another method of fixing the problem of increased kinematic displacements under the action of unsymmetrical load [12], [15]. Different types of cable trusses are known, such as convex cable trusses, convex-concave cable trusses, cable trusses with centre compression strut or parallel cable truss [14]. However, one of the most efficient and convenient for application is concave cable truss (Fig. 2) [15]. Cable truss usage allows for the development of bridges with reduced requirements for girder stiffness, but overall bridge rigidity will be ensured by prestressing of stabilization cable [8]. The deck can be made of light composite materials [16], [17].

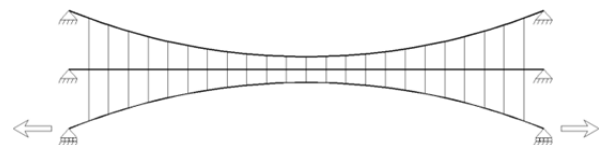


Fig. 2. Suspension bridge stabilization by prestressing.

Dynamic approach is one of the necessary bridge design parts after the collapse of Tacoma Narrows Bridge [18], [19]. At present, analyses of natural frequencies of prestressed suspension structures are performed with labour-intensive discrete methods [20], [21], [22].

The aim of this paper is to determine natural vibration frequencies and mode shapes of prestressed suspension bridge physical model depending on the prestressing level.

II. DESCRIPTION OF EXPERIMENTAL MODEL

Physical model was developed to determine natural frequencies of prestressed suspension structure (Fig. 3, 4). The span of the physical model of prestressed suspension structure was equal to 2.1 m. Main cable camber was equal to 0.275 m. The deck was connected to the main cable by suspensions in 15 points. Model width was equal to 0.4 m [23].

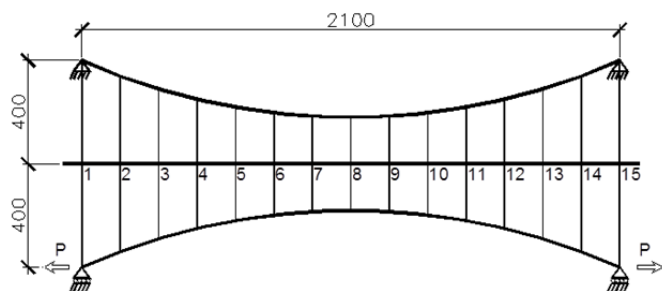


Fig. 3. Scheme of the physical model of the prestressed suspension structure.



Fig. 4. Physical model of prestressed suspension bridge with a single cable.

The elements of the model of prestressed suspension structure were made of steel cables with modulus of elasticity 60 000 MPa. Tensile strength of wires for cables was equal to 1770 MPa. The diameters and cable types of elements are shown in Table I [[23]].

TABLE I

CHARACTERISTICS OF CABLE ELEMENTS OF THE PHYSICAL MODEL

Elements	Cable type	Diameter	Breaking force
Main cable	6x19+WSC	10.0 mm	63.0 kN
Stabilization cable	6x19+WSC	8.0 mm	40.3 kN

The deck of the model of prestressed suspension structure was made from oriented strand board (OSB). It did not have significant load bearing capacity. It only distributed load among suspensions due to deformability of OSB [23].

Prestressing was organized in a stabilization cable and developed by rotating a screw and moving a bar. To enable cable to move, it was supported by the block (Fig. 5). The tensile force in a stabilization cable was measured by electronic dynamometer Scaime IPB50 (Fig. 6). Electronic dynamometer work principle is based on changes in electrical bridge resistance. The precision of measurements for electronic dynamometers is 0.25 kg [24].

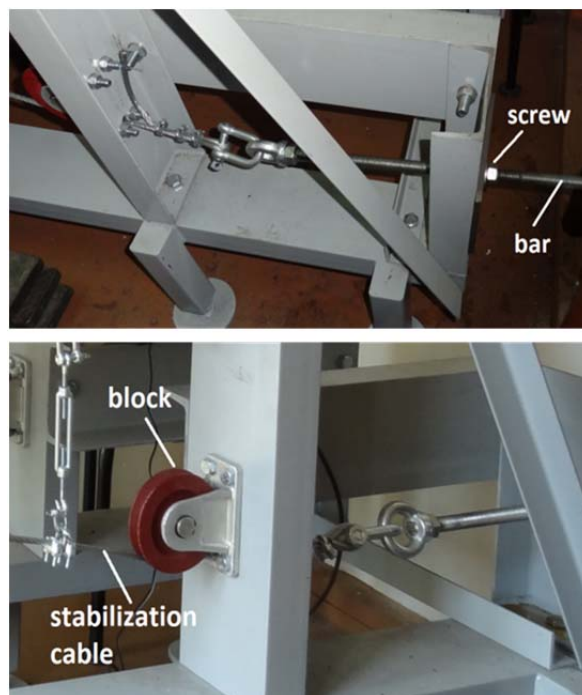


Fig. 5. Prestressing mechanism.



Fig. 6. Electronic dynamometer.

To connect a deck with the load bearing cable, adjustable suspensions were used that allowed levelling the deck. Suspensions were connected to the cables using U-bolt clips to prevent moving them along the cable (Fig. 7) [24].



Fig. 7. Deck connection to the cable by using suspensions.

Acceleration sensors were used to get natural frequencies of the model (Fig. 8).



Fig. 8. Acceleration sensor.

Acceleration sensors were situated on points 3, 5, 7, 9, 11 and 13 of the model (Fig. 9). Acceleration sensors measured acceleration at a defined time interval with a step equal to 0.006255 s and saved it to internal memory. After experiment data could be loaded to a PC.

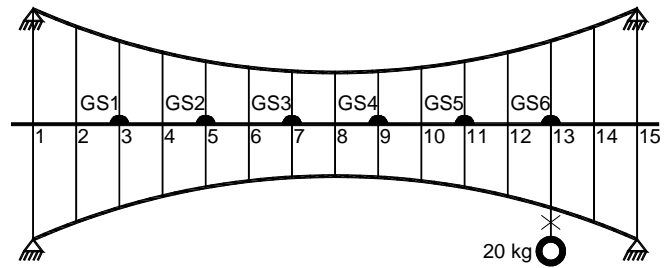


Fig. 9. Scheme of acceleration sensor placement on the model.

Vibration excitation in vertical direction was implemented by cutting suspended weight (20 kg) (Fig. 5). The weight was connected at point 13 to avoid losing some mode shape. Experiments were carried out for 6 prestressing levels: 0, 200, 400, 600, 800 and 1000 kg that corresponded to stresses in a stabilization cable equal to 0, 69.7, 139.4, 209.1, 278.7 and 348.4 MPa, respectively.

Vibration excitation in a horizontal direction was implemented by applying 20 kg load to point 13. The prestressing level was fixed at the level of 1000 kg (348.4 MPa) in this case.

### III. EXPERIMENTAL DATA HANDLING

For data handling from acceleration sensors, ME'scopeVES software was used. The software transforms acceleration-time dependence into frequency-response function using the Fourier transformation algorithm (Fig. 10). Frequency-response function consists of real and imaginary parts, or of magnitude and phase. Natural frequencies were recalculated by using magnitude-frequency dependence (Fig. 10). Mode shapes were calculated by connecting imaginary part peaks of each point for every natural frequency (Fig. 11) [25].

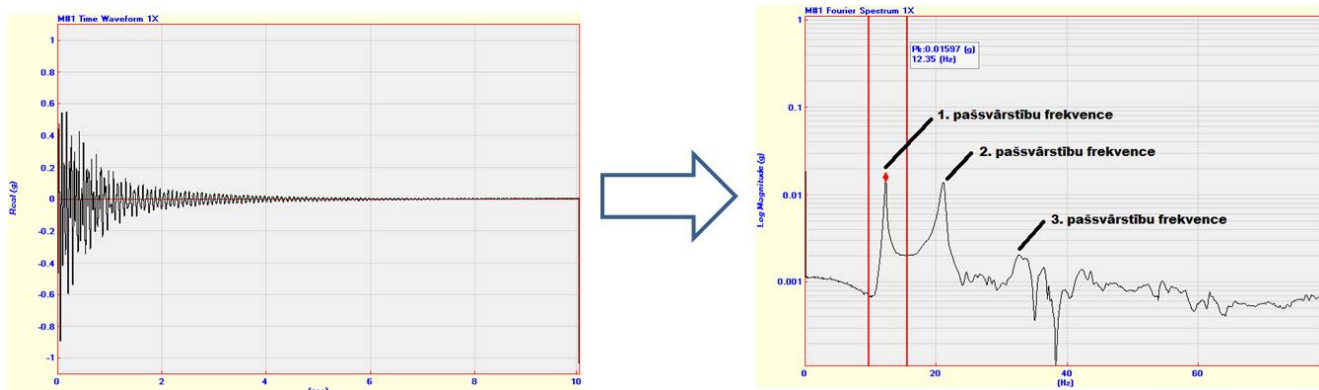


Fig. 10. Acceleration-time dependence transformation into frequency-response function.

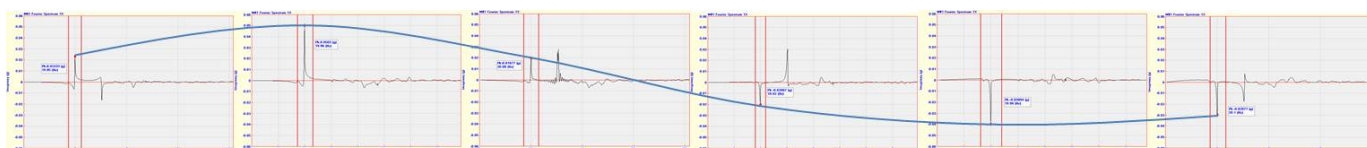


Fig. 11. Determination of mode shapes.

IV. EXPERIMENT RESULTS

Natural frequencies of prestressed suspension bridge physical model depending on prestressing level were determined. The first three experimentally calculated natural frequencies in vertical direction are generalized in Table II, Table III and Table IV, respectively. The first vertical natural frequency changed from 7.24 to 21.69 Hz, the second frequency changed from 14.55 to 32.61 Hz, and the third frequency changed from 21.78 to 40.53 Hz, while prestressing level changed from 0 to 1000 kg, respectively. Dependencies of natural frequencies on the prestressing level are shown as approximation curves in Fig. 12. Dependence of natural frequency on the prestressing level can be evaluated in the form of second order polynomial.

Natural frequencies in horizontal direction are generalized in Table V. Horizontal natural frequencies were 6.84, 8.56 and 27.59 Hz for the first, second and third mode shapes, respectively. Prestressing level was fixed at the level 1000 kg.

TABLE II  
NATURAL FREQUENCIES IN A VERTICAL DIRECTION

Prestressing level P, kg	1 <sup>st</sup> natural frequency, Hz						
	GS 1	GS 2	GS 3	GS 4	GS 5	GS 6	Average
0	7.18	7.27	7.18	7.33	7.23	7.26	7.24
200	12.37	12.32	12.36	12.35	12.46	12.39	12.38
400	15.26	15.33	15.28	15.40	15.35	15.42	15.34
600	18.18	18.23	18.11	18.11	18.00	18.10	18.12
800	19.95	19.97	20.11	19.92	19.99	20.06	20.00
1000	21.71	21.69	21.77	21.56	21.80	21.62	21.69

TABLE III  
NATURAL FREQUENCIES IN A VERTICAL DIRECTION

	2 <sup>nd</sup> natural frequency, Hz						
	0	14.56	14.44	14.75	14.87	13.96	14.71
200	21.14	20.66	21.24	21.12	20.79	21.18	21.02
400	24.63	24.55	24.59	24.85	24.58	24.9	24.68
600	28.19	27.8	28.17	28.17	27.45	28.15	27.99
800	30.42	30.22	30.83	30.38	30.49	30.59	30.49
1000	32.61	32.54	32.75	32.44	32.75	32.58	32.61

TABLE IV  
NATURAL FREQUENCIES IN A VERTICAL DIRECTION

	3 <sup>rd</sup> natural frequency, Hz						
	0	21.84	21.41	21.93	22.31	22	21.17
200	28.62	26.72	26.62	26.79	26.82	27.07	27.11
400	31.61	30.66	30.56	30.79	30.51	30.95	30.85
600	35.75	34.45	34.41	34.51	34.12	34.28	34.59
800	38.4	37.57	37.78	37.72	36.18	37.72	37.56
1000	40.59	40.75	40.99	40.6	39.38	40.86	40.53

TABLE V  
NATURAL FREQUENCIES IN HORIZONTAL DIRECTION, Hz

Natural Frequencies	GS 1	GS 2	GS 3	GS 4	GS 5	GS 6	Average
1 <sup>st</sup> frequency	6.86	6.81	6.89	6.83	6.82	6.82	6.84
2 <sup>nd</sup> frequency	8.43	8.46	8.87	8.54	8.52	8.52	8.56
3 <sup>rd</sup> frequency	27.23	27.48	27.92	27.68	27.69	27.54	27.59

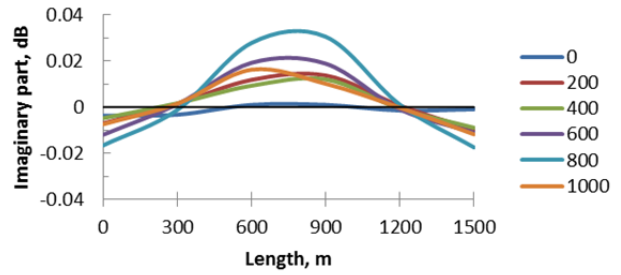


Fig. 14. Mode shape of the 2<sup>nd</sup> natural frequency

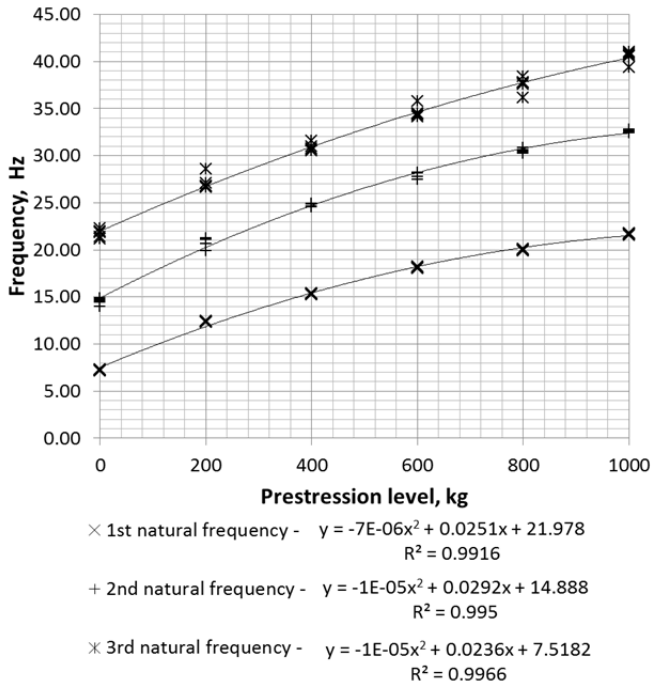


Fig. 12. Dependence of natural frequencies on the prestressing level.

Mode shapes for the first two natural frequencies in vertical direction are shown in Fig. 13 and Fig. 14, respectively. Mode shape for the third natural frequency was not possible to detect precisely. As our model span was equal to 2.1 m and girder ends were not connected to supports, the first mode shape consisted of two half waves, the second and third mode shapes consisted of three and four half waves, respectively. Mode shapes are shown in Fig. 15.

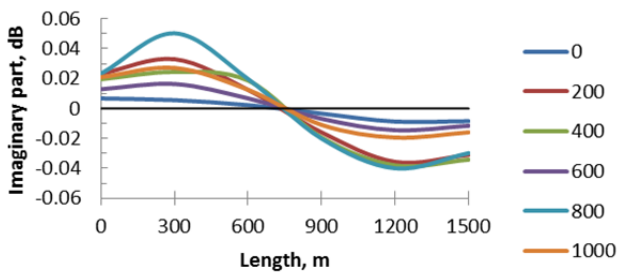


Fig. 13. Mode shape of the 1<sup>st</sup> natural frequency.

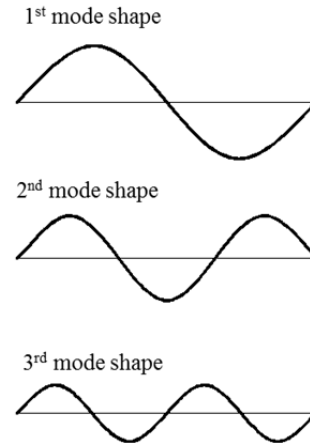


Fig. 15. Mode shapes of physical model natural frequencies.

## V. CONCLUSIONS

Natural frequencies of the physical model of prestressed suspension bridge depending on prestressing level were determined. The first vertical natural frequency changed from 7.24 to 21.69 Hz, the second frequency changed from 14.55 to 32.61 Hz, and the third frequency changed from 21.78 to 40.53 Hz, while prestressing level changed from 0 to 1000 kg, respectively. Dependence of natural frequency on the prestressing level can be evaluated in the form of second order polynomial. Horizontal natural frequencies were 6.84, 8.56 and 27.59 Hz for the first, second and third mode shapes, respectively.

Mode shapes of natural frequencies of the model were determined. It was shown that the first natural frequency mode shape consisted of two half waves, the second mode shape consisted of three half waves, etc. Mode shape with one half wave did not appear.

Experiments showed that dynamic characteristics of prestressed suspension bridge could be regulated by changing the prestressing level. By increasing the prestressing level, it is possible to increase natural frequency and vice versa. This advantage of prestressed suspension bridge allows improving dynamic characteristics of the bridge and excluding possibility of resonance appearance.

## ACKNOWLEDGMENTS

This research has been supported by the European Social Fund within the framework of the project "Support for the Implementation of Doctoral Studies at Riga Technical

University". The authors are thankful to the Structural Analysis Department of RTU and especially to Prof. I. Radins for the opportunity to use acceleration sensors and for advice and consultations on sensor efficient use and data handling.

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