Vibration Measurements on a Cable-Stayed Cyclist Arch Bridge for Assessment of the Dynamic Behaviour

Stefan Verdenius, Okke Bronkhorst, and Chris Geurts

Abstract The new cable-stayed arch bridge *Tegenbosch* (Eindhoven, the Netherlands) needed an assessment of its dynamic behaviour under wind loading due to its slender design. Because of wind-induced vibration issues on a number of bridges in the Netherlands with similar designs, it was decided to examine if vortex excitation, wind-rain induced vibration, galloping or parametric excitation might occur. Measurements were performed to determine the natural frequencies and damping ratios of the 32 cables and the deck. All cables were individually assessed, by measuring the vibrations of the cables induced with a step relaxation excitation by pre-tensioning and releasing a lashing strap. The natural frequencies of the cables were determined by evaluating the transfer functions of the measured excitation force and acceleration; damping ratios were obtained with the half-power bandwidth method. To determine the natural frequencies of the deck, 12 accelerometers were placed at different locations on the deck, after which the deck was excited using a 250 kg impact hammer at five locations. The first natural frequency of the cables varied between 2.11 Hz for the longest cable and 8.51 Hz for the shortest cable. The lowest value of the logarithmic decrement for damping found was 0.0059. Based on the damping values, a lowest Scruton number of 58 was determined using NEN-EN 1991-1-4, meaning that vortex excitation will not lead to any problems. Using the measured natural frequencies it is shown that the critical wind velocity for galloping is larger than the occurring wind speed. The same conclusion holds for wind-rain induced vibrations, where the critical velocity is calculated using the natural frequency and the damping value. The lowest horizontal natural frequency of the deck was found to be 0.41 Hz; the lowest vertical natural frequency is 2.05 Hz. Since the natural frequencies of some of the cables coincide with the natural frequencies of the deck, parametric excitation might occur. In case parametric excitation is indeed a problem in practice, it is advised to add extra damping to the system.

Keywords Cable-stayed bridge · Wind-induced vibrations · Natural frequency · Damping · Parametric excitation

---

S. Verdenius (✉) · O. Bronkhorst · C. Geurts
Unit Building, Infrastructure and Maritime, TNO, Delft, The Netherlands
e-mail: stefan.verdenius@tno.nl

Z. Wu et al. (eds.), *Experimental Vibration Analysis for Civil Engineering Structures*,
Lecture Notes in Civil Engineering 224,
https://doi.org/10.1007/978-3-030-93236-7_12

1 Introduction

The city of Eindhoven in The Netherlands has developed a new cable-stayed bridge for bicycles, named *Tegenbosch.* This bridge has a span of 132 m and a width of only 6 m, resulting in a slenderness of 22. Due to its slender design, an assessment of the dynamic behaviour of the bridge was needed to verify that vibrations of the hangers would not occur, as was the case for the *Erasmusbridge* (Rotterdam) and the *Hovenring* (Eindhoven) where vibrations possibly led to fatigue damage [1, 2]. In the case of the *Erasmusbridge*, a number of cables started to vibrate a few months after the opening of the bridge due to a combination of wind and rain. A number of possible measures was examined, such as coupling of the cables (leading to a shorter vibrating length and thus resulting in higher natural frequencies and more damping) and adaptation of the cable surface (to prevent water streams along the length of the cable). After careful consideration it was decided to add two dampers to each cable, which removed the vibration problem. At the *Hovenring*, a 'floating' circle-shaped bicycle bridge, vibrations due to wind occurred shortly after opening. Due to its circular shape wind is always unfavourable for one or more cables. As a temporary measure, cables were coupled. Also for the *Hovenring* the permanent solution was found in adding dampers.

Based on these experiences, it was decided to perform an experimental campaign before the opening of the cyclist bridge *Tegenbosch.* These measurements had as goal to assess whether vibrations might occur due to vortex excitation, galloping, the combination of rain and wind, and parametric excitation, thereby allowing the asset owner to take measures if needed.

2 Assessment of Wind-Induced Bridge Vibrations

Wind-induced vibrations in bridges can be caused by different phenomena:

- Vortex excitation
- Galloping
- Wind-rain induced vibrations
- Parametric excitation

This section describes these phenomena and discusses guidelines which can be used for their assessment. Vortex excitation can lead to vibrations when, due to wind blowing across a structural member such as a cable, vortices are shed alternately from one side to the other, whereby alternating low-pressure zones are generated on the downwind side of the structure giving rise to a fluctuating force acting at right angles to the wind direction [3]. To prevent vortex excitation, NEN-EN 1991-1-4 [4] specifies that the critical wind speed needs to be larger than 1.25 times the 10 min average wind speed v_m for the area of interest:

$$\frac{bn}{S_t} > 1.25 v_m \tag{1}$$

In Eq. (1) b is the cable diameter, n is the natural frequency of the cable and S_t is the Strouhal number. In case the critical wind speed is lower than 1.25 times the average wind speed v_m, which is for instance the case when natural frequencies are low, a second equation is given in NEN-EN 1991-1-4 to determine to what extent vortex excitation can occur. Hereto the Scruton number S_c is determined:

$$S_c = \frac{2\delta m_{i,e}}{\rho b^2} \tag{2}$$

In Eq. (2) $m_{i,e}$ is the equivalent mass of the cable per length, ρ the density of the air and δ the logarithmic decrement of damping. The equivalent mass can be determined according to Appendix F.4 from NEN-EN 1991-1-4. Since the cables from bridge *Tegenbosch* have a constant mass over the complete length of the cable, $m_{i,e}$ can be taken equal to the mass per length. While no minimum value for the Scruton number is given in NEN-EN 1991-1-4, research from Hansen [5] and Grala et al. [6] shows that excitation is limited if the Scruton number is larger than 20.

Galloping is the vibration of a flexible construction perpendicular to the wind direction. For galloping to occur, the cross section of the construction must be asymmetric. In general galloping will not occur for hangers, because they have symmetric cross sections. However, when ice is attached to the surface of the cable the cross section can be asymmetric and galloping can occur. Galloping has been observed on in-service bridges and has been reproduced in several wind tunnel experiments, e.g. [7, 8]. For galloping to occur, NEN-EN 1991-1-4 specifies that the critical wind speed must be larger than 1.25 times the average wind speed v_m:

$$2S_c\, nb/a_G > 1.25 v_m \tag{3}$$

The starting wind speed as formulated in Eq. (3) is dependent on the Scruton number S_c (and thus on the damping δ and equivalent mass per length $m_{i,e}$ of the cable), the natural frequency of the cable and the diameter of the cable. The parameter a_G is an instability factor, given in table E.7 from NEN-EN 1991-1-4.

A third phenomena is related to the combination of wind and rain, leading to vibrations of the cables. No guidelines for these vibrations are given in NEN-EN 1991-1-4, but a model is given in the research of Berkel [9]. In this research it is stated that for these vibrations to occur it must be raining, and the occurrence depends on the critical wind speed:

$$v_{crit} = \frac{4n\delta m}{-\rho b C_{y,1}} \tag{4}$$

The critical wind speed is again dependent on the natural frequency of the cable n and the damping of the cable δ. The cable diameter b and mass per length m also play an important role. The coefficient $C_{y,1}$ in Eq. (4) is the first derivative of the lift coefficient, taken equal to 0.86. The critical wind speed must be between 10 m/s and 18 m/s for these vibrations to occur. Lower wind speeds do not excite the cable, and higher wind speeds blow the rain of the cable. Wind-rain induced vibrations only occur if the cable is placed under an angle of 20 to 60 degrees and if the surface is smooth, so that the rain water can flow along the cable. This flow of water can then, due to the wind, create two streams of water that influence the air flow around the cable.

Parametric excitation is the phenomena that the cables resonate with the deck, see e.g. [10, 11]. This occurs if the natural frequency of a cable is equal or close to the natural frequency of the deck. NEN-EN 1993-1-11 [12] states that the natural frequency of the cables should be more than 20% higher or lower than the natural frequency of the deck to prevent parametric excitation. This can either be achieved by changing the natural frequencies by adapting the construction, or the excitation can be suppressed by adding dampers to either deck or cables.

Concluding, it can be stated that to assess these four phenomena the natural frequencies of cables and deck must be known, as well as the damping of the cables. To determine these dynamic characteristics of the bridge *Tegenbosch* a measurement campaign was performed which is described in the next section.

3 Measurement Setup

3.1 Bridge Tegenbosch

The bridge *Tegenbosch*, shown in Fig. 1, consists of a 21 m high arch which supports the deck with 32 cables. The cables are M64 S460 Macalloy bars, with a mass of 22.2 kg/m, varying in length from 8.76 m to 24.77 m. Due to the length of the cables in combination with the limited length of the bars, all cables consisted of two or three rigidly coupled bars. The planned force in the cables ranges from 295 to 400 kN.

3.2 Cables

Vibration measurements were performed on all 32 cables to determine the natural frequencies and damping ratios. All cables were assessed one by one; Fig. 2a and b show pictures of the measurement setup for one cable. For each measurement, four Sundstrand QA700 accelerometers (range of 30 g) were used, placed at two locations along the length of the cable to prevent loss of data in case one of the measurement locations is in a node of the cable. At each location, one accelerometer measured vibrations parallel to the bridge (x-direction); the other accelerometer measured perpendicular to the bridge (z-direction). Once the accelerometers were

Fig. 1 Bicycle bridge Tegenbosch [13]

attached to the hanger, a lashing strap was used to pretension the cable in a direction of 45 degrees with respect to the x- and z-direction, see Fig. 2c. An HBM U9C load cell (range of 5000 N) was used to determine the tension in the lashing strap. After pre-tensioning the strap to 1000 N, the strap was released and the cable was left to vibrate for almost one minute. This process was repeated five times per cable, while continuously monitoring the accelerations of the cable.

3.3 Deck

To measure the natural frequencies of the deck, 12 Sundstrand QA700 accelerometers were placed on the deck at multiple positions, as depicted by the numbers in Fig. 3. The red dots indicate accelerometers measuring in vertical direction only; the green dots indicate locations where accelerometers measure in both vertical and horizontal (z-) direction. The letters A to E in Fig. 3 indicate the excitation positions. The exact locations of the accelerometers and excitations are listed in Table 1. The excitation locations were chosen such that the fundamental modes of the deck are excited appropriately. Note that the accelerometers were positioned such that they are not exactly in a node (1/2L, 1/3L or 1/4L with L being the length of the bridge). At each excitation location listed in Table 1 the deck was excited five times, while continuously measuring the accelerations at all locations. The deck was excited using a movable 250 kg impact hammer as shown in Fig. 2d. To introduce enough

Fig. 2 Pictures of the setup of the measurements: **a** Two measurement positions along the length of the cable, **b** at each location two accelerometers were placed, measuring in two directions. **c** The step-relaxation excitation of the cables was realised with a lashing strap. **d** The deck was excited with a 250 kg impact hammer

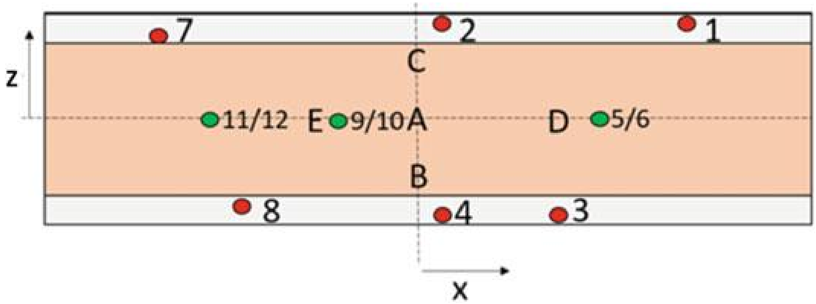

Fig. 3 Numbered locations of the accelerometers on the bridge deck measuring in two directions (green) and vertical direction only (red). The letters A to E indicate the excitation locations

Table 1 Positions of the accelerometers and excitation locations

Accelerometer	X [m]	Z [m]		Excitation	X [m]	Z [m]
1	42	2.8		A	0	0
2	5	2.8		B	0	−1.2
3	25	−2.8		C	0	1.2
4	5	−2.8		D	25	0
5/6	30	0		E	−10	0
7	−45	2.4				
8	−30	−2.4				
9/10	−10	0				
11/12	−35	0				

energy in the low frequency range, rubber slabs were placed on top of the deck. The impact of the hammer on the deck was measured using a piezoelectric Kistler load cell with a range of 60 kN. After the deck was excited five times with the hammer at all five locations, an additional measurement was done by measuring the natural vibration of the deck for 10 min (without excitation).

4 Data Evaluation

To determine natural frequencies and damping of the cables, the measured accelerations of the cable and the force in the lashing strap were evaluated. As an example both signals are shown synchronous in time in Fig. 4 for one accelerometer at one cable for all five consecutive excitations. Data was sampled with a rate of 500 Hz and filtered with an 8th order Butterworth-filter with a cut-off frequency of 30 Hz. In Fig. 4 the different stages of the step-relaxation excitation (tightening the strap, releasing the strap and free vibration of the cable) can clearly be distinguished. The upper figure shows the force in the lashing strap, the lower figure shows the acceleration of the cable.

The individual excitations are indicated in Fig. 4 using red lines as the start of the excitation (releasing the lashing strap) and black lines as the end of the cable vibration and the start of a new excitation by tensioning the lashing strap. Only the time segments between the red and black lines were used for data evaluation; the period of tightening the lash is thus not evaluated. Each accelerometer of each cable was assessed individually.

All five segments from Fig. 4 were combined into one continuous signal, and the transfer function of the applied force in the lashing strap and the measured acceleration was determined. The transfer function was determined using the built-in Matlab Fourier Transform function ‘tfestimate’ in combination with a Hanning window. The resulting spectral image of one accelerometer of one cable is shown in Fig. 5a, in

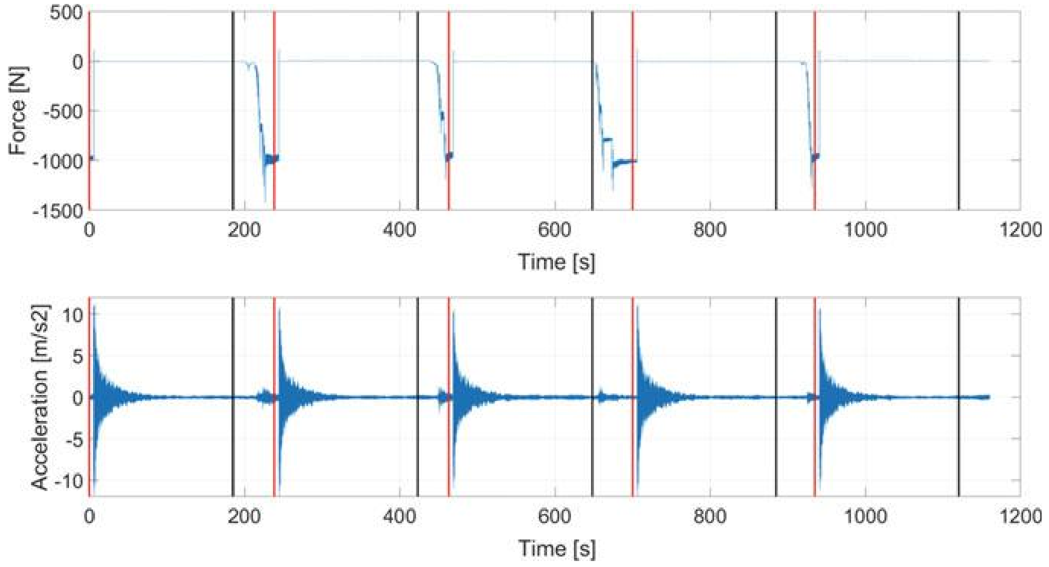

Fig. 4 Example of the registered excitation force (top) and acceleration (bottom) at one cable as an effect of five consecutive excitations

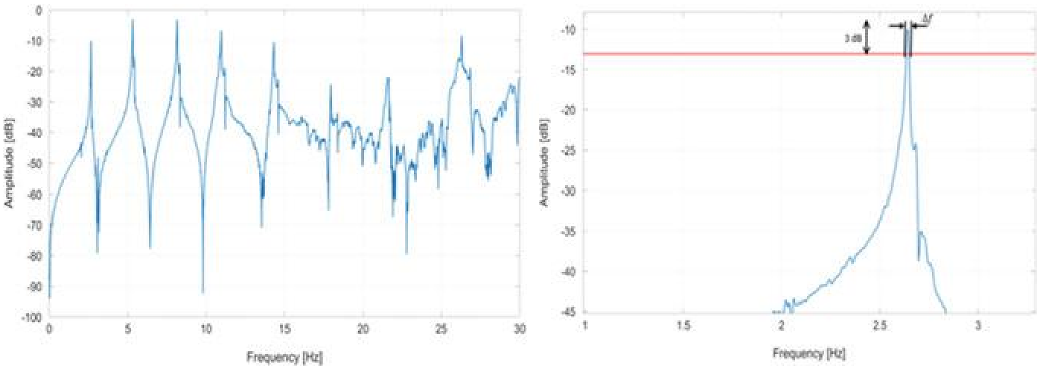

Fig. 5 Example of a transfer function for one accelerometer of one cable: **a** Visualization of the first natural frequencies. **b** Detailed depiction of determining Δf , the width of the transfer function at a magnitude of 3 dB below the peak of the transfer function

which the individual natural frequencies can clearly be distinguished as peaks in the amplitude. Transfer functions were determined for all four accelerometers individually. For some hangers slightly differing natural frequencies were found for the x- and z-direction. Although these differences were very small (on average around 1%), assessment took place on the results of both the x- and z-direction.

A similar procedure was followed to determine the natural frequencies of the deck. For each excitation position (A to E) individual transfer functions were determined for each accelerometer. On top of this, the natural frequencies of the deck in case of no excitation (the ‘freerun’) were determined by taking the Fourier Transform of the measured accelerations only.

Damping of the cables was determined by applying the half-power bandwidth method to the spectral representation of the transfer function [14]. Since the amount of damping might differ per mode, the logarithmic decrement of damping δ was determined for each of the lowest three frequencies by using Eq. (5):

$$\delta = \frac{2\pi}{\sqrt{\frac{Q^2}{0.25} - 1}} \tag{5}$$

The parameter Q in Eq. (5) is determined by dividing the natural frequency f_e by the width of the transfer function Δf at a magnitude of 3 dB below the magnitude of the natural frequency, as schematically depicted in Fig. 5b.

5 Results

5.1 Natural Frequencies and Damping Values

Natural frequencies and logarithmic damping decrements of all cables were determined to assess if vibrations would take place. The first natural frequency ranged from 2.11 Hz for the longest cable to 8.51 Hz for one of the shortest cables. The lowest value of the logarithmic decrement of damping δ was found to be 0.0059; the highest value was 0.1292. In the design of the bridge, a logarithmic decrement of a minimum of 0.0063 was assumed based on the experience from previous projects (*Hovenring*). For the 192 natural frequencies that are examined, only one value (0.0059) was marginally below this minimum.

Regarding the results of the deck, it was found that the freerun lead to the lowest horizontal natural frequency (0.41 Hz) which was not found when using the impact hammer (0.80 Hz). The first vertical natural frequency was 2.05 Hz, found at all excitation positions (including freerun).

5.2 Dynamic Phenomena

Using Eq. (1) in combination with a cable diameter b of 60 mm, a Strouhal number S_t of 0.18 and an averaged wind speed v_m of 25.7 m/s (wind area III, open surrounding and a reference height of 30 m), the first natural frequency of the cables should be larger than 90 Hz for vortex excitation not to occur. Since this condition is not met, it was examined to what extent vortex excitation could occur. Hereto the Scruton number S_c is determined through Eq. (2). When using the lowest value of the logarithmic decrement found (0.0059), a Scruton number of 58 was calculated. It is thus shown that the criterium $S_c > 20$ by Hansen [5] regarding vortex excitation is met.

The starting wind speed for galloping is calculated using Eq. (3), with a value of 1.0 for a_G as listed in table E.7 of NEN-EN 1991-1-4. When solving Eq. (3) for each cable individually with its corresponding Scruton number and lowest natural frequency, a minimum starting wind speed of 37 m/s is found. Since this wind speed is more than 1.25 times the average wind speed v_m (25.7 m/s) no galloping will occur.

For rain-wind vibrations to occur, the wind speed as defined in Eq. (4) must be between 10 and 18 m/s. When determining the critical wind speed v_{crit} for the situation of bridge *Tegenbosch*, a minimum wind speed of 43 m/s is found, which is more than twice the wind speed at which vibrations due to rain and wind are found to occur.

The condition regarding parametric excitation cannot be met, since multiple natural frequencies of the deck coincide with one or more cables. For example, the natural frequency of 2.05 Hz of the deck is very close to the lowest natural frequency of the cables (2.11 Hz), meaning that parametric excitation might occur. Since all cables have different natural frequencies, it is unlikely that parametric excitation of the full deck will occur. However, in case parametric excitation does turn out to be a problem in practice, additional damping could be added to the system as was for example done for the *Erasmusbridge*.

6 Conclusions

All 32 cables of the cable-stayed bridge *Tegenbosch* were assessed to determine if vortex excitation, wind-rain induced vibrations or galloping would take place. To this end, each cable was individually excited using a lashing strap, whilst measuring the acceleration in two directions. Evaluating the transfer function of the applied force and the measured acceleration in the frequency domain led to the natural frequencies and logarithmic decrement of damping per cable. For all cables it was found that theoretically neither vortex excitation, nor wind-rain induced vibrations or galloping would occur. In a similar way the vibration of the deck was measured using an impact hammer, from which the natural frequencies of the deck were determined. Since these natural frequencies coincide with the natural frequencies of some of the cables, parametric excitation might occur. However, since all cables have different natural frequencies, it is unlikely that parametric excitation of the full deck will occur. In case parametric excitation turns out to be a problem in practice, additional damping could be added to the system to temper the vibration.

Acknowledgements The authors would like to thank the experimental team of TNO that performed the measurements on the bridge, being Erik Slis, Peter van der Meer and Ron Lautz. Special thanks goes to Henri Steenbergen for helping in the evaluation of the data. Finally the authors would like to thank the city of Eindhoven for their help and assistance in the measurements.

References

1. Reusink JH, Zware dempers houden tuien definitief in bedwang, Bouwen met staal 137, July 1997
2. Fietsrotonde Hovenring Eindhoven afgesloten: kabels op knappen – foto’s en video, Omroep Brabant, January 2012
3. Fu F (2018) Design and analysis of tall and complex structures. Butterworth-Heinemann
4. NEN-EN 1991-1-4+A1+C2, Eurocode 1: Belastingen op constructies – Deel 1-4: Algemene belastingen – Windbelastingen, December 2011
5. Hansen SO, Vortex-induced vibrations of structures, Structural Engineers World Congress 2007, November 2007
6. Grala P, Loredo-Souza AM, Rocha MM, A comparison study between seven procedures to predict vortex-induced vibrations on industrial chimneys, Revista Sul-Americana de Engenharia Estrutural, August 2018
7. Yamauchi K, Uejima H, McTavish S, Larose G (2016) Effects of a helical fillet on the wind-induced response of bridge cables in dry conditions. In: Proceedings of the 8th international colloquium on bluff body aerodynamics and applications
8. Cheng S, Larose G, Savage M, Tanaka H, Irwin P (2008) Experimental study on the wind-induced vibration of a dry inclined cable – part I: Phenomena. J Wind Eng Ind Aerodyn 96
9. van Berkel P, van der Veen C, Noorlander K (2000) Trillingen in tuibruggen door regen en wind, Cement
10. Sun BN, Wang ZG, Ko JM, Ni YQ (2003) Parametrically excited oscillation of stay cable and its control in cable-stayed bridges. J Zhejiang Univ
11. Pinto da Costa A, Lilien J (1994) Parametric excitation of cables of cable-stayed bridges. In: International conference A.I.P.C-F.I.P
12. NEN-EN 1993-1-11+C1, Eurocode 3: Ontwerp en berekening van staalconstructies – Deel 1-11: Ontwerp en berekening van op trek belaste componenten, December 2011
13. www.meerhoven.nl
14. Papagiannopoulos GA, Hatzigeorgiou GD, On the use of the half-power bandwidth method to estimate damping in building structures, Soil Dynamics and Earthquake Engineering 31, March 2011