1. Introduction

The Hovenring bridge is a pedestrian circular-shaped bridge located in Eindhoven (Netherlands). It is constituted by a 72m diameter deck, which is sustained by 24 cables connected to a central tower of 70m height and by 4 pillars displaced at 90° angular distance, the one from the other.

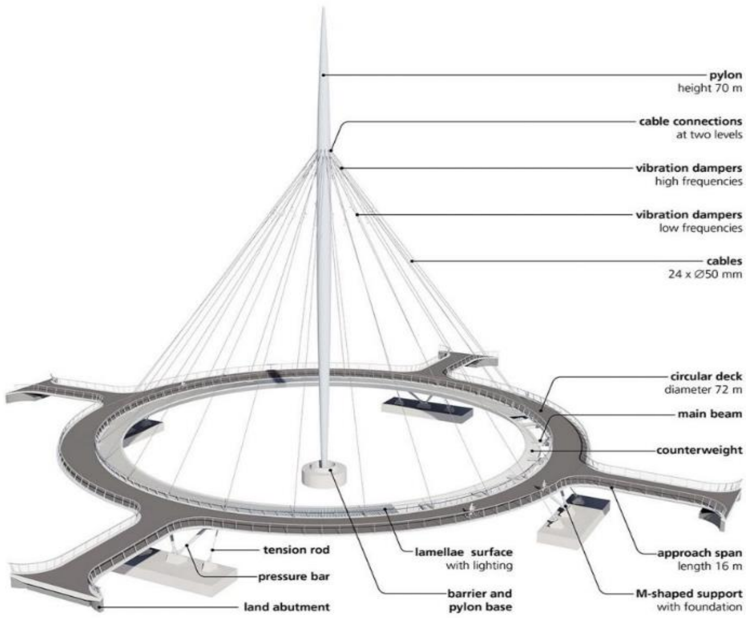


Figure 1: Hovenring bridge schematization.

The aim of this assignment is to identify the actual values of tension in the stay cables of the Hovenring pedestrian bridge, and to assess a comparison with the design ones.

2. System Description

Each cable is composed by the following elements (ordered from the tower to the deck):

- Nut and washer
- M72 threaded bar
- Cylindrical and conical socket
- Cable (full lock coil Φ50mm)
- Cylindrical and conical socket
- M100 threaded bar
- Nut and washer

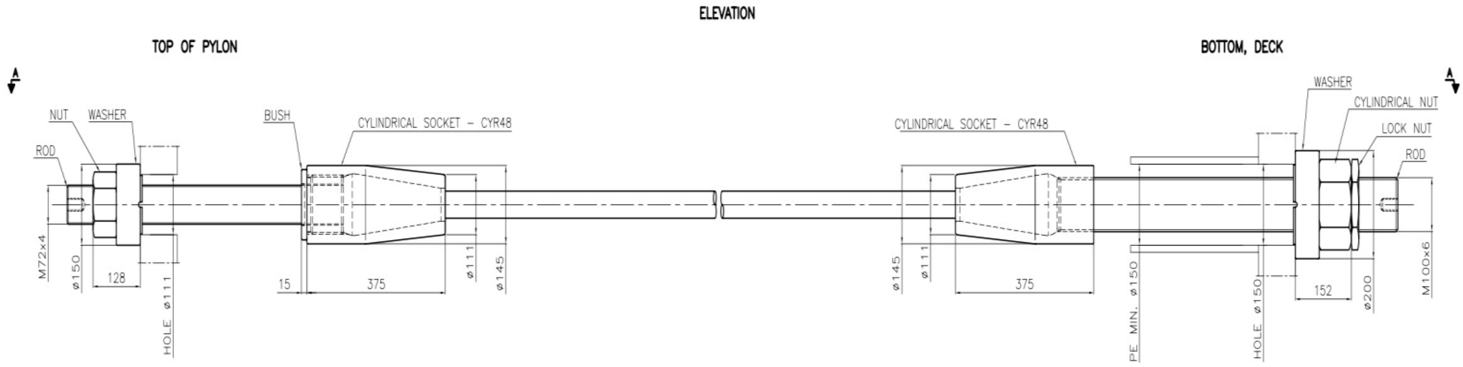


Figure 2: cable assembly.

Furthermore each cable is equipped by 2 TMDs, one deputed to dampen high frequency vibrations and the other the low frequency ones and are placed, respectively, at 3 m and 10 m from the end of the conical socket on the tower-side of the cable. They are tuned in order to protect the structure from large displacements in certain frequency ranges.

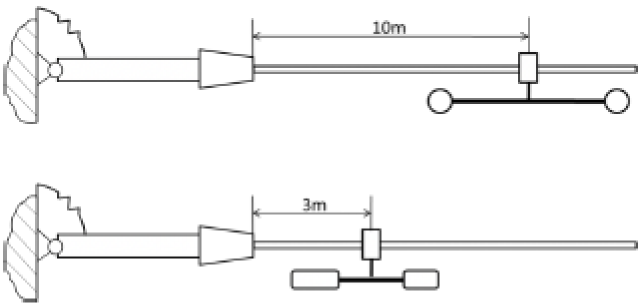


Figure 3: low frequency damper (above) and high frequency damper (below), and their locations.

An experimental campaign lighted up that the constraints on the deck side can be modelled as hinges with torsional stiffness of $9x10^6$ Nm/rad, which is then implemented into the FEM code.

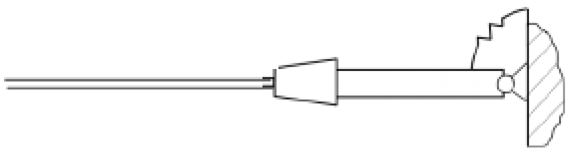
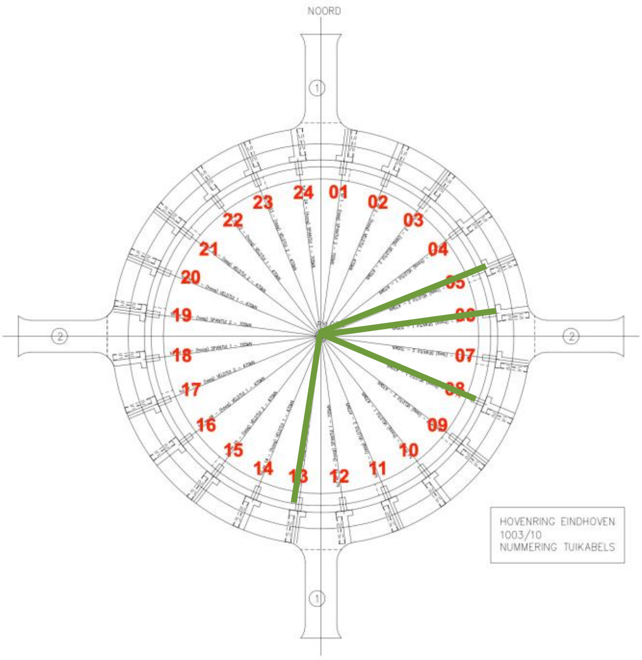


Figure 4: modelling of the deck-side constraint with a hinge with torsional stiffness of 9e6 Nm/rad.

The length of the cables is tuned by screwing the nuts onto the threaded bars on the deck-side of the cable.

Due to the increased weight, in correspondence of the access roads the design tensions of the cables are larger than the others, as reported in the table.



Number	Type	Nominal Tension [kN]	Nominal total length [m]
Cable 01	Spantui 2	705	52.647
Cable 02	Veldtui 1	470	53.423
Cable 03	Veldtui 2	470	52.647
Cable 04	Veldtui 1	470	53.423
Cable 05	Veldtui 2	470	52.647
Cable 06	Spantui 1	705	53.423
Cable 07	Spantui 2	705	52.647
Cable 08	Veldtui 1	470	53.423
Cable 09	Veldtui 2	470	52.647
Cable 10	Veldtui 1	470	53.423
Cable 11	Veldtui 2	470	52.647
Cable 12	Spantui 1	705	53.423
Cable 13	Spantui 2	705	52.647
Cable 14	Veldtui 1	470	53.423
Cable 15	Veldtui 2	470	52.647
Cable 16	Veldtui 1	470	53.423
Cable 17	Veldtui 2	470	52.647
Cable 18	Spantui 1	705	53.423
Cable 19	Spantui 2	705	52.647
Cable 20	Veldtui 1	470	53.423
Cable 21	Veldtui 2	470	52.647
Cable 22	Veldtui 1	470	53.423
Cable 23	Veldtui 2	470	52.647
Cable 24	Spantui 1	705	53.423

Figure 5: cables identification and parameters, analysed cables are 05,06,08,13.

The cables under analysis are numbered 5, 6, 8, 13.

3. Experimental setup

Each cable is instrumented with a triaxial accelerometer placed at 10 m from the cable socket. The Free Motion test was made for each cable, performed for a period of 100 s with a sampling frequency of 128 Hz.

The excitation was produced manually, by an operator standing on a cherry picker that stimulates the cable by swinging it near the MEMS accelerometer and leave it free to vibrate. The operator, knowing from the FEM model that the first natural frequency is between 1Hz and 2Hz, has the task to give a stimulus so that the cable makes around 2 oscillations per second, thus exciting the cable close to its first natural frequency. The response will be dominated predominantly by the contribution of the first vibration mode.

Data are collected for cables 5, 6, 8, 13 (with reference to the previous picture).

Acceleration time history of cable 5 is plotted below.

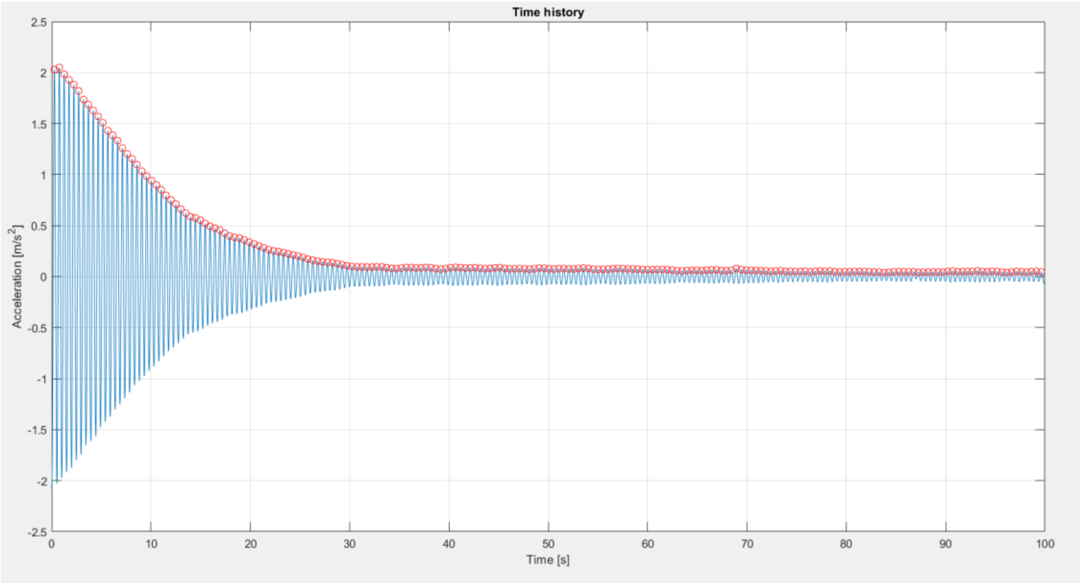


Figure 6: time history of acceleration of cable 06, mean is already subtracted, peaks are highlighted.

From the acquired data the mean value is then subtracted, so to exclude the contribution of gravity felt by the sensor, due to the inclination of the cable.

From the plot it is possible to identify three regions:

1. Large amplitudes region due to non-linear effects (red)
2. Region of smaller amplitudes and so slightly smaller damping ratio (green)
3. Region in which the TMD is not efficient resulting in the lowest damping ratio (blue)

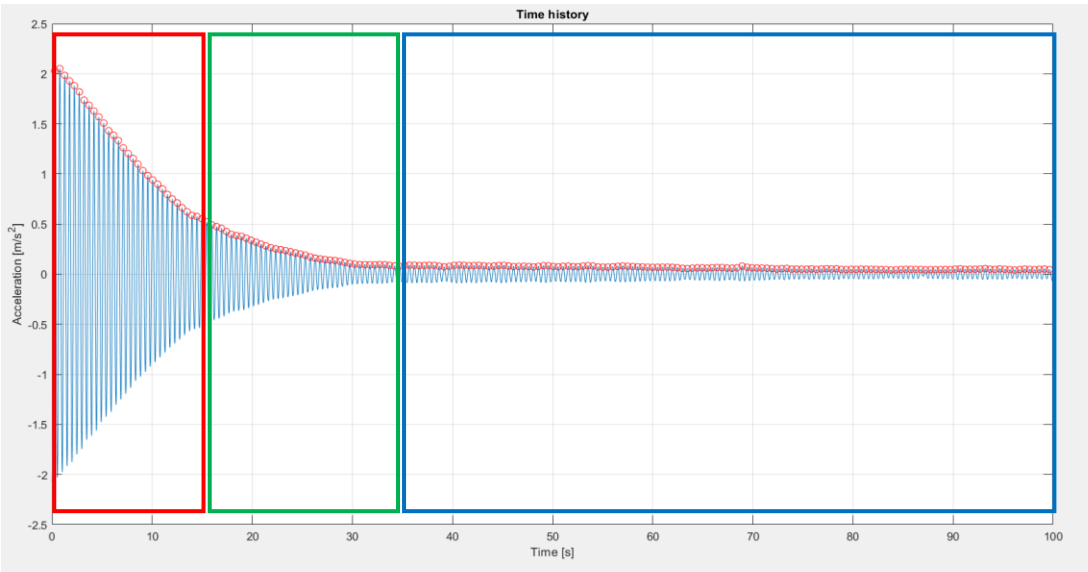


Figure 7: zones of the time history.

3. Data treatment

First, peak values are extracted, each associated to the time instant it is referred to, exploiting the Matlab function findpeaks.

Then, logarithmic decrement is evaluated, across intervals of 4 peaks as to increase accuracy (filtering out some disturbances), where i refers to each 4-peaks interval:

$$\delta_i = \log\left(\frac{\ddot{y}(t)}{\ddot{y}(t+T_i)}\right)$$

Non-dimensional damping is then computed as:

$$h_i = \frac{\delta_i}{2\,\pi}$$

Plotting the parameter h the results are messy and not clear to read.

In order to have a smoother and more comprehensible shape we can apply a Moving Average Filter with a number of points equal to 20 (Npt=20).

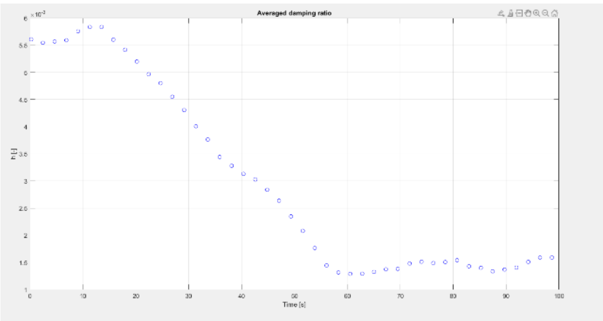


Figure 8: Non-dimensional damping ratio of cable 05.

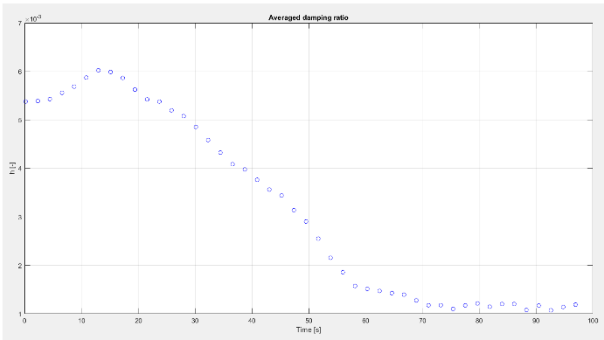


Figure 9: Non-dimensional damping ratio of cable 06.

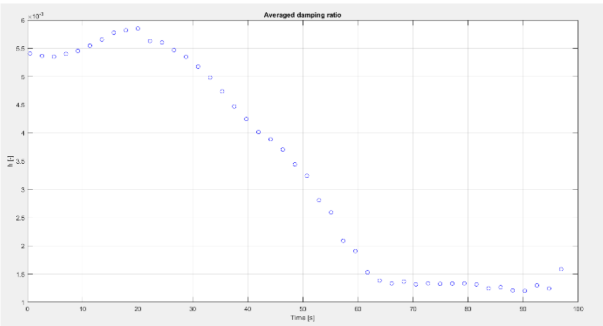


Figure 10: Non-dimensional damping ratio of cable 08.

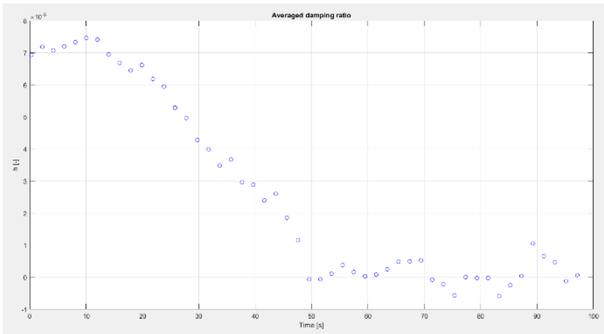


Figure 11: Non-dimensional damping ratio of cable 13.

Now the shape is simpler to read and, as expected, the trend is decreasing with time.

The oscillation frequency is computed as

$$f_i = \frac{N-1}{t(peak_{i+3}) - t(peak_i)} = \frac{3}{3T_i} \quad [Hz]$$

The natural frequency is computed as: $f_{0_i} = \frac{f_i}{\sqrt{1-h^2{}_i}}$

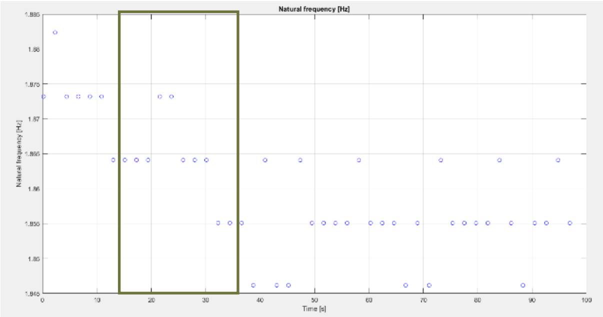


Figure 12: Natural frequency of cable 05, interest zone is highlighted.

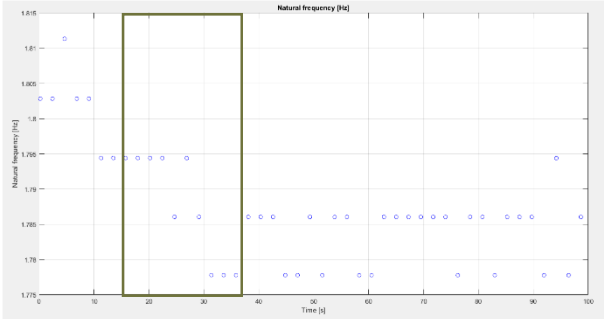


Figure 13: Natural frequency of cable 06, interest zone is highlighted.

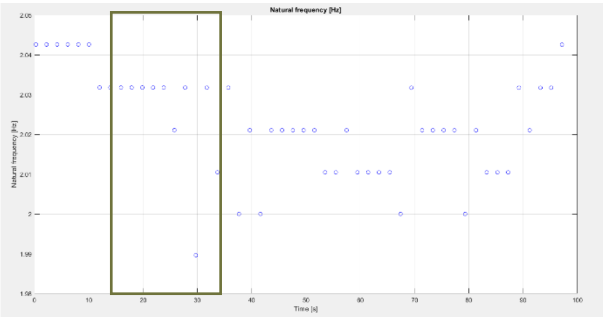


Figure 14: Natural frequency of cable 08, interest zone is highlighted.

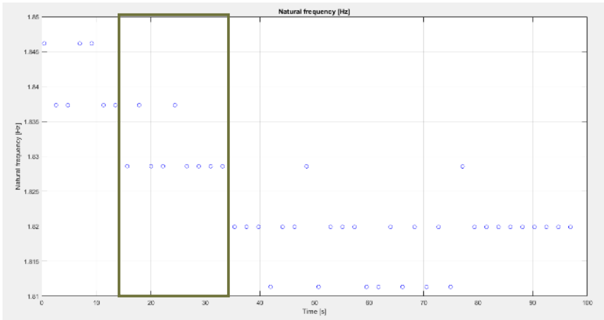


Figure 15: Natural frequency of cable 13, interest zone is highlighted.

For the assessment of the tension of the cables, only the second region of the time history is considered (in the time interval between 15s and 35s) because it's the range in which the TMDs work in their operative conditions. In this range, the mean values of damping ratio and natural frequency are computed.

Damping ratio		
Cable 05	h =	0,50%
Cable 06	h =	0,54%
Cable 08	h =	0,55%
Cable 13	h =	0,55%

Natural frequency			
Cable 05	f0 =	1,7907	Hz
Cable 06	f0 =	1,8650	Hz
Cable 08	f0 =	1,8312	Hz
Cable 13	f0 =	2,0250	Hz

Table 1: reference values for damping ratios and natural frequencies computed as average in the 15-35 s interval.

4. Comparison with FE model

In detail, the overall cable system is modelled with:

- 6 elements for each threaded bar
- 6 elements for the sockets (2 for the cylindrical part, 4 for the conical one)
- 204 elements for the cable

It's important to notice that we can't choose the cable element to model the entire cable because doing so we are neglecting the bending stiffness along the cable. We have to choose the Beam Elements because we must take into account the bending stiffness due to the presence of sockets and threaded bars

Properties	Unit	Threaded bar M100	Socket D145	Threaded bar M72	Socket D129	Cable
ø (stiff)	[m]	0.095	0.145	0.068	0.129	0.05
ø (stress)	[m]	0.093	0.145	0.067	0.129	0.05
E	[N/m²]	2.06E+11	2.06E+11	2.06E+11	2.06E+11	1.65E+11
Area	[m²]	7.01E-03	1.65E-02	3.66E-03	1.31E-02	1.68E-03
Density	[kg/m³]	7.85	7.85	7.85	7.85	8.393
Unit mass	[kg/m]	55.1	129.6	28.8	102.6	14.1
EA	[N]	1.44E+09	3.40E+09	7.55E+08	2.69E+09	2.78E+08
J_{Stiff}	[m⁴]	3.91E-06	2.17E-05	1.07E-06	1.36E-05	1.66E-07
J_{Stress}	[m⁴]	3.62E-06	2.17E-05	9.95E-07	1.36E-05	-
EJ_{Stiff}	[Nm²]	8.06E+05	4.47E+06	2.20E+05	2.80E+06	2.75E+04
W	[m³]	7.81E-05	2.99E-04	2.97E-05	2.11E-04	5.34E-06

Table 2: Mechanical properties of the different portions of the cable – assembly.

The FEM code computes the eigenfrequencies by solving the eigenvalues/eigenvectors problem by enforcing null determinant of the matrix $[K_{FF}]\,[M_{FF}]^{-1}$, where the mass and stiffness matrices are referred to the system in free nodal coordinates.

The input file is modified only in the tension of the elements and iterations are carried out until the output value of the frequency, provided by the FEM code, matches the value obtained experimentally.

The first attempt for the value of tension is the design value, the second value is a guess value and the following ones are obtained by linear interpolation of the previous two.

Tables show the results.

	Cable 5 - VELDTUI2			
	Target frequency		1,7907 Hz	
	Tension [kN]	Nat. Frequency [Hz]	Line slope	Line x=0 value
Design tension	470,0	1,7635	0,0017	0,9457
Guess value	490,0	1,7983		
Actual tension	485,6	1,7907		
	Difference from design		+ 15,63 kN	
			+ 3%	

Table 3: results for cable 05.

Cable 6 - SPANTUI1	
Target frequency	1,8650 Hz

	Tension [kN]	Nat. Frequency [Hz]	Line slope	Line x=0 value
Design tension	705,0	2,0376		
Guess value	600,0	1,9357	0,0010	1,3534
	527,1	1,8287	0,0015	1,0544
	551,9	1,8670	0,0015	1,0118
Actual tension	550,6	1,8651		
	Difference from design		- 154,43 kN	
			- 22%	

Table 4: results for cable 06.

	Cable 8 - VELDTUI1			
	Target frequency		1,8312 Hz	
	Tension [kN]	Nat. Frequency [Hz]	Line slope	Line x=0 value
Design tension	470,0	1,7343		
Guess value	490,0	1,7686	0,0017	0,9283
	526,5	1,8284	0,0016	0,9658
Actual tension	528,2	1,8311		
	Difference from design		+ 58,21 kN	
			+ 12%	

Table 5: results for cable 08.

	Cable 13 - SPANTUI2			
	Target frequency		2,0250 Hz	
	Tension [kN]	Nat. Frequency [Hz]	Line slope	Line x=0 value
Design tension	705,0	2,0527		
Guess value	690,0	2,0457	0,0005	1,7237
	645,6	2,0144	0,0007	1,5588
	660,7	2,0270	0,0008	1,4729
Actual tension	658,3	2,0251		
	Difference from design		- 46,72 kN	
			- 7%	

Table 6: results for cable 13.