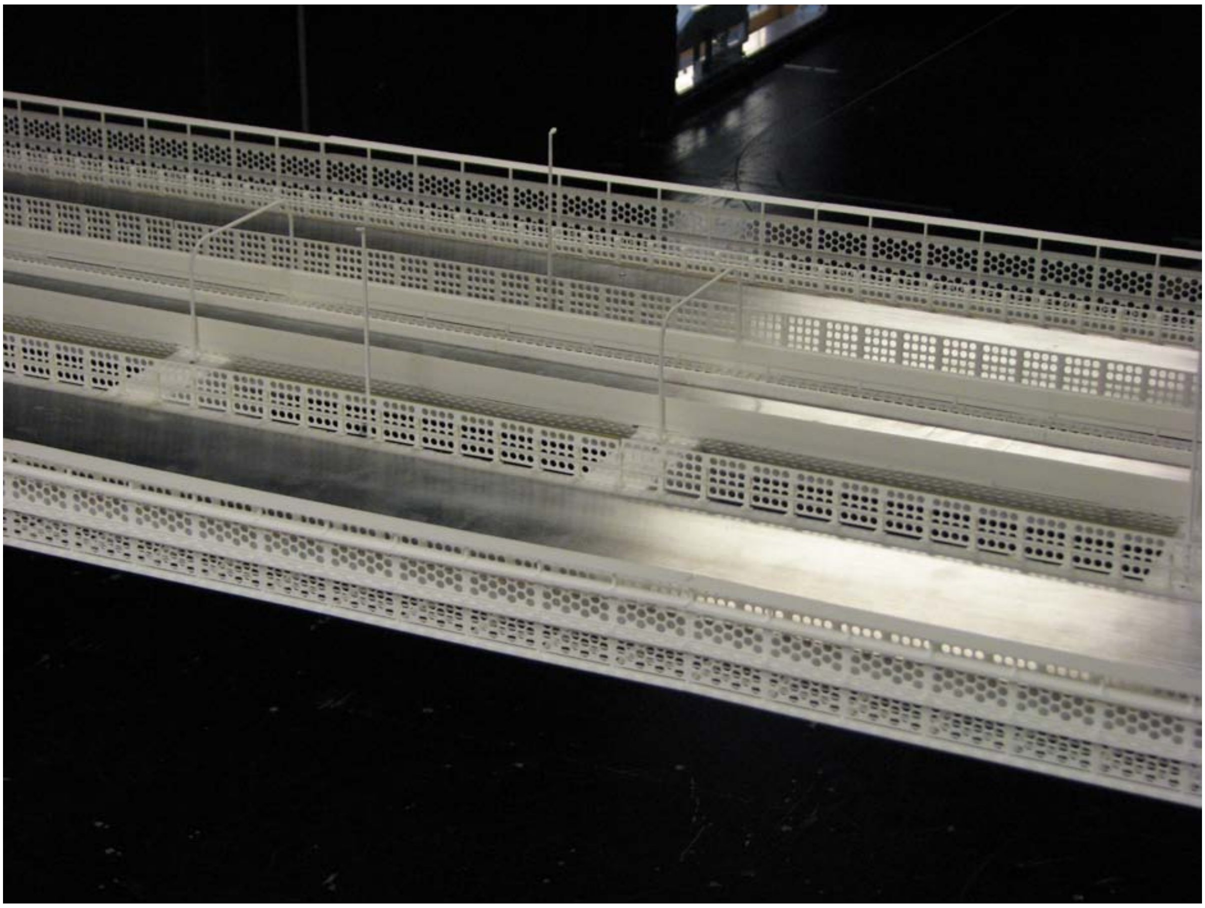

EUROLINK S.c.p.A

Additional Static & Stability Tests for the Messina Strait Bridge

FORCE 110-26444.02a Rev. 1/2010-12-07

Project No. and Title of Report:

FORCE 110-26444.02a
Additional Static & Stability Tests for the Messina Strait Bridge

Client: EUROLINK S.c.p.A	**Client's Ref.:** Allan Larsen, COWI A/S
Author(s): Søren V. Larsen	**Date:** 2010-12-07
	Approved by: A. Roger Damsgaard

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APPENDICES:

1. Introduction

FORCE Technology was commissioned by EUROLINK S.c.p.A to conduct an additional investigation of the bridge deck of the Messina Strait Bridge. Static tests, stability and damping tests were conducted for a configuration referred to as C5/63°. COWI A/S acted as the Client's representative. The present section model tests were conducted as extension to the test programme identified as Sub-test D4.

The present report describes the additional section model tests performed to establish the static force coefficients as well as the stability limit and damping values at two wind speeds.

The section model tests were performed on a 1:80-scale section model of the bridge deck in FORCE Technology's 2.6 m wide boundary-layer wind tunnel. The tests were conducted at FORCE Technology in September 2010.

The work was performed as an extension to the Agreement between FORCE Technology and Eurolink S.c.p.A. dated 2010-06-21. The present work was performed according to parts of Addendum 2 (dated 2010-11-04).

2. Summary and Conclusions

This report presents the results of the wind-tunnel tests conducted to establish aerodynamic data for configuration C5 with 63° inclined panels on the rail girder for the Messina Strait Bridge.

A 2.55 m long section model built at a geometric scale of 1:80 for previous investigations was used and modified for the present tests. The model was tested in smooth flow and turbulent flow in FORCE Technology's 2.6 m wide Boundary-Layer Wind Tunnel.

The following aerodynamic parameters were established:

1) Static force coefficients in smooth flow for 1 configuration
2) Aerodynamic stability and damping in smooth and turbulent flow for 1 configuration

All tests in this series were conducted with the road girders having 2% outward slope. The present configuration was referred to as C5/63°.

The main findings are summarised in the following. The present configuration is described in Section 3.1.

Static Tests

The static force coefficients at 0° and their variations with angle of wind incidence (first derivatives) are shown in Table 2.1. Figure 6.2 show plots of all the determined coefficients for the various configurations, with the drag and lift coefficients, C_d and C_l, being fixed in a wind coordinate system, and C_x and C_z being body fixed coefficients, see Section 6.

		C5 63° rail girder edge
C_d	(0°)	0.104
C_l	(0°)	-0.061
C_m	(0°)	0.005
$\frac{dC_d}{d\alpha}$	(-1° to +1°)	-0.123
$\frac{dC_l}{d\alpha}$	(-1° to +1°)	0.334
$\frac{dC_m}{d\alpha}$	(-1° to +1°)	0.187

Table 2.1. Static aerodynamic force coefficients and their slopes (based on a deck width of B= 60.4 m).

Stability Tests
The aerodynamic stability was investigated for the configuration C5 with 63° panels on the railway girder. Stability tests were conducted for ±4° and 0°, and in smooth and turbulent flow.

The estimated critical wind speeds for onset of aerodynamic instability are listed in the following table.

Configuration	Flow	Angle	$U_{red,cr}$ $[U_{cr} / (f_t \cdot B)]$	U_{cr} [m/s]
C5 with 63° rail girder edge	Smooth	-4°	>25	>125
		0°	23.7*	119*
		+4°	24.0	120
C5 with 63° rail girder edge	Turbulent	-4°	16.5**	83**
		0°	16.2	81
		+4°	25.1	126

Table 2.2. Estimated aerodynamic stability limits as reduced wind speed $[U_{cr}/(f_t \cdot B)]$ and full-scale wind speed [m/s].

* For the configuration C5/63° in smooth flow at 0°, it was observed that the damping of the model for especially vertical motion was very low in the range of reduced wind speeds $18 < U_{red} = U/(f_t \cdot B) < 22$. However, released from a initial displacement the model was aerodynamically stable, but the damping was very small.

**For the configuration C5/63° in turbulent flow at -4°, the measured displacement and rotation are contaminated by the model hitting the wind tunnel wall from approximately $U_{red} = U/(f_t \cdot B) = 15$ and higher. This was caused by the large negative displacement in combination with the buffeting response.

Aerodynamic Damping

In connection with the stability tests the damping of the bridge section was estimated based on free decay tests conducted at wind speeds corresponding to 54 m/s and 75 m/s full-scale, respectively. Results are presented in Section 7.2.

3. Model Design

3.1 Prototype Structure

The Messina Strait Crossing comprises a suspended main span of 3300 m. The total length of the bridge is 3666 m. The bridge deck comprises three closed box girders and the overall deck width is approximately 60 m.

An elevation of the prototype structure is shown in Figure 3.1.

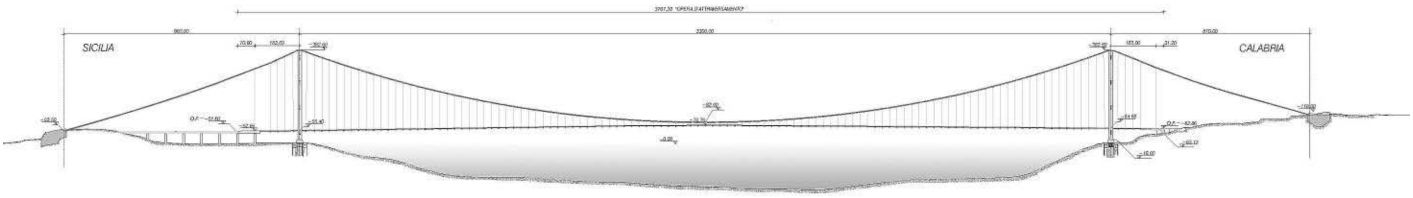


Figure 3.1 Elevation of the Messina Strait Crossing.

Figure 3.1 shows the basic cross section of the prototype bridge deck and its main dimensions. In the present case the rail girder was fitted with panels having an angle of 63° to horizontal, see Figure 3.4.

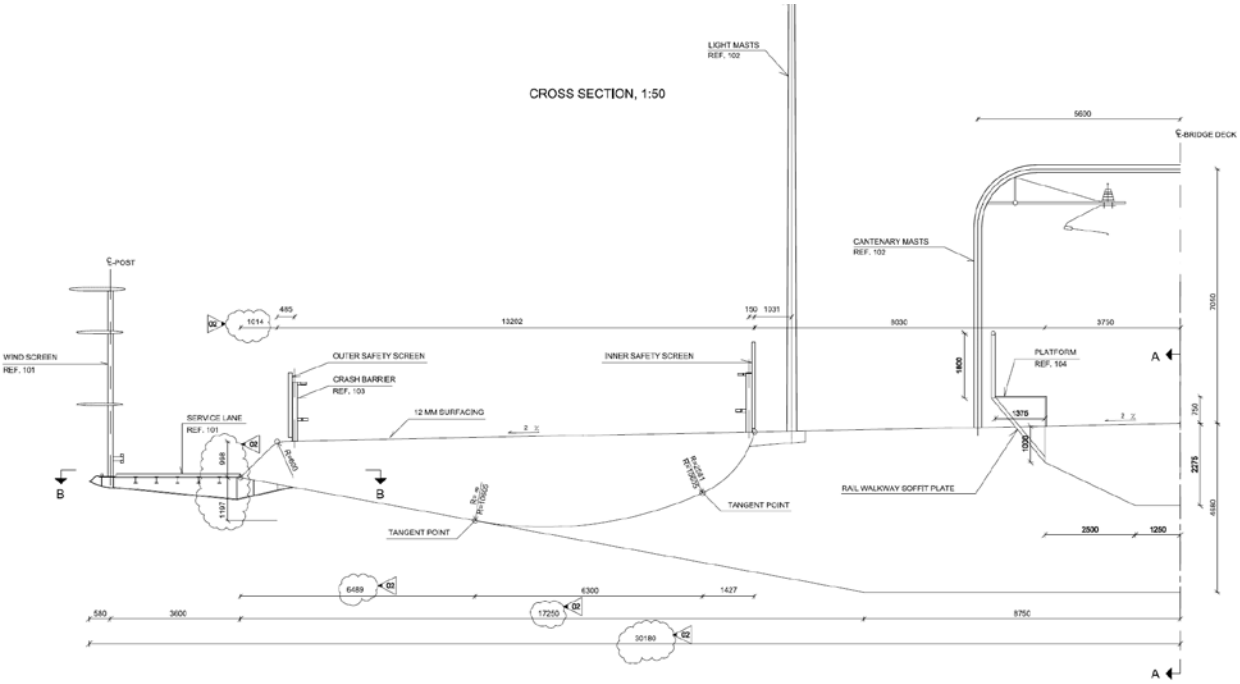


Figure 3.2. Cross-section of prototype bridge deck.

3.2 Scaling Parameters

A combination of geometrical, mass and stiffness considerations resulted in the selection of a 1:80 geometrical scale for the section model of the Messina Strait Bridge deck, see [1].

For the present tests, the model designed and constructed for the Sub-tests D4 was used. The present model was modified compared to the model used in the previous additional tests, ref. [5], with respect to the configuration of the cross beams. The previous model was fitted with seven cross beams (one placed at the mid span of the model, and three placed on either side) However, for consistency with earlier tests, ref. [4] and earlier, it was decided to have six cross beams on the present model (three placed on either side of the model's mid span).

3.3 Section Model Design

The 1:80 geometrical scale section model of the bridge deck was built with the properly scaled outer shape of the prototype structure.

The various configurations were obtained by using the different screens from the Sub-tests 1, see [4].

The tested configuration and its details are described in the following. For completeness all configurations from the Sub-Test 1 are listed in the table below together with a new configuration referred to as C8 (inner safety screens only). It should be noted that configuration C8 was not included in the Sub-tests 1 (110-25465), but in 110-26444.02 only.

#	**Inner Safety Screens (2.4m)**	**Outer Safety Screens (1.8m)**	**Soffit Plate**	**Solid Railway Screen**
C1	off	Off	off	on
C2	off	Off	porous	on
C3	off	Off	solid	on
C4	on	Off	porous	on
C5	**on**	**On**	**porous**	**on**
C6	on	Off	porous	off
C7	off	Off	porous	off
C8	on	Off	porous	off

Table 3.1. Summary of screen configuration.

The positions of the screens are shown in the following figure.

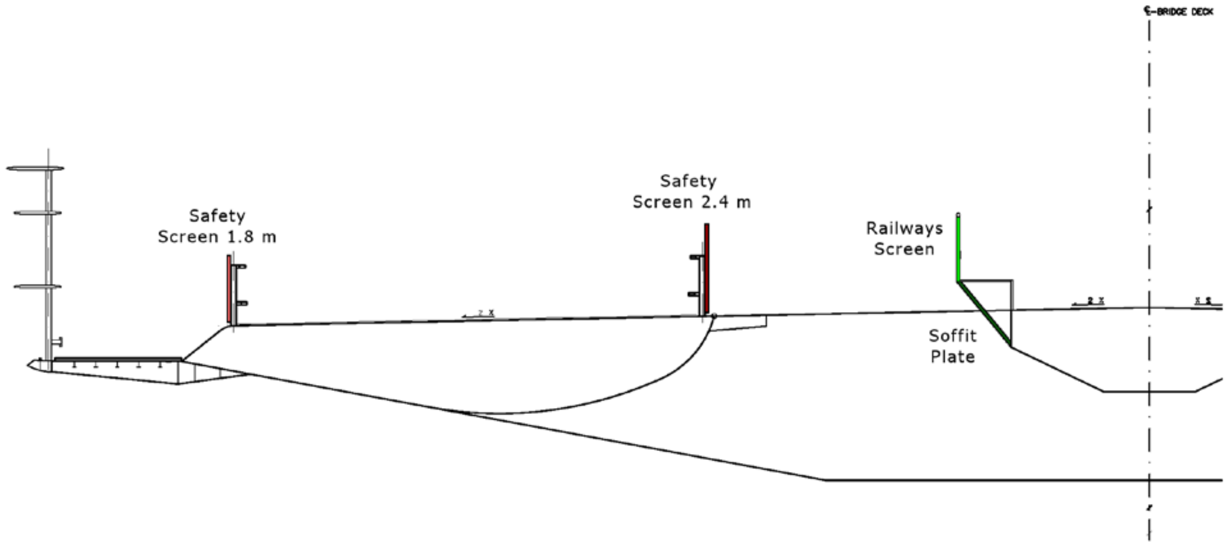


Figure 3.3. Positions of screens on the bridge deck.

Configuration C5 was fitted with slanted panels on the rail girder. The panels were given an angle with horizontal of 63°, see the following figure.

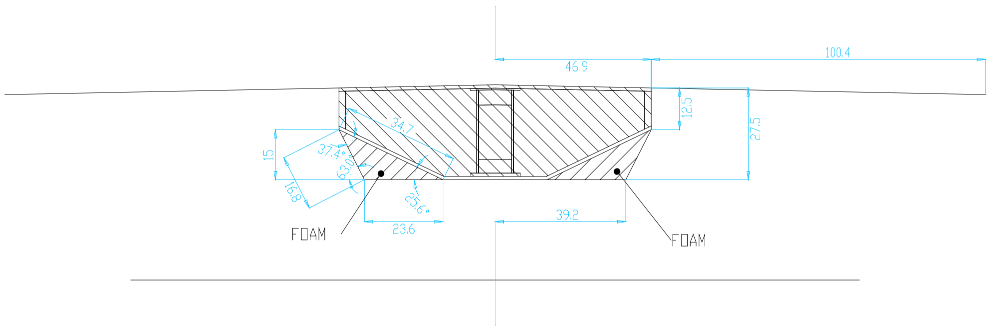


Figure 3.4. Modified railway girder configuration – 63° rail girder edge: C5/63°.

Further, a 80 mm tall gutter plate on the edge of the road girder, see Figure 3.5, was simulated by a 1 mm by 1 mm trip mounted this location on the model.

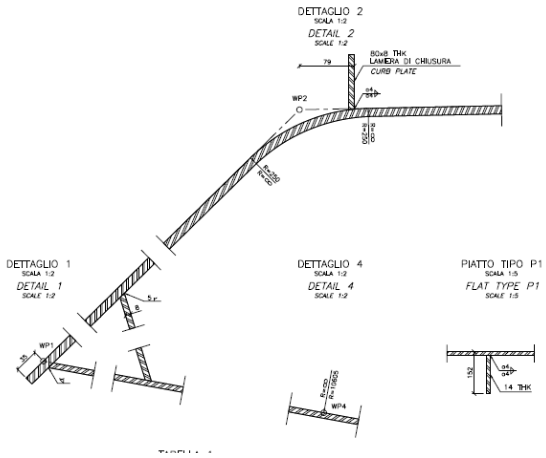


Figure 3.5. Gutter plate on road girder.

4. Wind Tunnel and Flow Conditions

The section model tests were conducted in FORCE Technology's 2.6 m wide x 1.8 m high x 21 m long Boundary-Layer Wind Tunnel II. The model was placed 14.5 m downstream of the inlet at the mid height of the wind tunnel. The ceiling of the wind tunnel was adjusted so that it was horizontal throughout the length of the wind tunnel.

The wind-tunnel tests were performed in smooth and turbulent flow. The smooth flow condition corresponds to an empty tunnel (i.e., without exposure upwind of the model). The smooth flow condition has a turbulence intensity ($I_{u,\,w}$) of approximately 0.5%.

The turbulent exposure was obtained by three spires mounted 1.1 m from the wind tunnel inlet. The spires were 1.8 m high with a tapered width: 0.32 m at the floor to 0.18 m at the wind tunnel ceiling. This exposure resulted in turbulence intensities of approximately 7.5% for I_u and 7.4% for I_w.

5. Wind-Tunnel Test Programme

The test programme consisted of static and dynamic section model tests, the objective being to determine the static wind loads, the aerodynamic stability and the aerodynamic damping.

The test programme is outlined in Table 5.1.

#	Test	Angles	Configuration	Flow
11	Stability and damping tests	-4°, 0°, +4°	C5 63° rail girder edge	Smooth
12	Stability and damping tests	-4°, 0°, +4°	C5 63° rail girder edge	Turbulent
13	Static tests	-10° to +10°, Δ=1°	C5 63° rail girder edge	Smooth

Table 5.1. Test programme for section model tests – C5/63°.

6. Static Tests

6.1 Static Force Coefficients Definition

The static aerodynamic force coefficients for the deck of the Messina Strait Bridge were determined based on wind-tunnel tests on a 1:80 geometrical scale model of a section of the deck in smooth flow.

A typical force coefficient is defined as follows:

$$C_{x,z,l,d} = \frac{\overline{F}_{x,z,l,d}}{\overline{q}\, BL} \tag{6.1a}$$

$$C_m = \frac{\overline{M}}{\overline{q}\, B^2 L} \tag{6.1b}$$

Where:

C	=	Aerodynamic coefficient
$\overline{F}$	=	Time-averaged (mean) aerodynamic force
$\overline{M}$	=	Mean overturning moment (torque)
B	=	The bridge deck width (60.4 m in the present case, 60.74 m for previous tests)
L	=	The model span length
$\overline{q}$	=	The mean wind velocity pressure[1] at deck level; $\overline{q} = \frac{1}{2}\rho \overline{V^2}$ where:
ρ	=	Air density [kg/m^3]
$\overline{V}$	=	Mean wind velocity at deck level in [m/s]

The subscripts x, z, l, d and m refer to the x and z body-force components, lift, drag and overturning moment, respectively.

The procedure for the determination of the static coefficients consists of mounting the 2.55 m long section model of the bridge in a static rig equipped with two 3-component force balances. The force balances measure the vertical, lateral and torsional reactions at the extremities of the model. The reactions are combined to obtain: $\overline{F}_l, \overline{F}_d$ and $\overline{M}$, respectively.

These quantities are subsequently normalized according to the equations above. This procedure is repeated for several angles of attack of the model (from –10° to +10° in increments of 1^o, measured from the horizontal plane).

[1] The mean velocity pressure is measured directly (by micro manometers), consequently the value of the air density and the mean wind velocity are not determined explicitly.

The rate of change (or slope) of the coefficients with angle of attack α in radians is evaluated from these tests in the vicinity of zero degrees (between –1° and +1°).

The drag and lift coefficients, C_d and C_l, are defined in the global coordinate system in relation to the wind. The body force coefficients, C_x and C_z, defined in the local coordinate system, are linked to the drag and lift coefficients by the following relationships:

$$C_x(\alpha) = C_d(\alpha)\cos\alpha - C_l(\alpha)\sin\alpha \tag{6.2a}$$

$$C_z(\alpha) = C_d(\alpha)\sin\alpha + C_l(\alpha)\cos\alpha \tag{6.2b}$$

A bridge deck width, B, of 60.4 m (full-scale) was used in the determination of the coefficients. The centre of measurement of the forces and moment was set at the shear centre of the section, 1.33 m (in full-scale) above the bottom of the bottom plate of the railway girder.

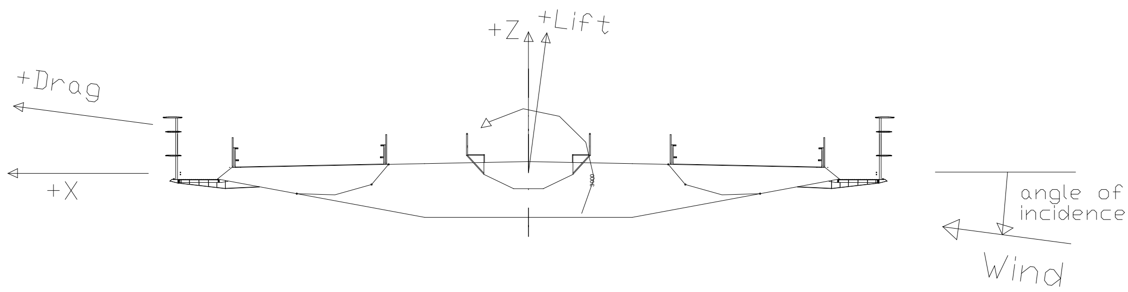


Figure 6.1. Sign convention for the static section model tests.

6.2 Results

The present tests were conducted at model-scale wind speeds of typically about 12 m/s. Figure 6.2 present the variations of the coefficients with angle of wind incidence, α, for the bridge deck.

A summary of the main static coefficients is given in Table 2.1 of Section 2. The rate of change (slope) of the coefficients around 0° was calculated based on the values at –1° and +1°, see also the tables in Section 2.

The measured coefficients have been corrected for the effect of blockage according to ESDU[2]. The blockage correction was in the order of 3-7% depending on the deck inclination.

[2] Engineering Sciences Data Unit Item 80024:" Blockage correction for bluff bodies in confined flows", Nov. 1980.

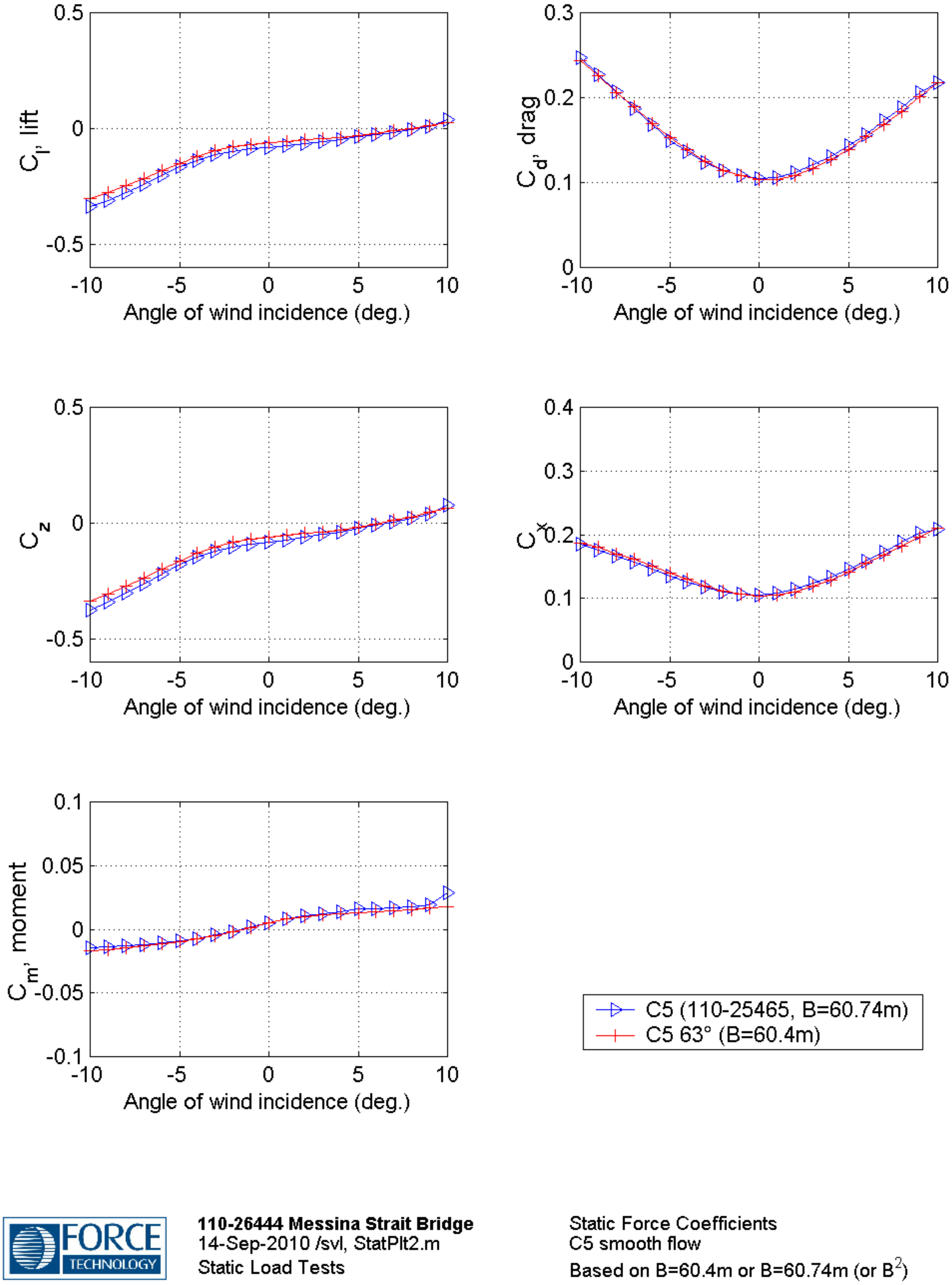


Figure 6.2. Variations of the static force coefficients – original C5 and C5/63°. Results based on deck width B. B=60.4 m in the present case, B=60.74 m for previous tests (110-25465).

	C5 63° rail girder edge		
α [°]	C_d	C_l	C_m
-10	0.243	-0.300	-0.017
-9	0.226	-0.276	-0.016
-8	0.206	-0.245	-0.014
-7	0.189	-0.216	-0.013
-6	0.170	-0.180	-0.011
-5	0.153	-0.149	-0.009
-4	0.138	-0.121	-0.008
-3	0.125	-0.097	-0.005
-2	0.115	-0.079	-0.002
-1	0.108	-0.068	0.001
0	0.104	-0.061	0.005
+1	0.104	-0.056	0.008
+2	0.109	-0.049	0.010
+3	0.117	-0.044	0.011
+4	0.127	-0.038	0.012
+5	0.139	-0.031	0.013
+6	0.154	-0.020	0.014
+7	0.168	-0.009	0.015
+8	0.184	0.001	0.015
+9	0.201	0.014	0.017
+10	0.217	0.026	0.018

Table 6.1. The static force coefficients with angle of incidence.

7. Stability & Damping Tests

The test set-up and methods were identical to those in the previous tests, see [4]. Due to the time constraints in the test execution, a full mass calibration of the rig was not performed. However, the present model - with the same ballast as in the previous tests - resulted in frequencies within two percent of the target values. Thus, the mass and mass moment of inertia were matched within approximately 4%.

The obtained frequencies and estimated mass properties are compared with the target values in the table below.

The resulting velocity scaling for the vertical and torsional response in the dynamic rig (Soft Rig) was approximately 1:6.4, 1 m/s in the wind tunnel corresponding to 6.4 m/s in full-scale.

	Prototype		Section Model Soft Rig	
	"Vacuum"	"In-Air"	Target	Obtained
$f_{vertical}$ (Hz)	0.0645	0.064	0.797	0.81
$f_{torsional}$ (Hz)	0.0831	0.083	1.031	1.01
Ratio: $f_{torsional}$ / $f_{vertical}$	1.29	1.29	1.29	1.25
Mass per unit length (kg/m)	53,200	53,683	8.388	8.24*
Mass moment of inertia per unit length (kg·m^2/m)	26,500,000	26,650,092	0.651	0.62*

Table 7.1. Dynamic properties of prototype structure and section model.
*Estimated values.

The model was restrained in the lateral direction, the horizontal motions of the deck having no significant influence on the stability of the deck, which is the normal assumption for section model tests.

In the dynamic rig (soft rig) the damping for vertical motion was approximately 0.3% of critical and for torsional motion it was about 0.2% of critical.

7.1 Stability Tests

The dynamic section model tests aimed at defining the aerodynamic stability limit of the deck. In the current tests, the stability limit of configuration C5 with 63° rail girder edge was investigated in smooth and turbulent flow for angles of wind incidence of -4°, 0° and +4°.

Variations of the mean and root-mean-square (rms) responses with reduced mean wind speeds at deck level are presented in the form of mean and rms vertical displacement normalised by the deck height (4.68 m full-scale). The pitch response is simply presented as the deck rotation in degrees. This section presents summary plots of the results obtained in the dynamic section model tests.

A summary of the main findings is given in Section 2. The detailed presentation given in Appendix A includes plots of the peak factor. The definition of the peak factor is given below.

$$peak\ \ factor = \frac{d_{\max} - d_{\min}}{2 \cdot rms} \tag{7.2}$$

d_{max} and d_{min} are the maximum and minimum values (e.g., deflection) of a given time series, respectively, and rms is the root-mean-square of the time series.

Each of the data points (except from the last point, where instability starts) on the response plots results from the measurements of stable, limited amplitude motion (as opposed to a negative total damping case where the amplitude continues to grow in magnitude for the same wind speed). The peak factor can be used to see whether the motion is in a "locked-in" state of sinusoidal motion or a random type motion.

The onset of an "instability" is defined as when the character of the response changes from a random type motion to that of a regular, sinusoidal motion, involving either pure torsional, pure vertical or a coupled vertical-torsional vibration. This can often be identified through an examination of the peak factor. A random signal has peak factors in the 3-4 range, while a pure sinusoid has a peak factor of $\sqrt{2}$ or 1.41. Alternatively, a torsional rms response of 0.5° can be chosen as the governing criteria.

However, in the present tests the identification of instability has been difficult in some cases due to the large buffeting response. It was not possible to obtain time series of the response where the harmonic response of starting instability could be observed in the peak factors. Consequently the test speed was gradually increased (and the response measured) until the self excited motion was observed or the test had to be stopped due to large response in order to safeguard the model and the rig.

Figure 7.1 shows results from the stability tests in terms of rms response.

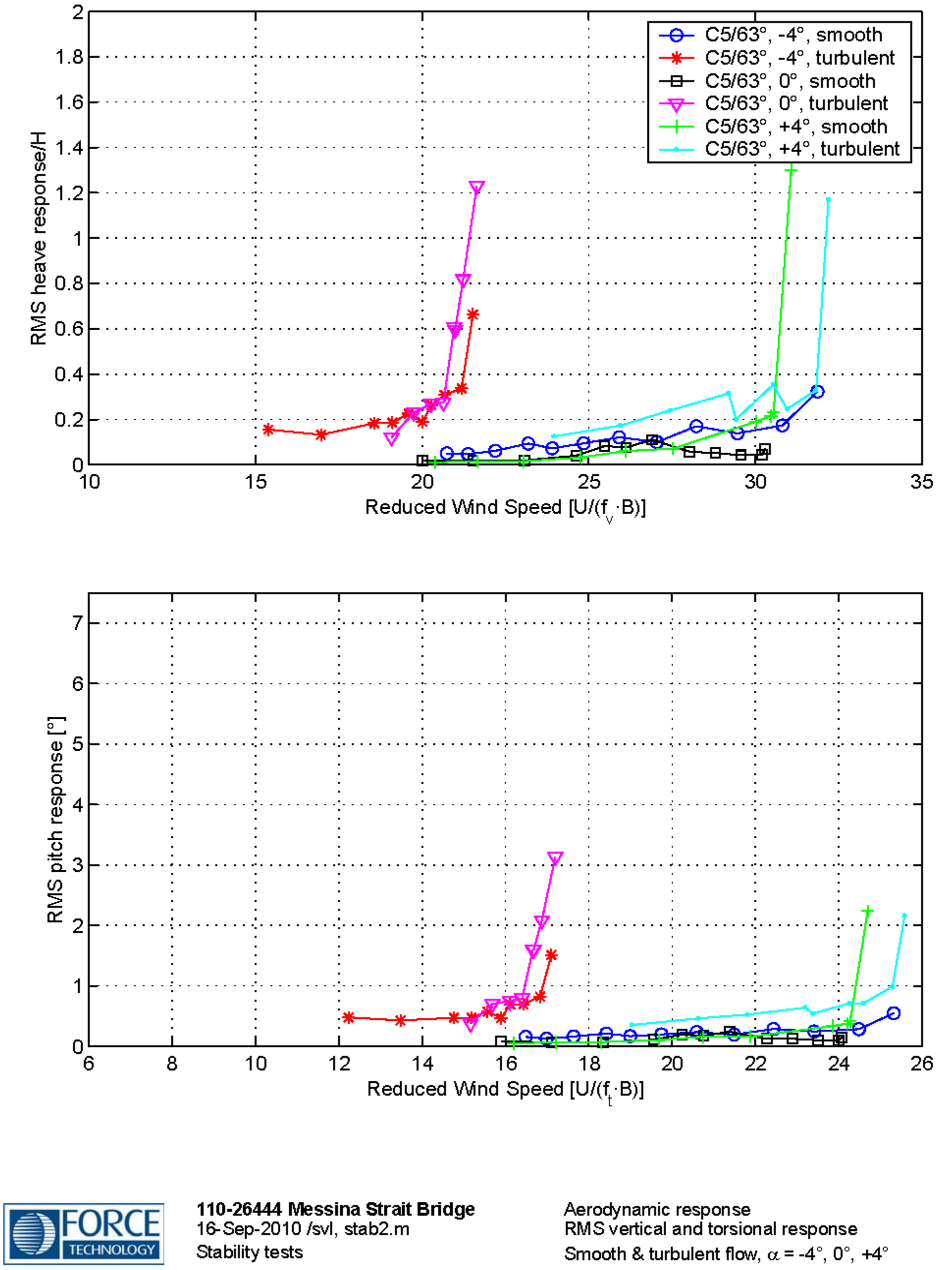


Figure 7.1. Response in stability tests.

7.2 Damping Tests

The damping level (i.e., the sum of the aerodynamic and structural damping) has been estimated in connection with the stability tests. At wind speeds corresponding to 54 m/s and 75 m/s (full-scale), respectively, the model was given a combined displacement in torsional and vertical direction (pitch and heave). Subsequently the model was released and the decay signals were recorded. Based on the decay signals the damping levels have been estimated. It should be noted that in some cases - especially at the higher wind speed – the damping was high and therefore for these cases the damping has been estimated based on a limited number of cycles of motion and consequently the damping estimation is a rough approximation. In many cases, the obtained decay signals exhibited damping level that was strongly amplitude dependent.

The vertical damping is presented for amplitudes up to 20 – 40 mm and the torsional damping is presented for an amplitude of approximately 1° - 2°.

The tests results are summarized in the following table.

Configuration	U [m/s]	flow	angle [°]	vertical damping [% crit]	torsional damping [% crit]
C5/63°	54	Smooth	0	5.0	2.3
C5/63°	75	Smooth	0	2.1	1.7
C5/63°	54	Turbulent	0	3.3	1.7
C5/63°	75	Turbulent	0	1.2	0.8
C5/63°	54	Smooth	4	3.6	3.5
C5/63°	75	Smooth	4	2.2	1.6
C5/63°	54	Turbulent	4	3.7	2.1
C5/63°	75	Turbulent	4	0.8	1.8
C5/63°	54	Smooth	-4	2.6	2.2
C5/63°	75	Smooth	-4	1.5	1.6
C5/63°	54	Turbulent	-4	1.8	1.7
C5/63°	75	Turbulent	-4	0.7	0.6

Table 7.2 Estimated damping levels (in % of critical).

8. References

[1] "Section Model Tests for the Messina Strait Crossing, Italy"
FORCE 2005011 rev. 3.1, 2005-04-18

[2] "Stability Tests for Modified Deck for the Messina Strait Crossing, Italy"
FORCE 2005263 rev. A, 2005-12-22

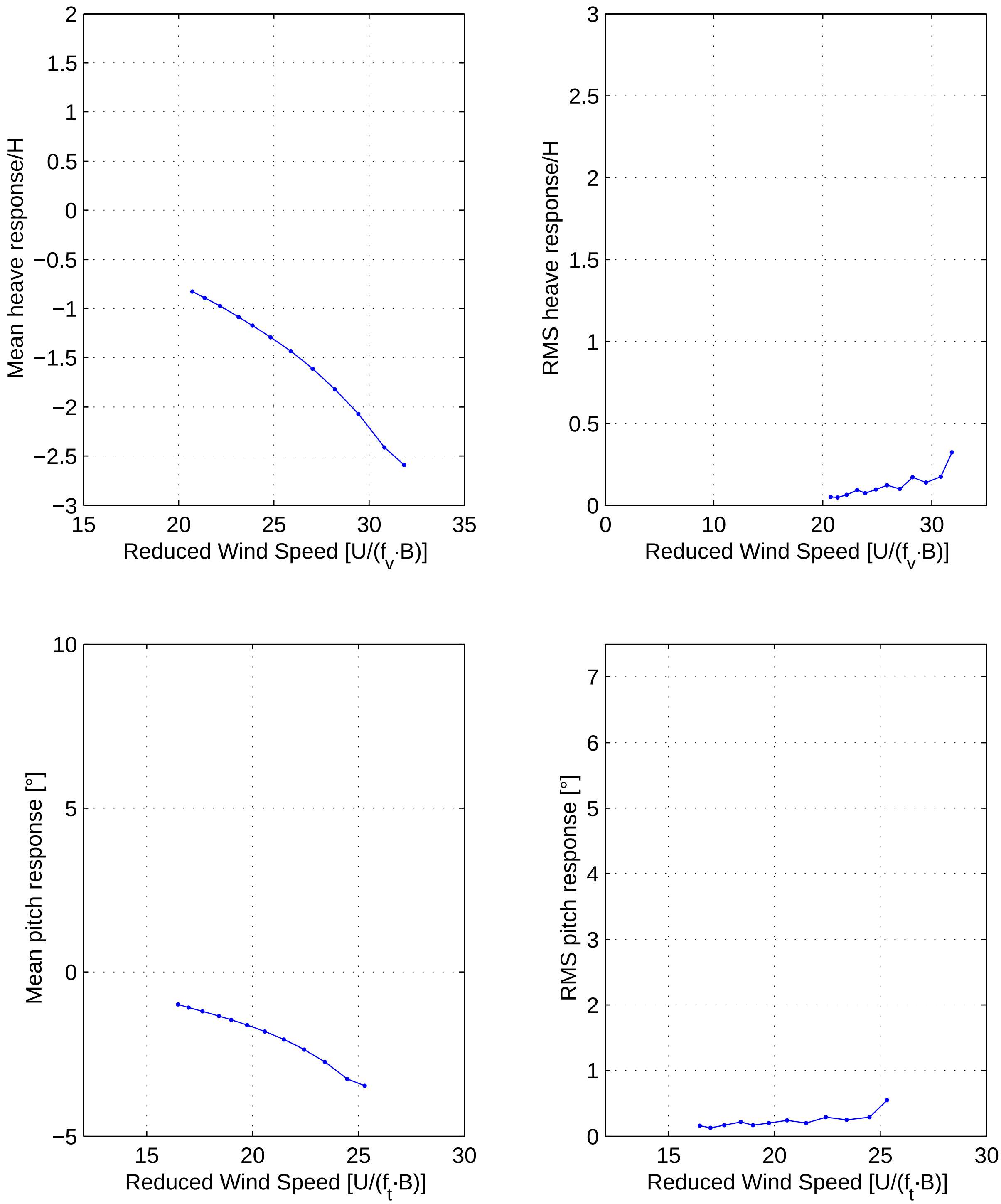
[3] "Static section model tests the Messina Strait Bridge"
FORCE 109-28238 rev. 1, 2010-01-13

[4] "Sub-Test 1 Section Model Tests for the Messina Strait Bridge"
FORCE 110-25465 rev. 1, 2010-06-25

[5] "Indicative Vortex-Shedding Tests, Static & Stability Tests for the Messina Strait Bridge"
FORCE 110-26444.02 rev. 1, 2010-12-07

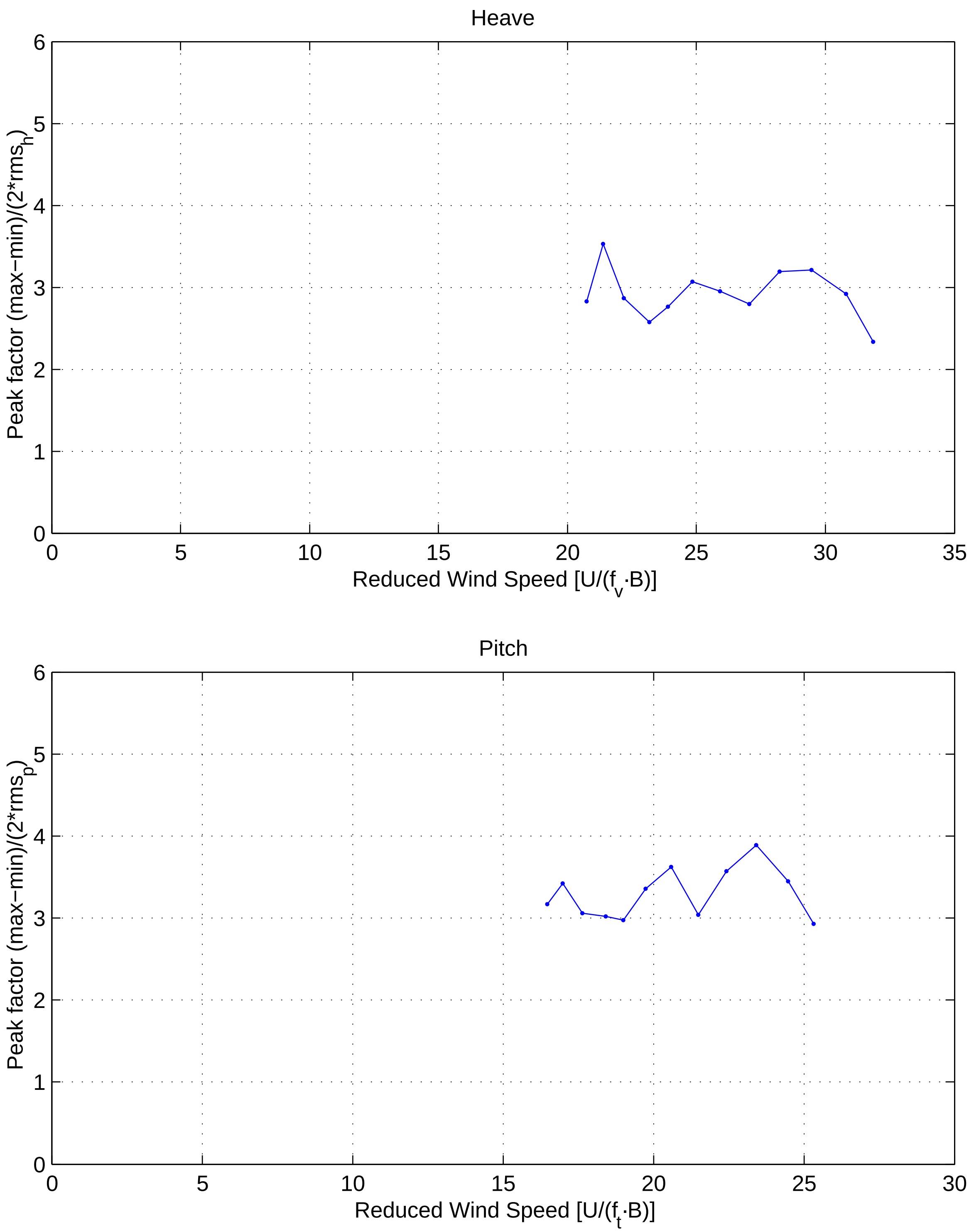
APPENDIX A

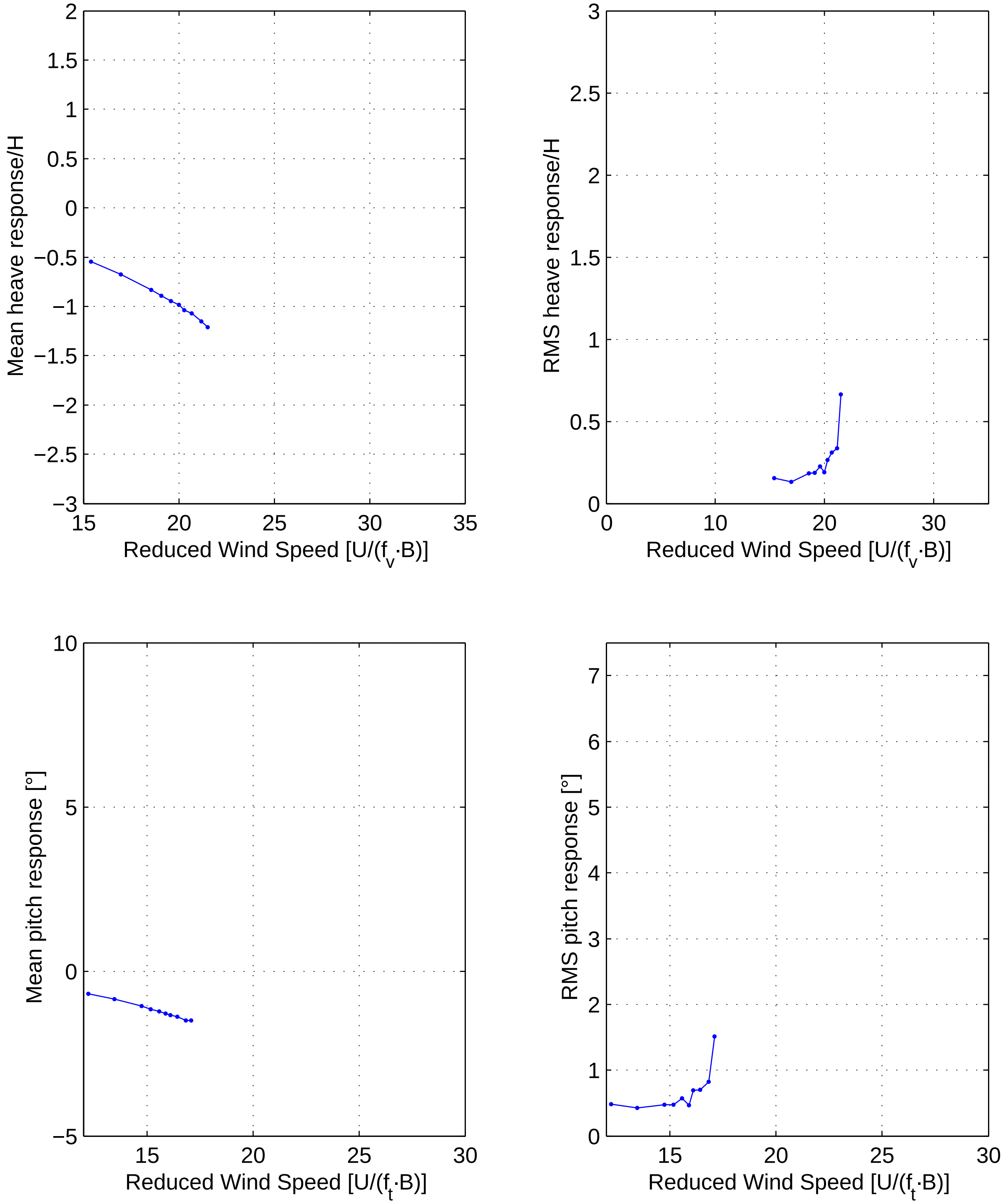
Stability Tests – Response Plots



110−26444 Messina Strait Bridge
16−Sep−2010 /svl, stab2.m
Mean and RMS Response

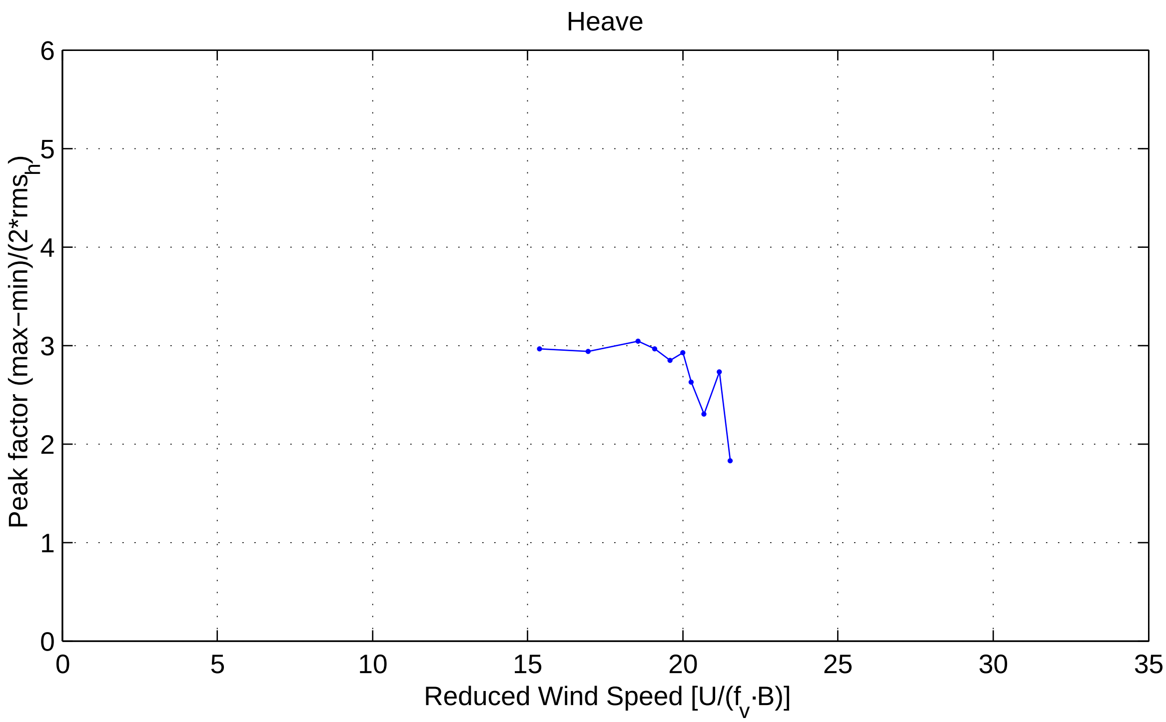
Stability Tests
Configuration C5 − 63° railway girder edge
Smooth flow, $\alpha = -4^{o}$


Heave
Peak factor (max−min)/(2*rms$_h$)
Reduced Wind Speed [U/(f$_v$·B)]
Pitch
Peak factor (max−min)/(2*rms$_p$)
Reduced Wind Speed [U/(f$_t$·B)]



110−26444 Messina Strait Bridge
16−Sep−2010 /svl, stab2.m
Mean and RMS Response

Stability Tests
Configuration C5 − 63° railway girder edge
Turbulent flow, $\alpha = -4°$


Heave
Peak factor (max−min)/(2*rms_h)
Reduced Wind Speed [U/(f_v·B)]
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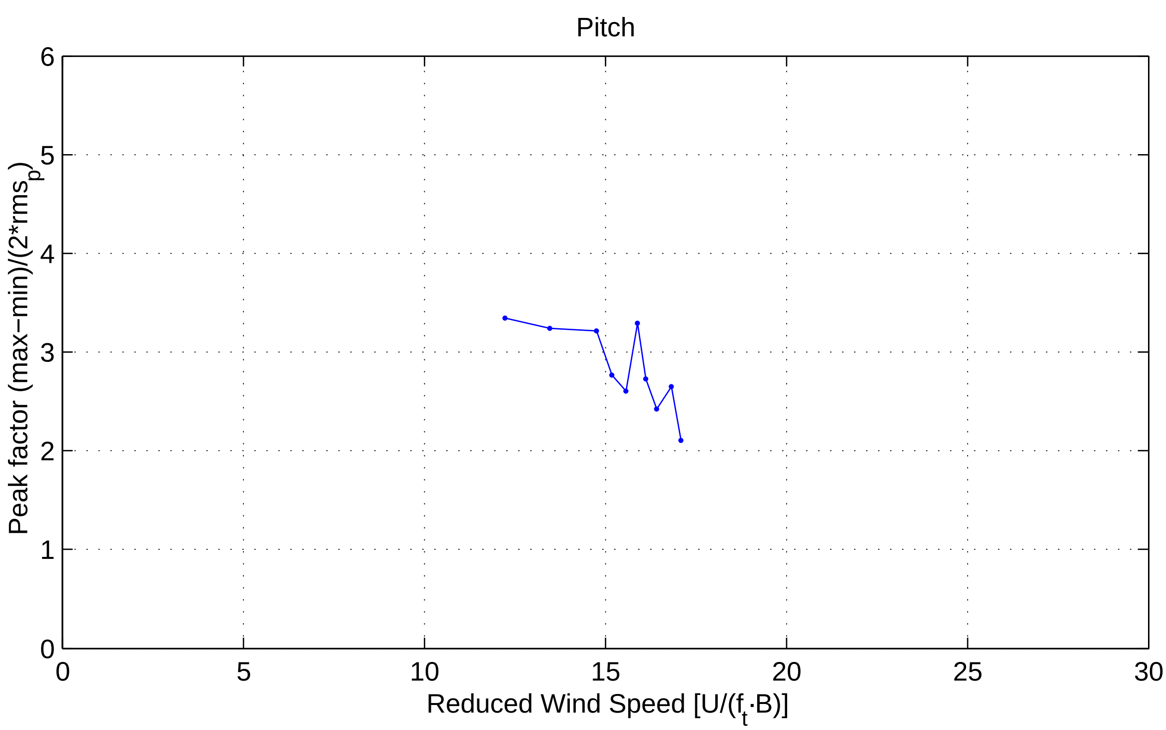
35


Pitch
Peak factor (max−min)/(2*rms_p)
Reduced Wind Speed [U/(f_t·B)]
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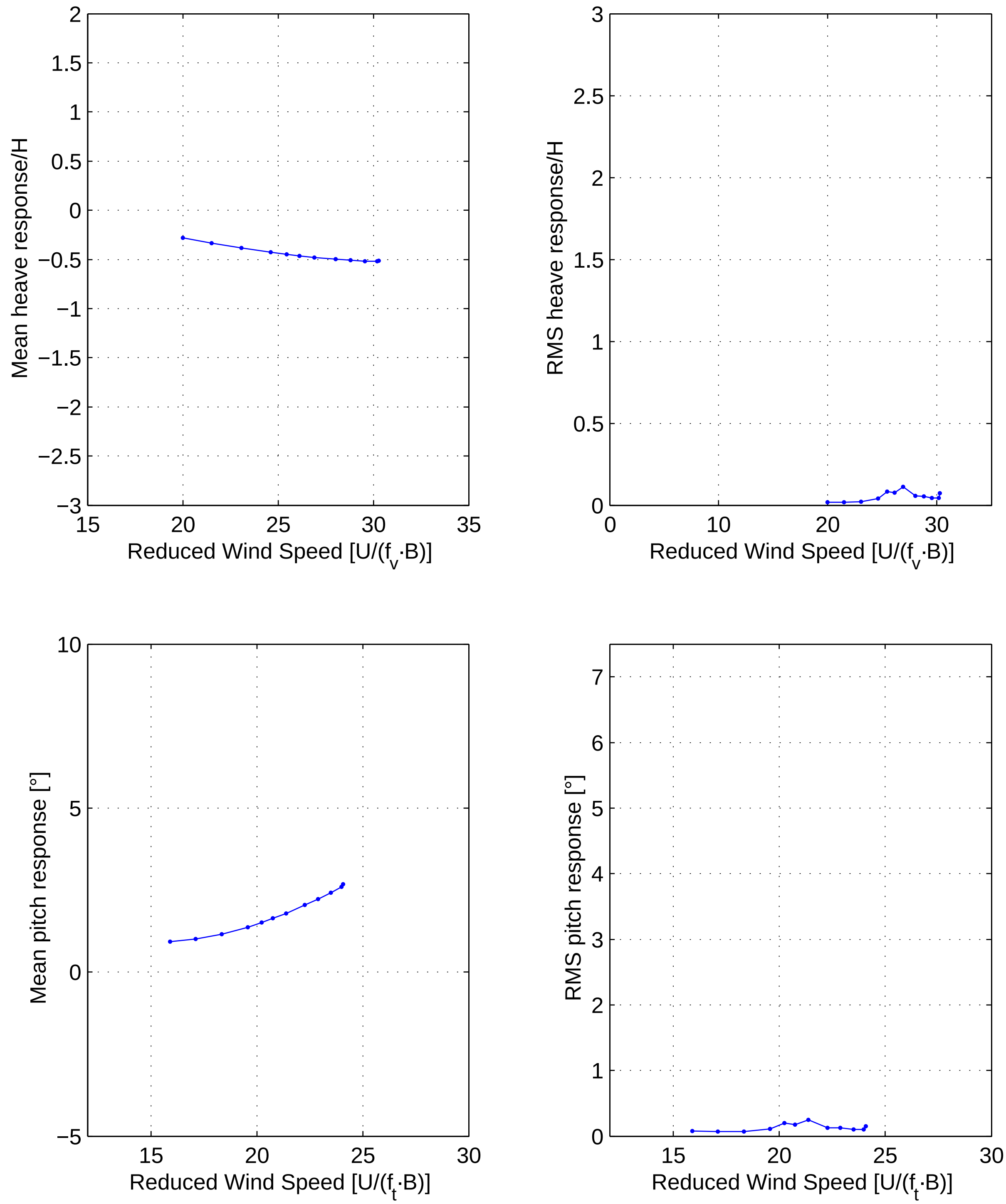

FORCE TECHNOLOGY

110−26444 Messina Strait Bridge
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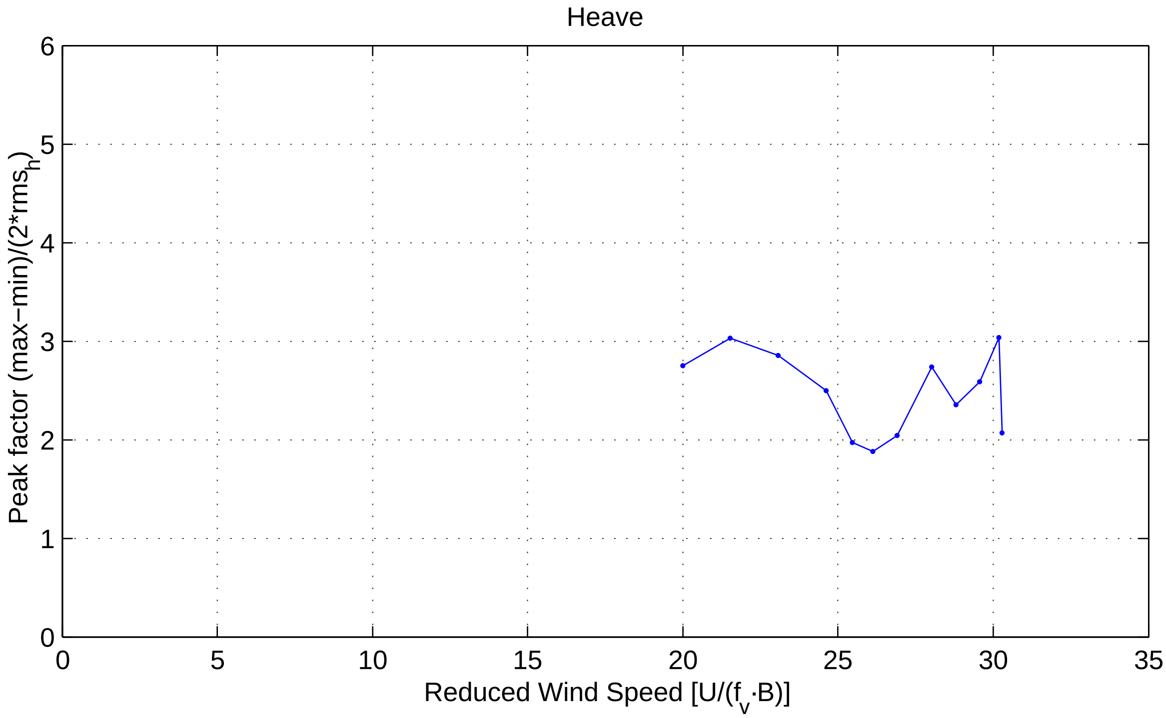
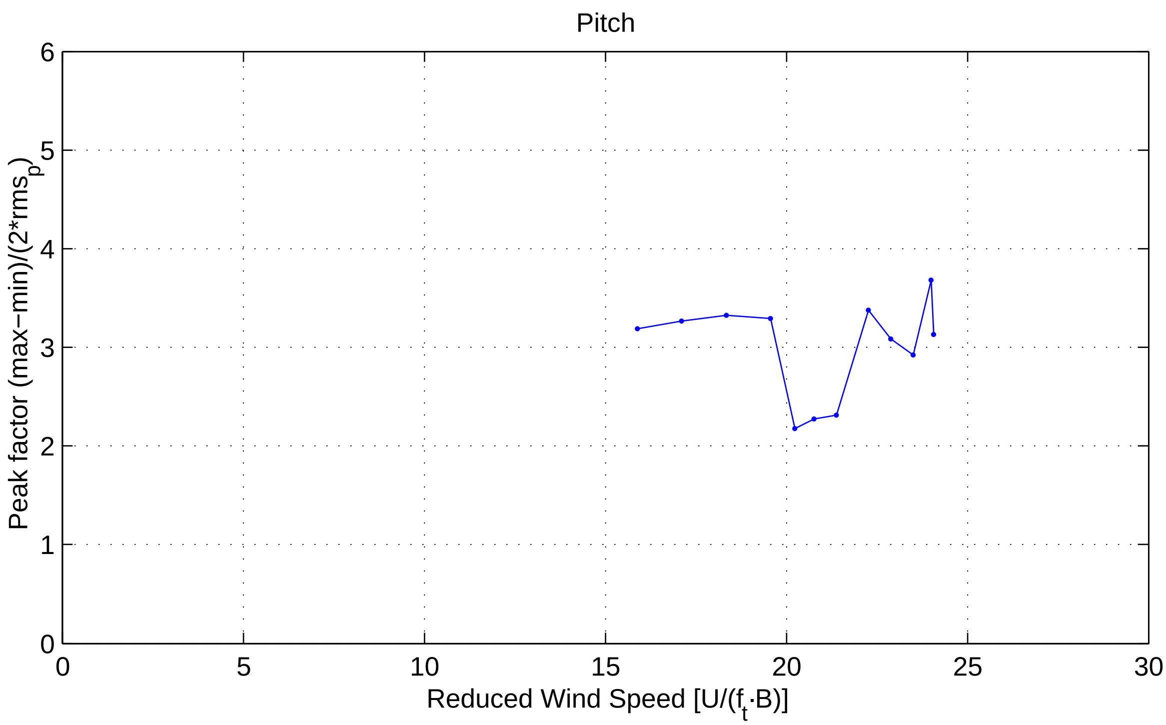
Mean and RMS Response

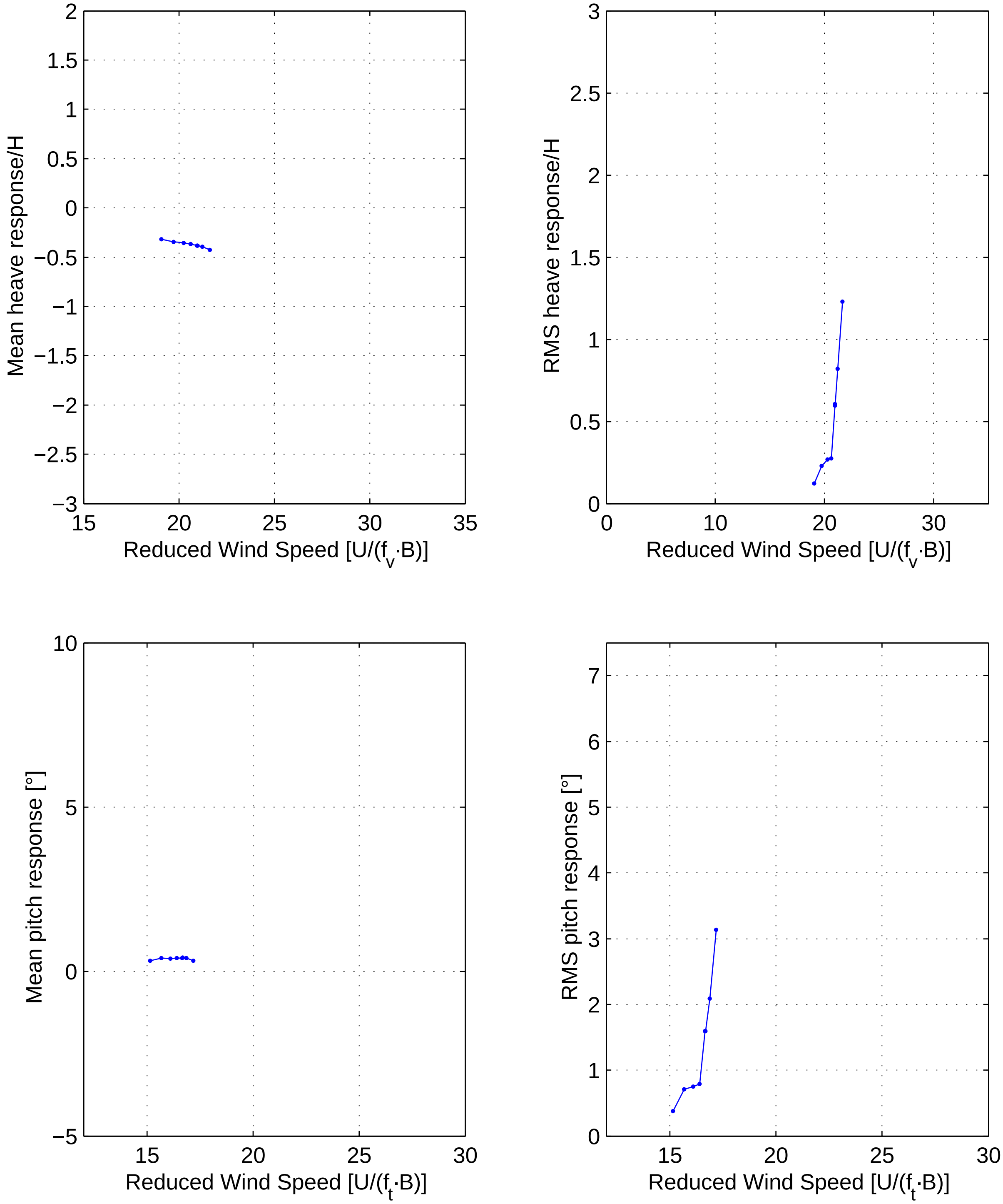
Stability Tests
Configuration C5 − 63° railway girder edge
Smooth flow, α = 0º

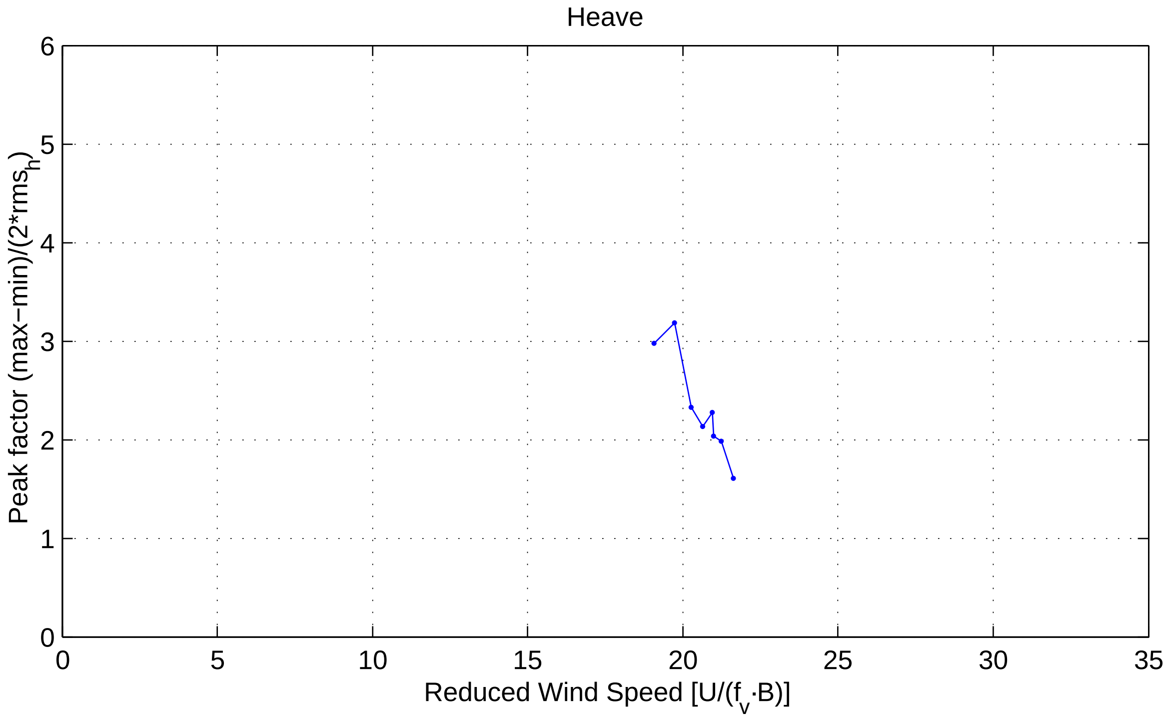


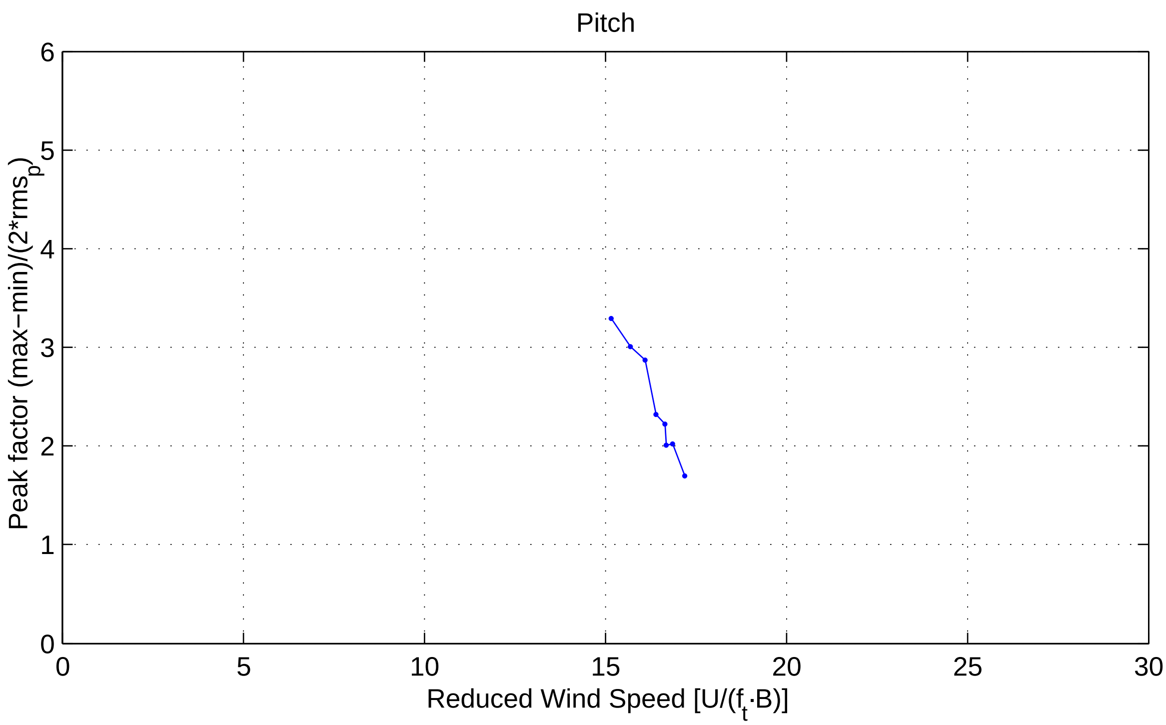
Heave
Peak factor (max−min)/(2*rms_h)
Reduced Wind Speed [U/(f_v·B)]
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35

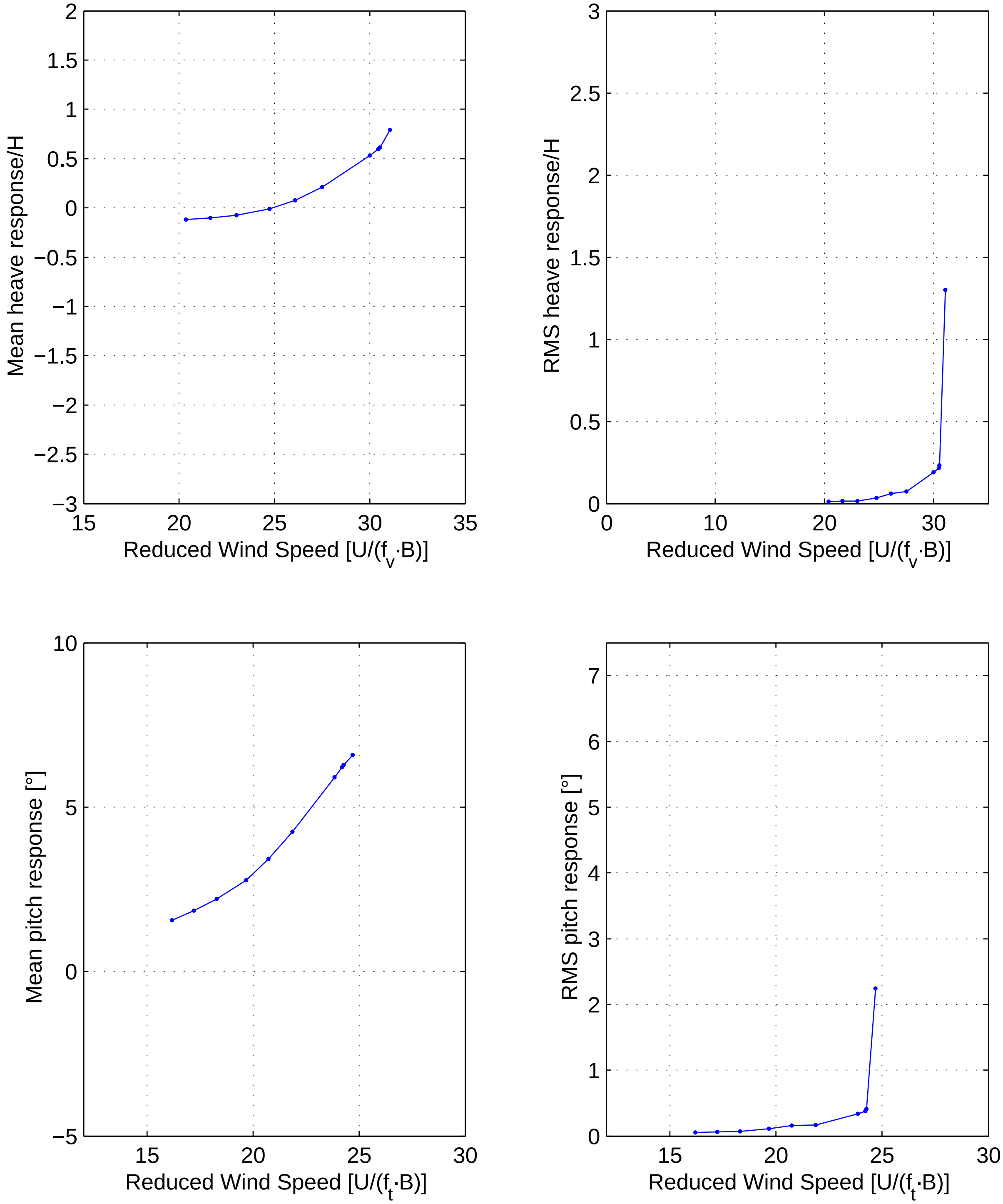


Pitch
Peak factor (max−min)/(2*rms_p)
Reduced Wind Speed [U/(f_t·B)]
0
1
2
3
4
5
6
0
5
10
15
20
25
30

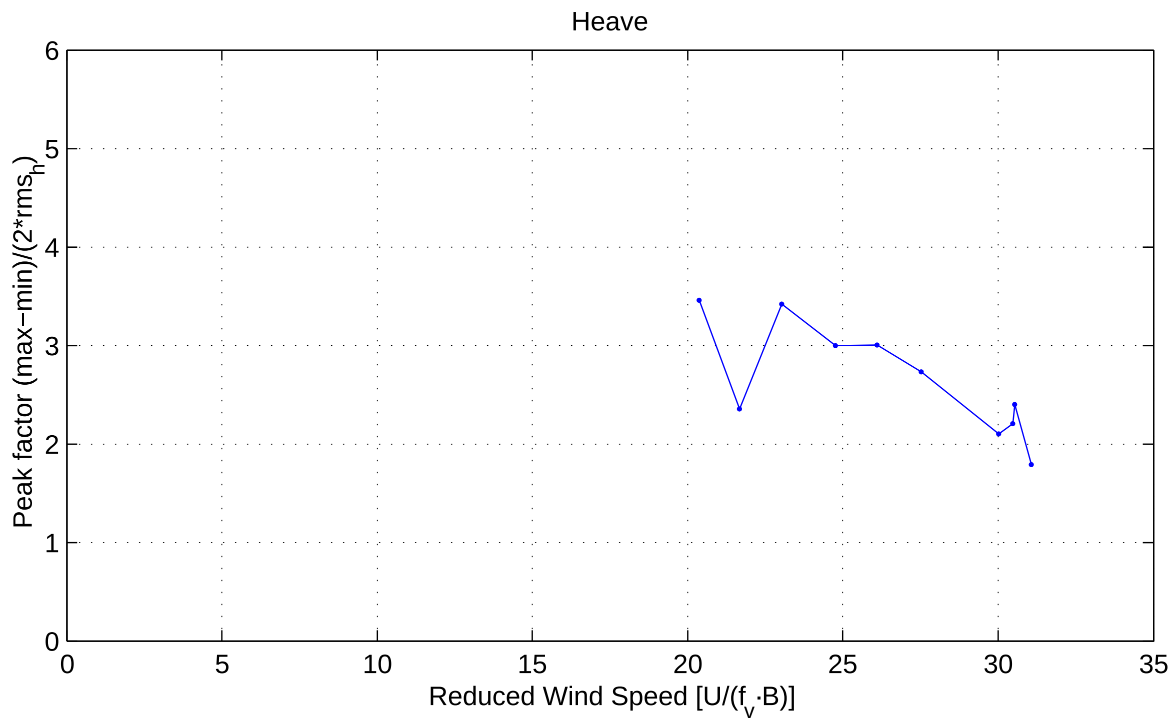

Mean heave response/H
Reduced Wind Speed [U/(f_v·B)]
RMS heave response/H
Reduced Wind Speed [U/(f_v·B)]
Mean pitch response [°]
Reduced Wind Speed [U/(f_t·B)]
RMS pitch response [°]
Reduced Wind Speed [U/(f_t·B)]


Heave
Peak factor (max−min)/(2*rms_h)
Reduced Wind Speed [U/(f_v·B)]

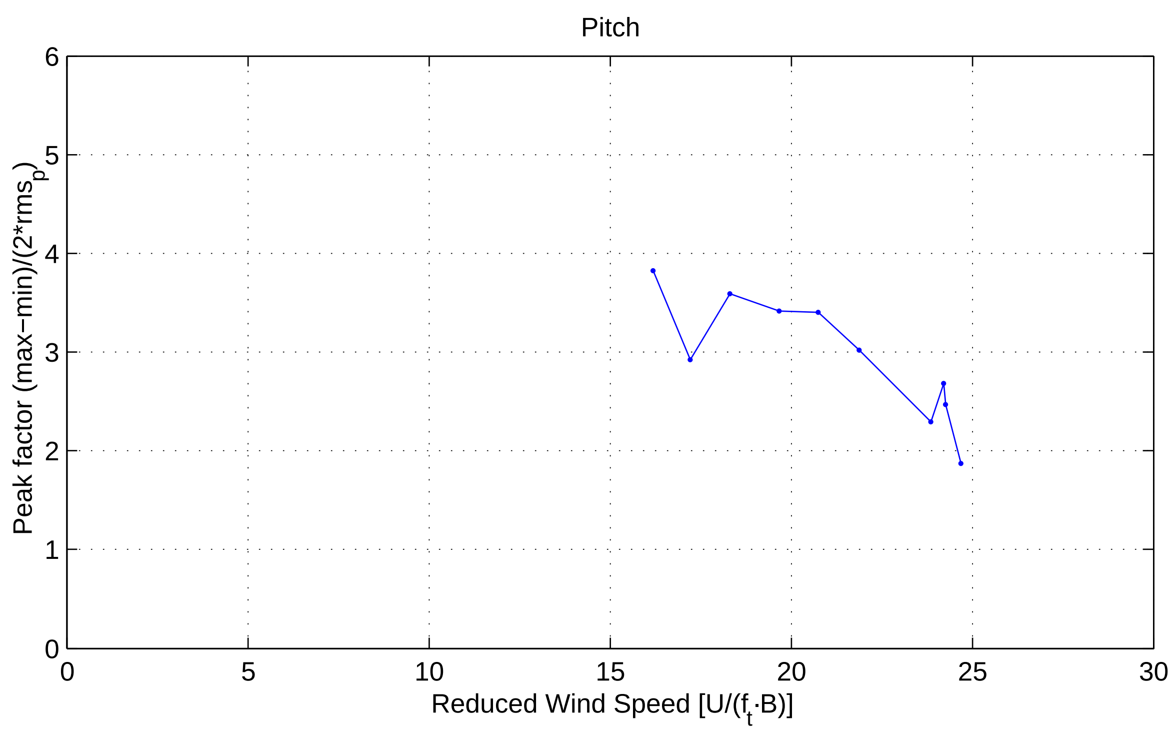

Pitch
Peak factor (max−min)/(2*rms_p)
Reduced Wind Speed [U/(f_t·B)]



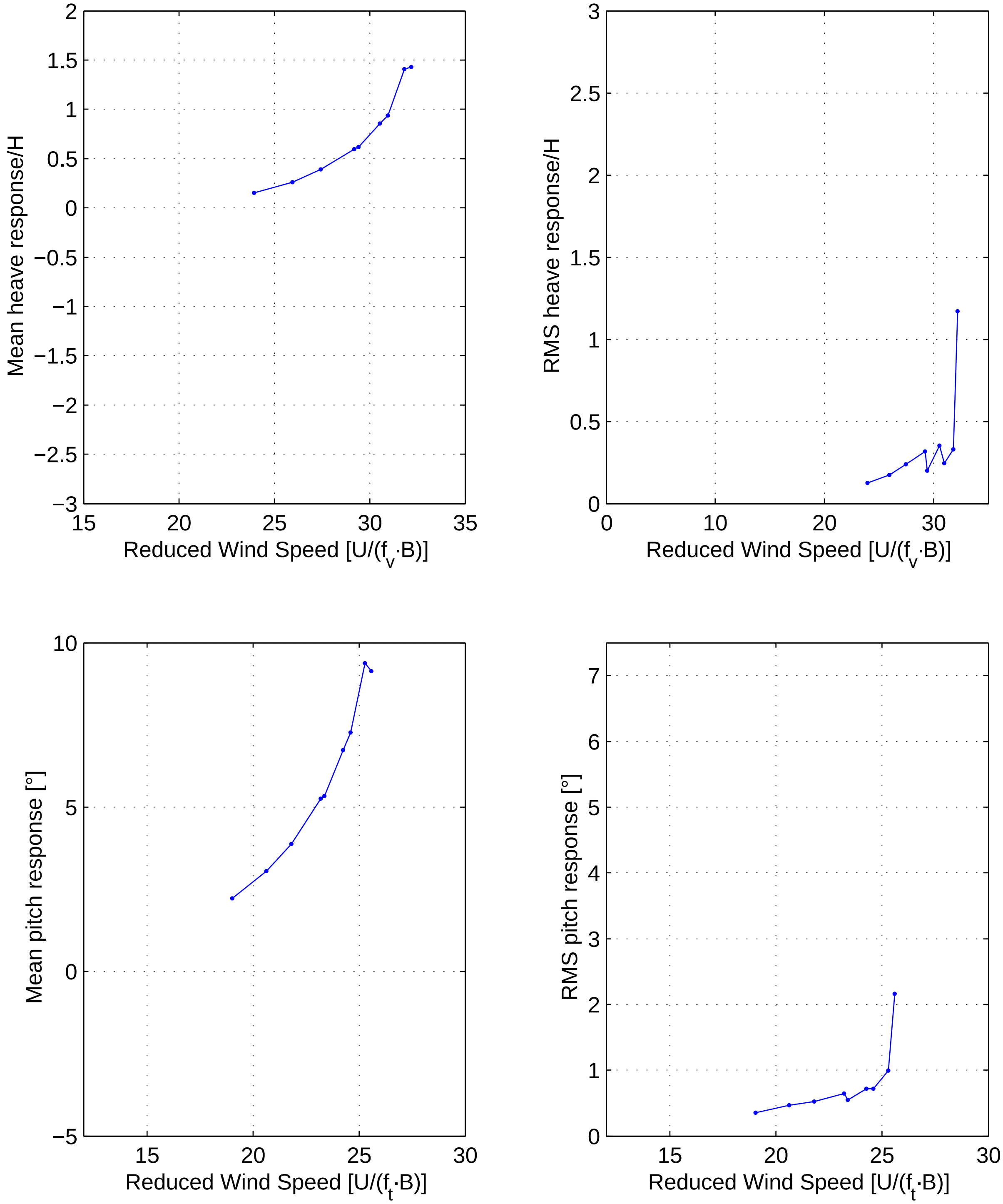
Mean heave response/H
Reduced Wind Speed [U/(f_v·B)]
RMS heave response/H
Reduced Wind Speed [U/(f_v·B)]
Mean pitch response [°]
Reduced Wind Speed [U/(f_t·B)]
RMS pitch response [°]
Reduced Wind Speed [U/(f_t·B)]



Heave
Peak factor (max−min)/(2*rms_h)
Reduced Wind Speed [U/(f_v·B)]



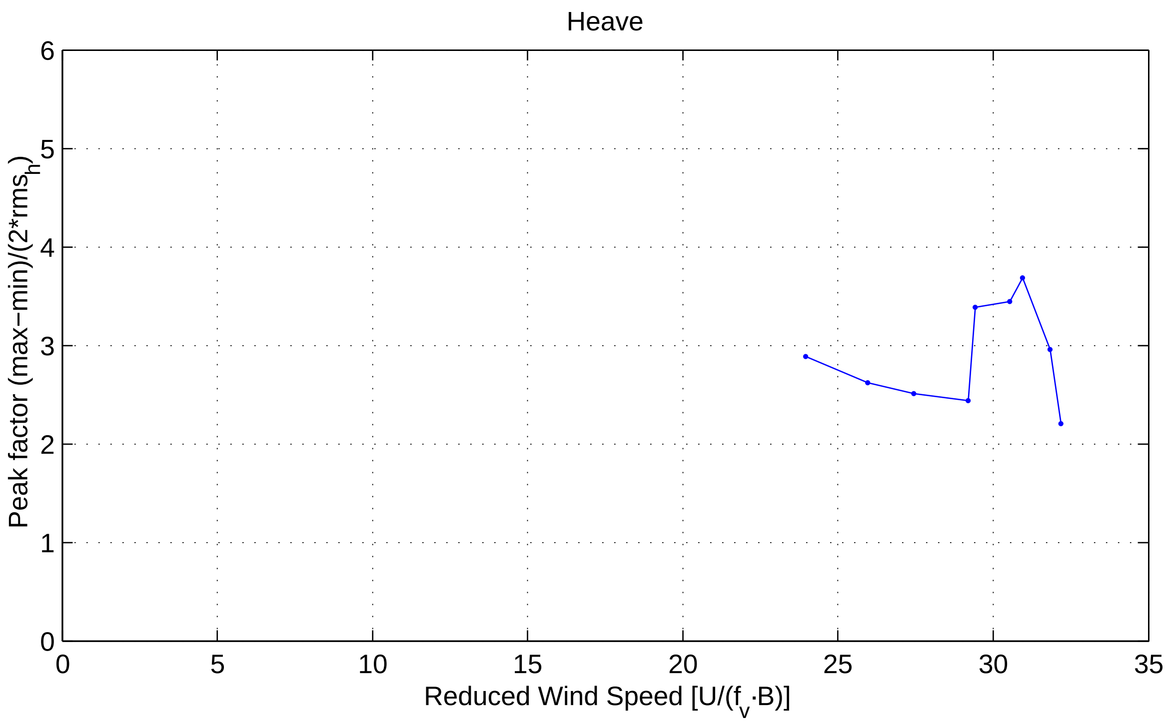
Pitch
Peak factor (max−min)/(2*rms_p)
Reduced Wind Speed [U/(f_t·B)]

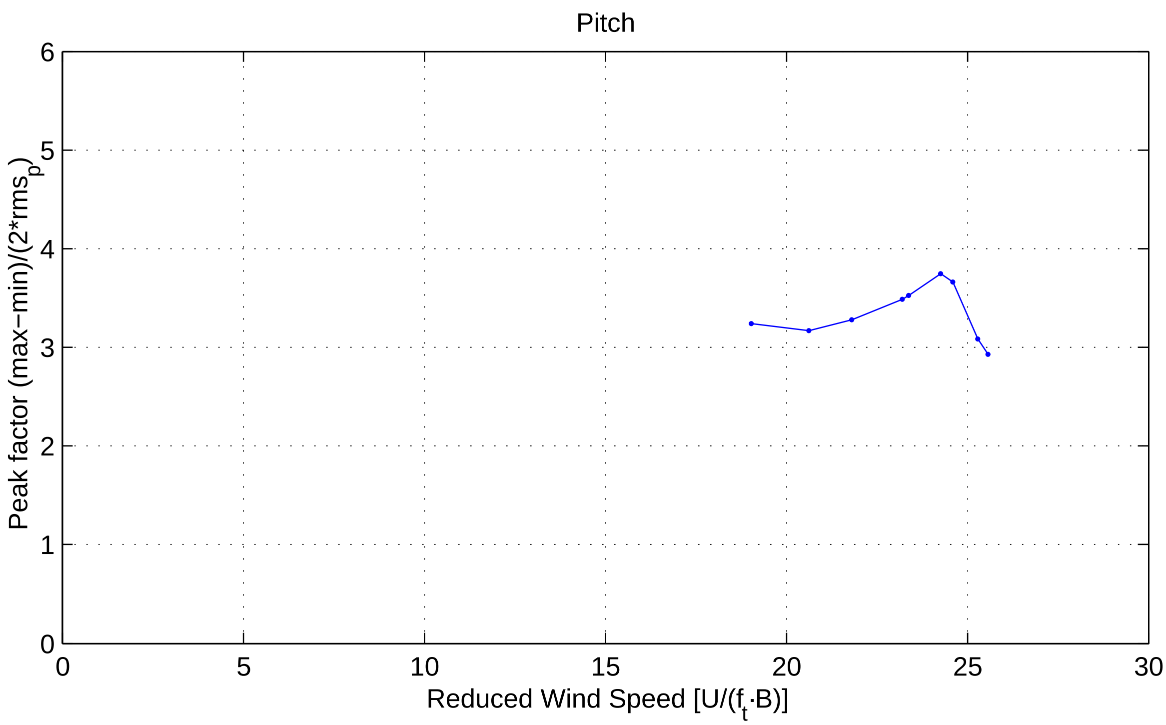


FORCE TECHNOLOGY

110−26444 Messina Strait Bridge
16−Sep−2010 /svl, stab2.m
Mean and RMS Response

Stability Tests
Configuration C5 − 63° railway girder edge
Turbulent flow, α = +4º


Heave
Peak factor (max−min)/(2*rms_h)
Reduced Wind Speed [U/(f_v·B)]
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35


Pitch
Peak factor (max−min)/(2*rms_p)
Reduced Wind Speed [U/(f_t·B)]
0
1
2
3
4
5
6
0
5
10
15
20
25
30

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