WIND LOADS ON FAN BLADES & BLADE DYNAMICS

Cofimco S.r.l.

Axial fans for the world

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Summary

1. Purpose of the document
2. Introduction
3. Loads
4. Dynamics
5. Load mitigation
6. Conclusions

Purpose of the document

Purpose of the document

The main scope of this document is to study the loads acting on the blades with and without wind and the related blade response. Three different conditions have been studied :

a) Wind Speed (WS) = 0
b) WS = 25 m/s (≈ 60 mph), constant
c) WS = 25 m/s, constant with wind screen

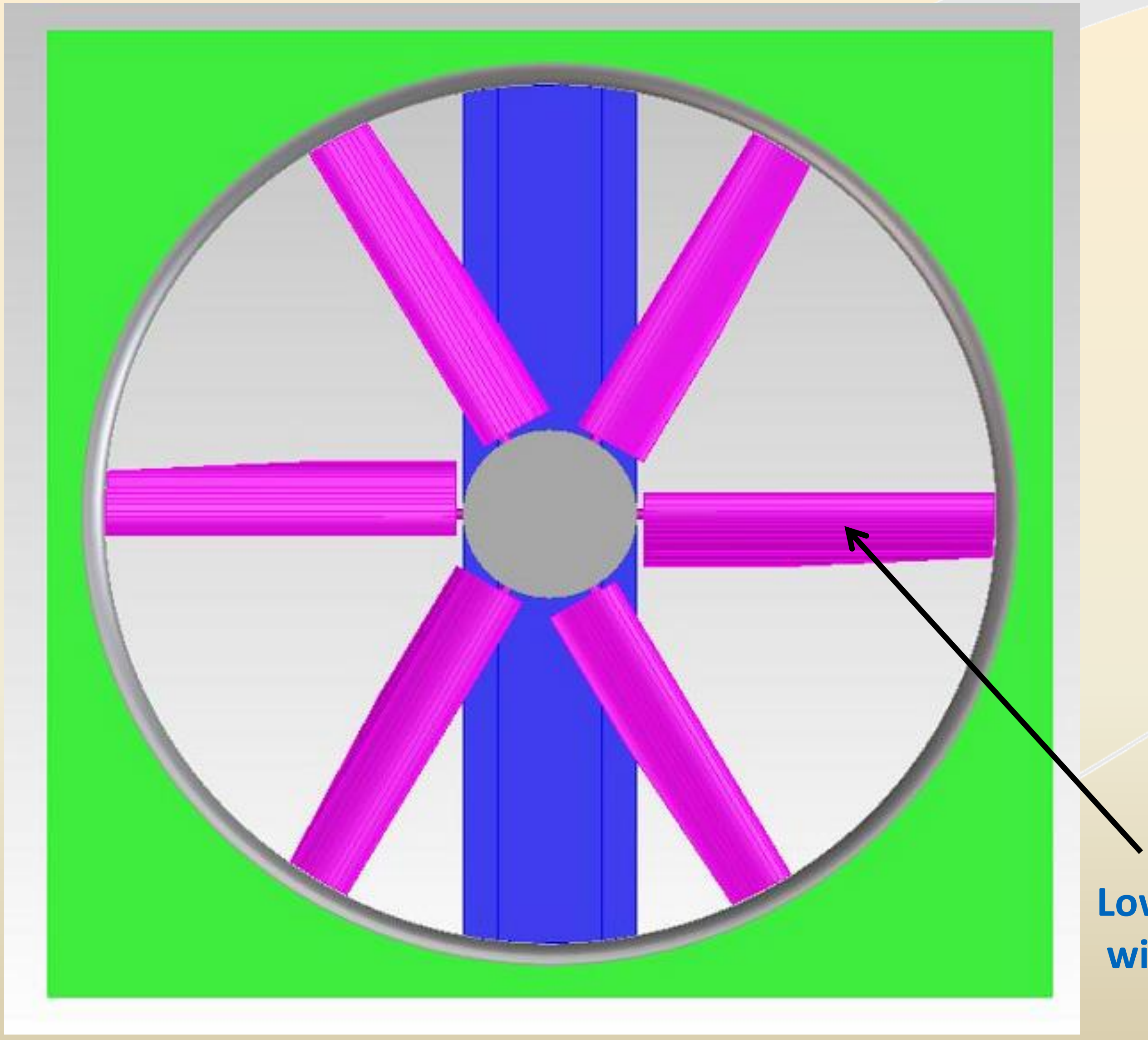
Nomenclature:

WS: Wind speed
BNF: Blade Natural Frequency
BOF: Blade Operative Frequency
BPF: Blade Passing Frequency
LF: Load Frequency
LP: Load Period
CPM: Cycles per Minute
AoA: Angle of Attack

CPS: Cycles per second
RPM: Revolution per minute
RBM, BM: Root Bending Moment
SH: Shear (Vertical load)
RT: Revolution period
Vy: Axial component of the flow speed
Fy: Axial component of the load on blades
NL: Nominal Load (Fy)

Introduction

Introduction (1): Fan & blades features



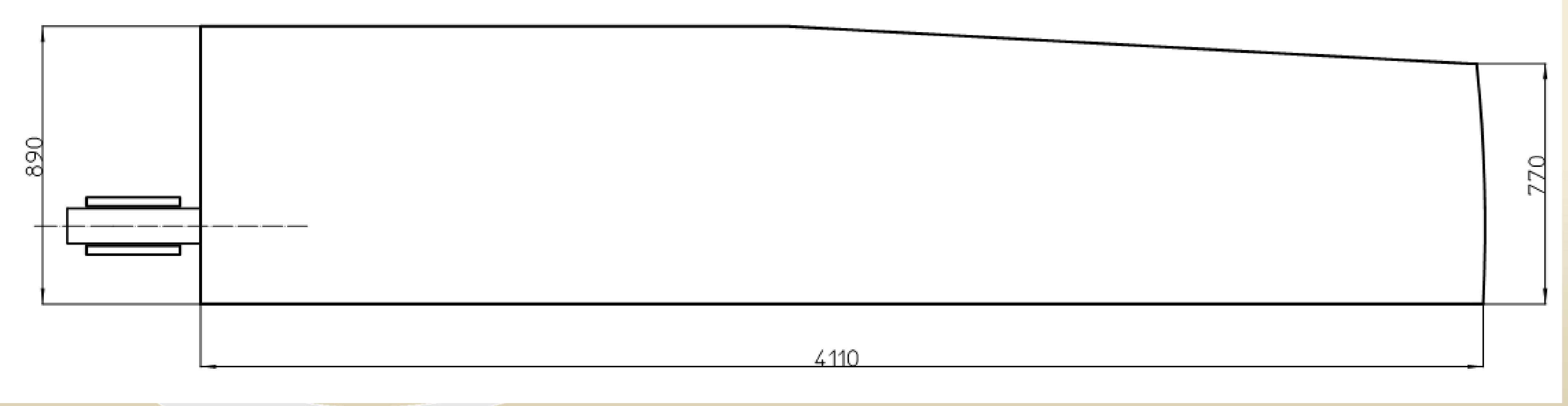
Low blade count,
wide chord (blade A)

The studied fan has the following features:

-Single cell	
-Diameter	34 ft (10363 mm)
-Hub diameter	≈ 7 ft (2000 mm)
-RPM	120 (2 cps)
-Nominal power:	≈ 160 KW (217 HP)

Introduction (2): Blade Features

The fan blades A have the following properties:	Blade A
Chord at root, mm	890 (2.9 ft)
Chord at tip, mm	770 (2.5 ft)
Blade Mass, Kg	112.6 (248 lbs)
Blade count	6
BOF mode1 & mode 2, Hz	6.7 – 39.5
Main features	Heavy, stiff, high BOF



Introduction (3): Study Approach

The study has been conducted by means of CFD (X_FLOW) simulation with the following approach:

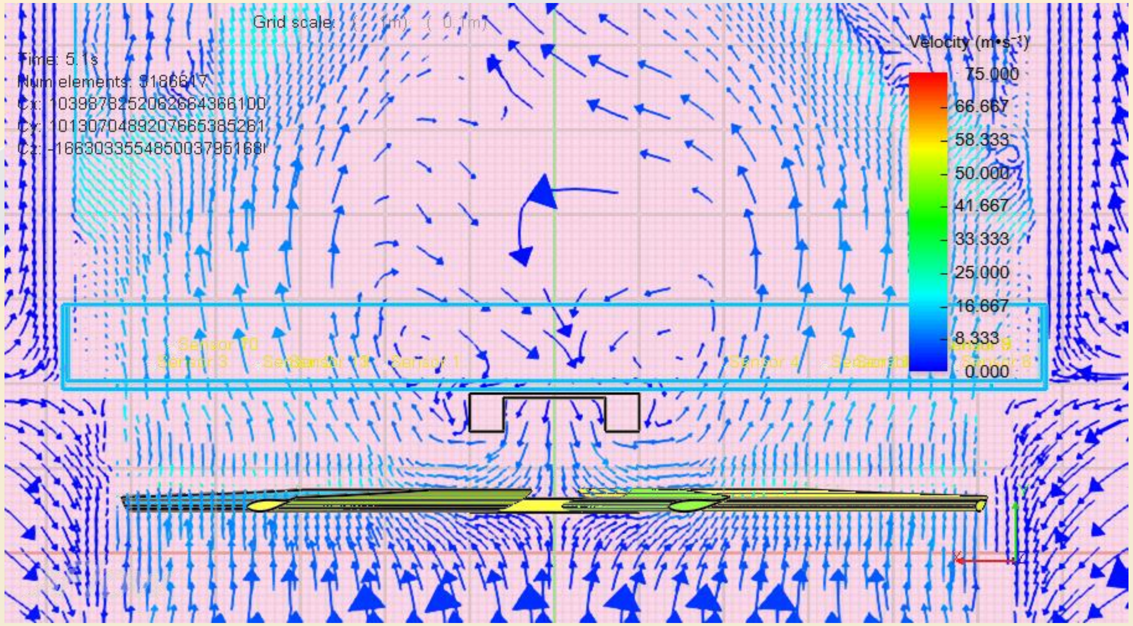
Phase 1 – Blade A: load and blade response	
Step 1a →	Load definition and response calculation @ WS = 0 & WS = 25 m/s
Step 1b →	Evaluation of the loads transmitted to the bridge for both WS = 0 & WS = 25 m/s

Phase 2 - Mitigation of the loads acting on the bridge	
Step 2a →	Blade A + Wind Screen
Load definition and response calculation @ WS = 25 m/s	
Step 2b →	Blade's Chord Reduction and Count Increase: Blade B1
Load definition and response calculation @ WS = 25 m/s, no Wind Screen	
Step 2c →	Blade's Chord Reduction, Count Increase, BOF Reduction and friction-damper: Blade B2
Load definition and response calculation @ WS = 25 m/s, no Wind Screen	

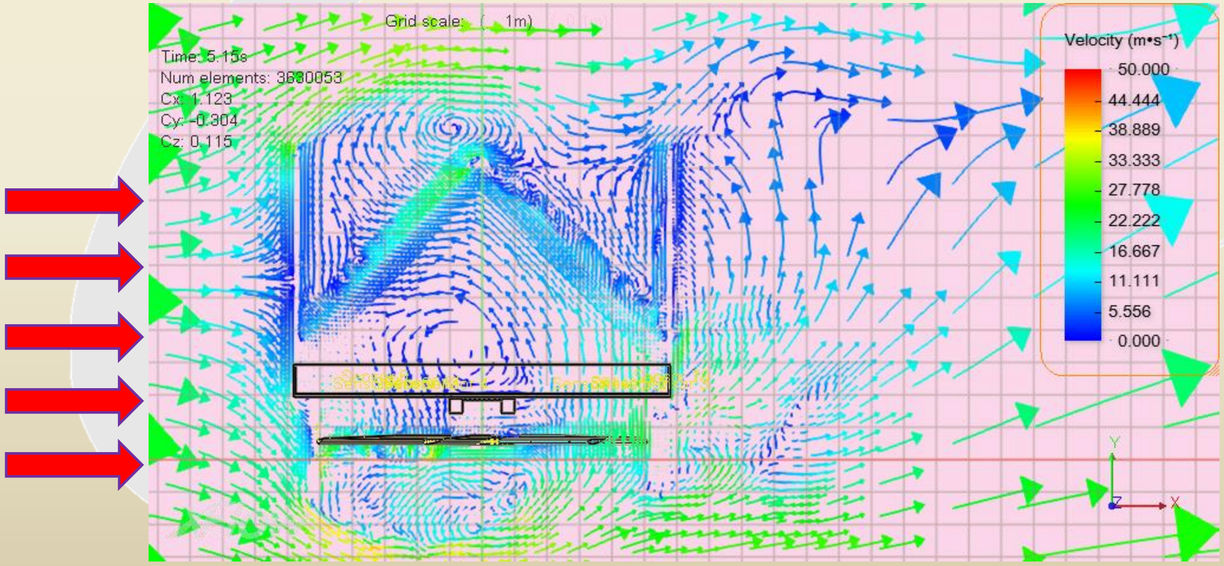
Loads

Loads (1): Blade A case studies

Two cases have been considered:



<u>First Case Study</u>:
WS=0

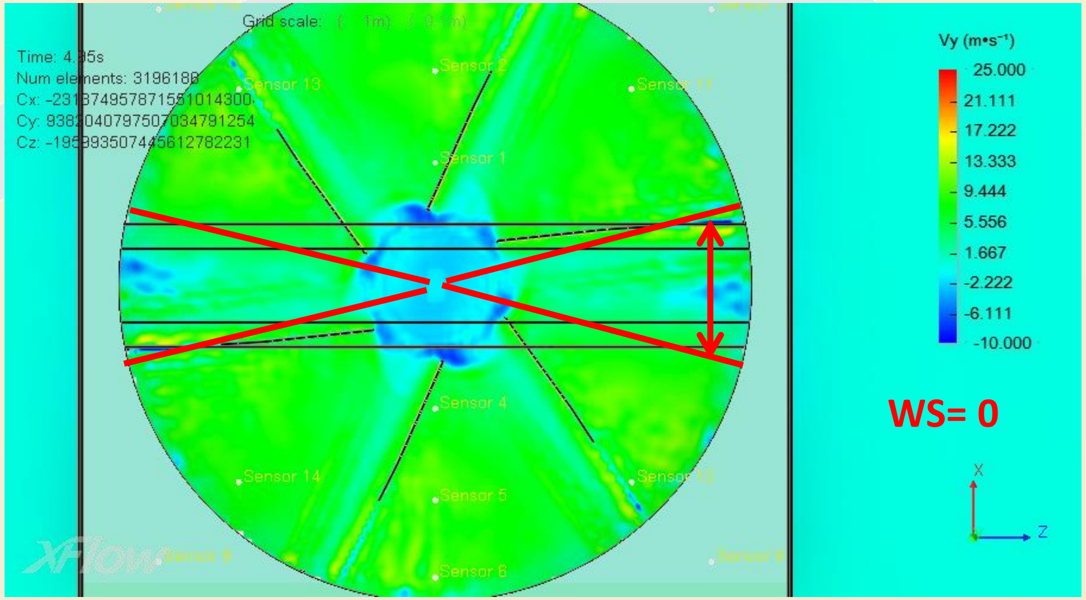


<u>Second Case Study</u>:
WS = 25 m/s – no wind screens
Wind direction perpendicular to the bridge
(25 m/s ≈ 60 mph)

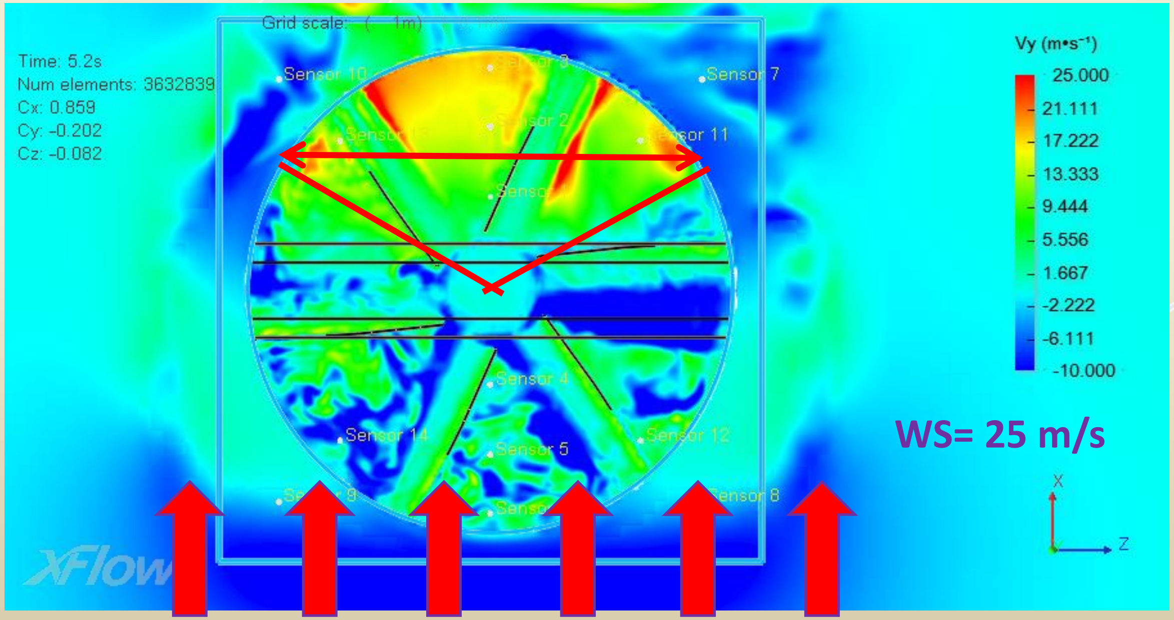
Loads (2): Flow Perturbations

The two case studies showed some interesting differences. Among them, the most relevant are:

- Load Dynamic component amplitude
- Number of pulses per round
- Width (duration) of the pulses
- Load spectra
- Load pattern regularity



First case study: WS = 0

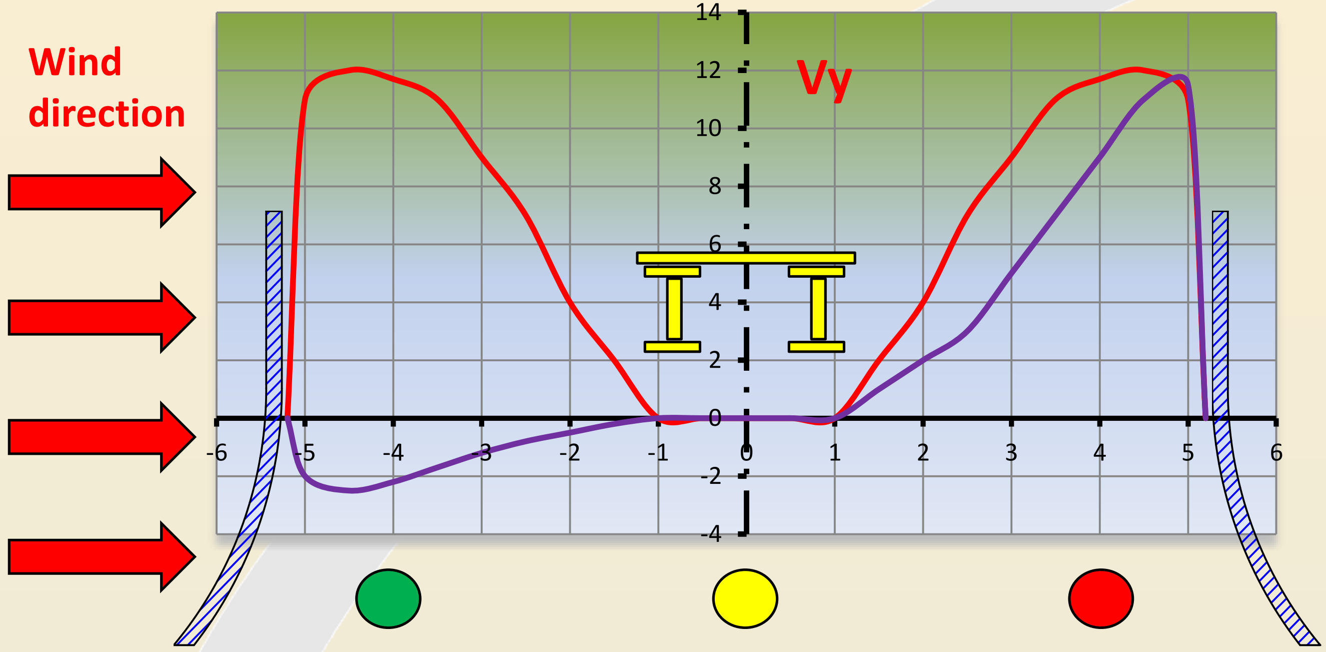


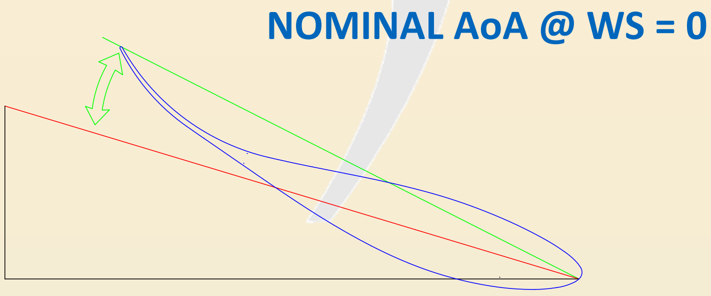
Second case study: WS = 25 m/s

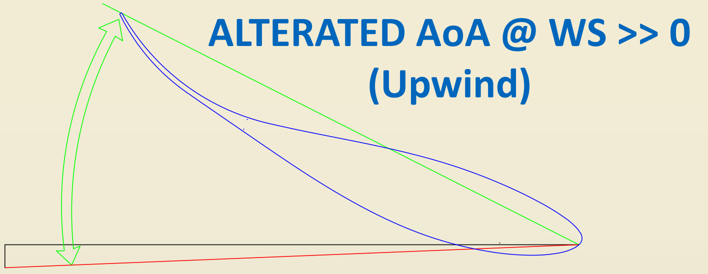
Loads (3): Angle of Attack (AoA)

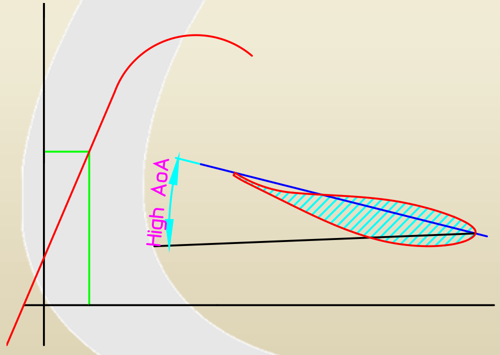
The ratio between the flow axial speed Vy and the blade speed defines the actual Angle of Attack (AoA).

Wind direction

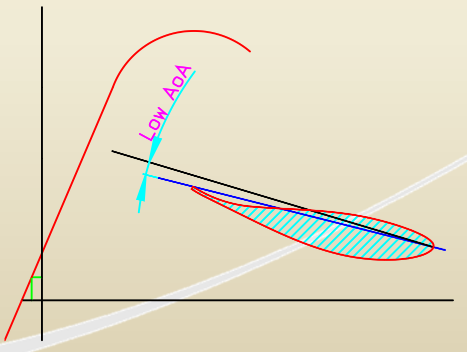








High AoA (upwind)

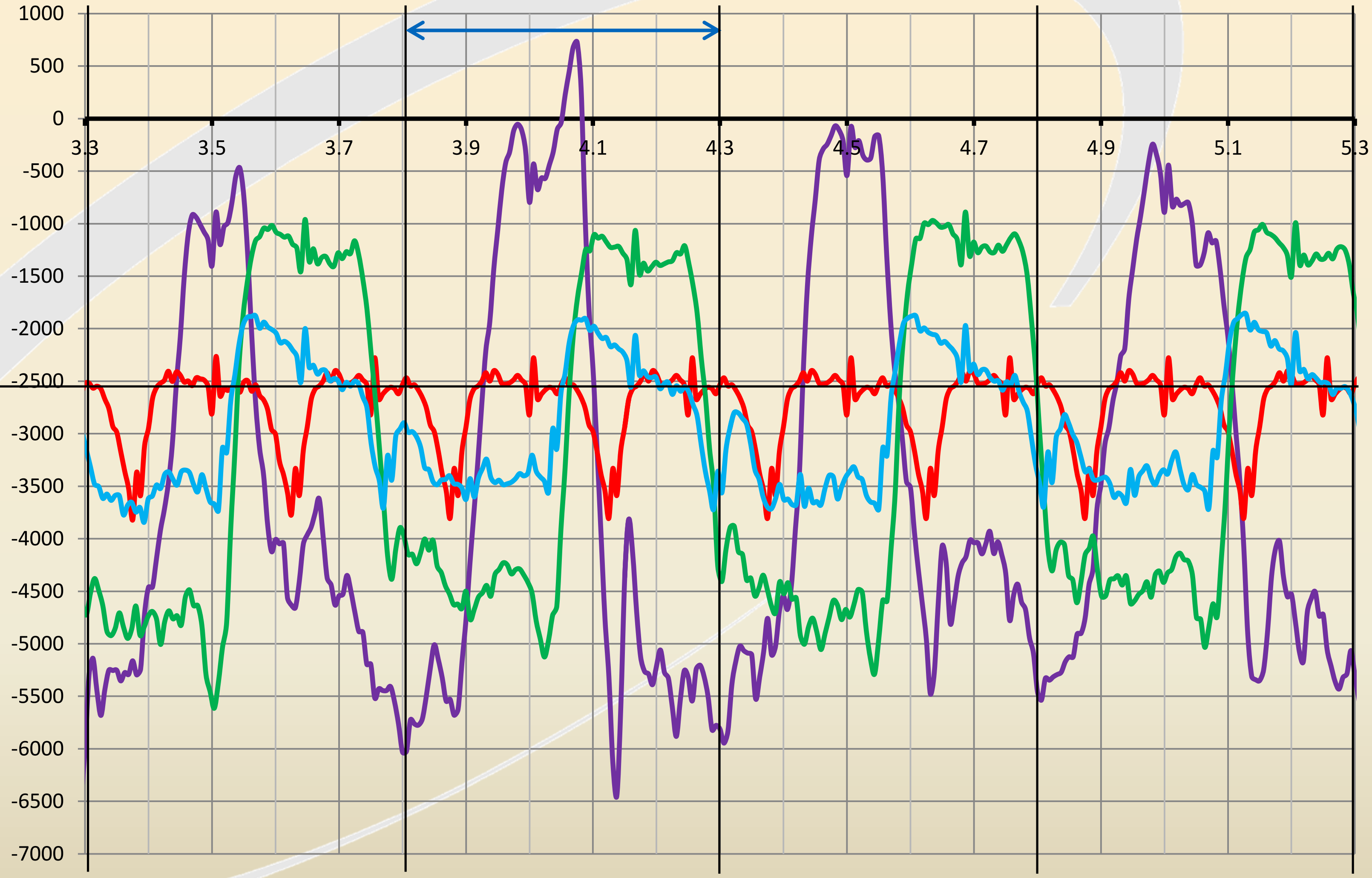


Low AoA (downwind)

The higher the WS, the higher the AoA fluctuation with the blade position around the fan and the load variation

Loads (4): Blade A @ 120 RPM

Revolution time @ 120 RPM = 0.5 s



Design Load: -2550 N

Vertical load, N
time history @
WS = 0,
WS = 7.5 m/s ≈ 17 mph
WS = 15 m/s ≈ 33 mph
WS = 25 m/s ≈ 60mph

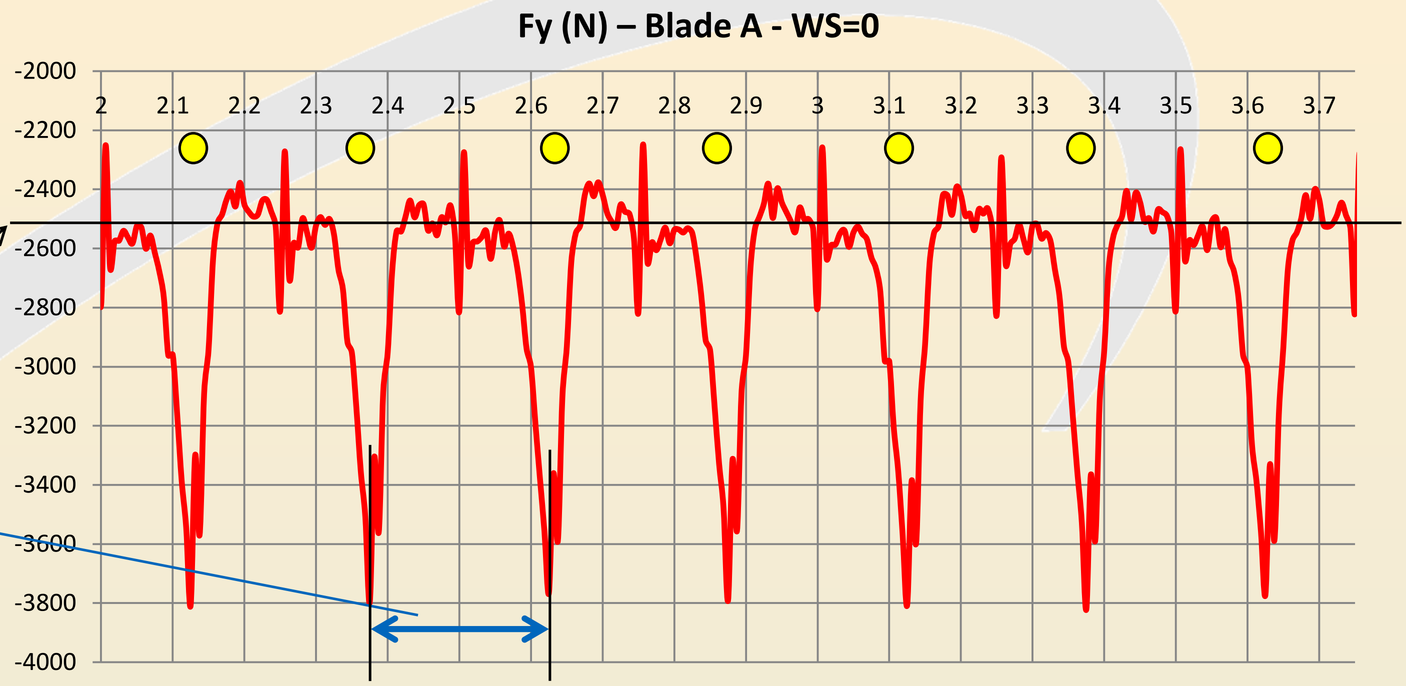
Loads are shifted in time for a better view

Loads (5): Blade A @ WS = 0

At the design speed (120 RPM - 2 CPS), we have:
Revolution Period (RT) = 0.5 s
Load Period (LP) = 0.25 s

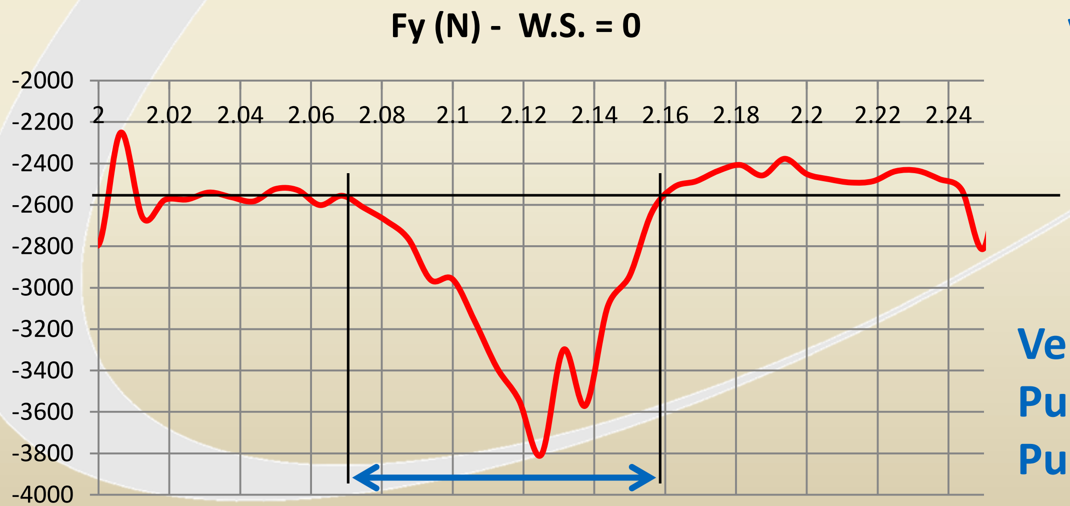
Static Load: 2550 N

LP: 0.25 s
LF: 4 Hz – 240 CPM - (2X)



Vertical load, time history, WS = 0

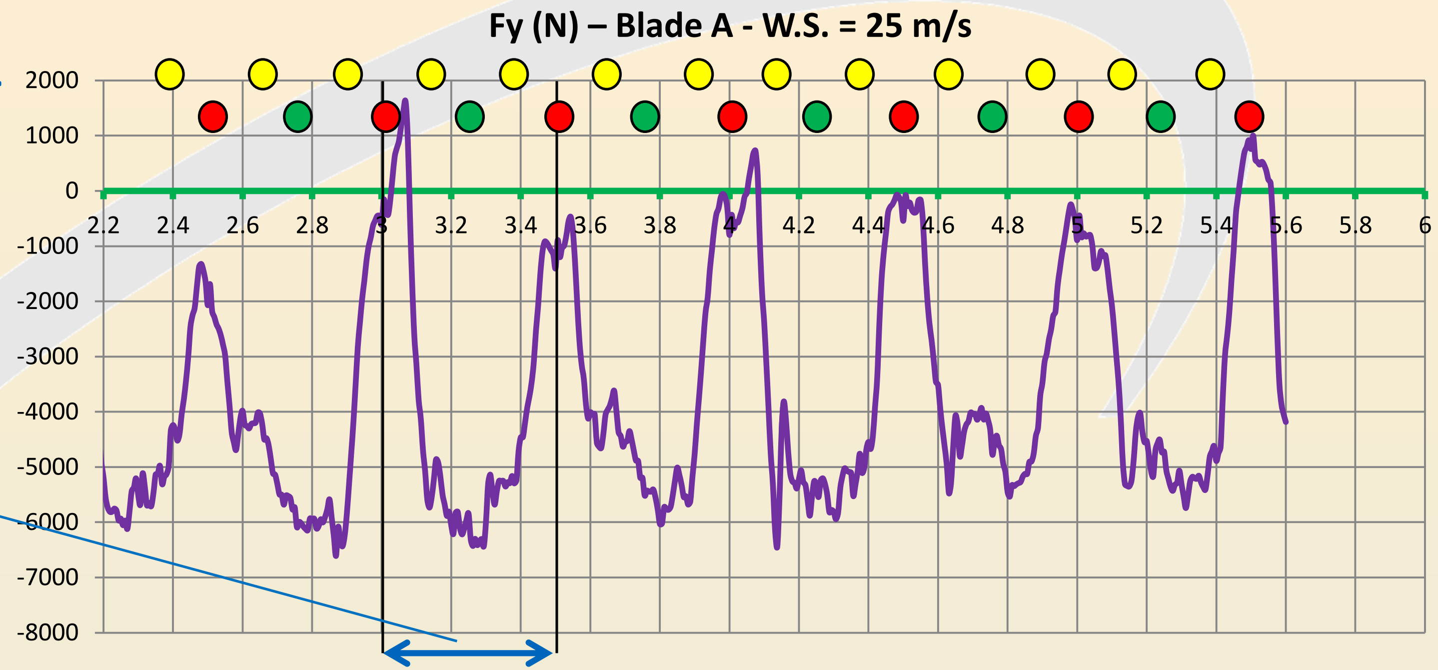
Blade under the Bridge



Vertical load - Pulse detail:
Pulse duration: 0.09 s
Pulse intensity: 1250 N

Loads (6): Blade A @ WS=25

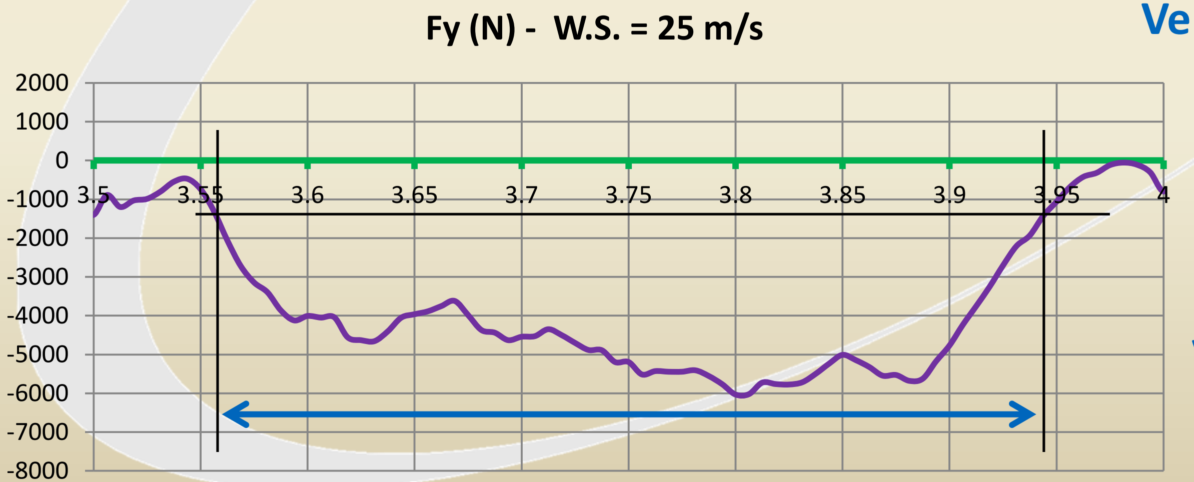
At the design speed (120 RPM - 2 CPS), we have:
Revolution Period (RT) = 0.5 s
Load Period (LP) = 0.5 s



LP: 0.5 s
LF: 2 Hz – 120 cpm - (1X)

Vertical load, time history, WS = 25

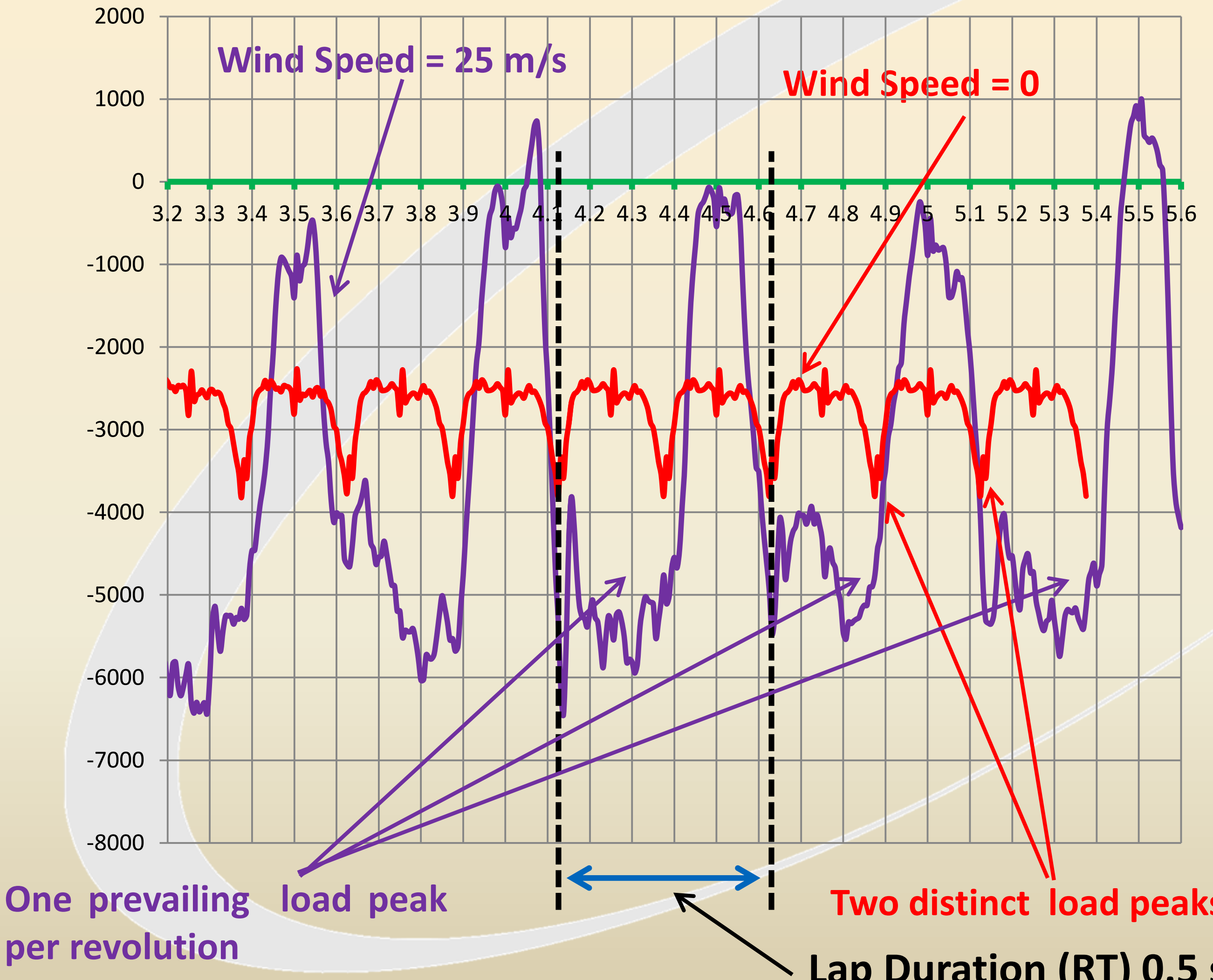
Blade under the Bridge (yellow)
Blade Upwind (green)
Blade Downwind (red)



Vertical load – Pulse detail:
Pulse duration: 0.38 s
Pulse intensity: 3450 N

Loads (7): Blade A - Loads comparison

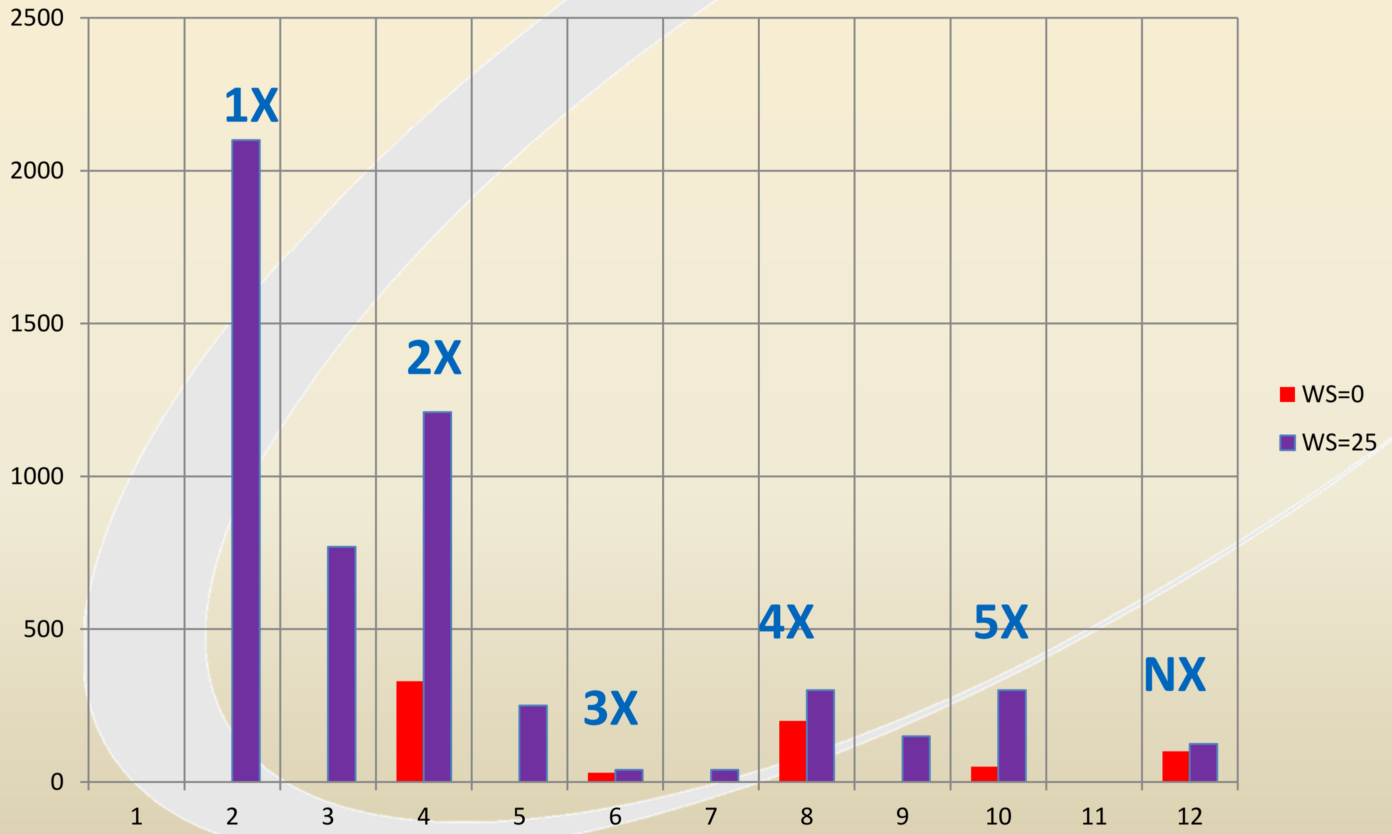
Vertical load, comparison: WS=0 m/s vs WS=25 m/s



Fan speed:
120 RPM, 2 CPS, RT=0.5 s

Loads (8): Blade A - Loads spectra

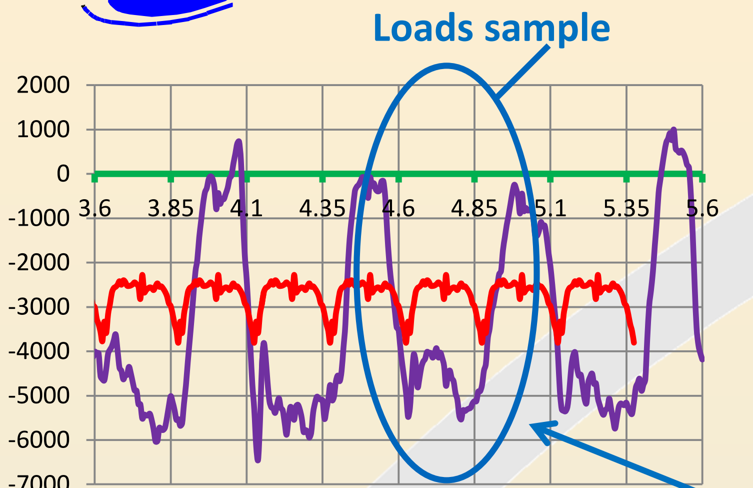
As a consequence, the load spectra have different shapes and significant components
(only the dynamic components are shown)



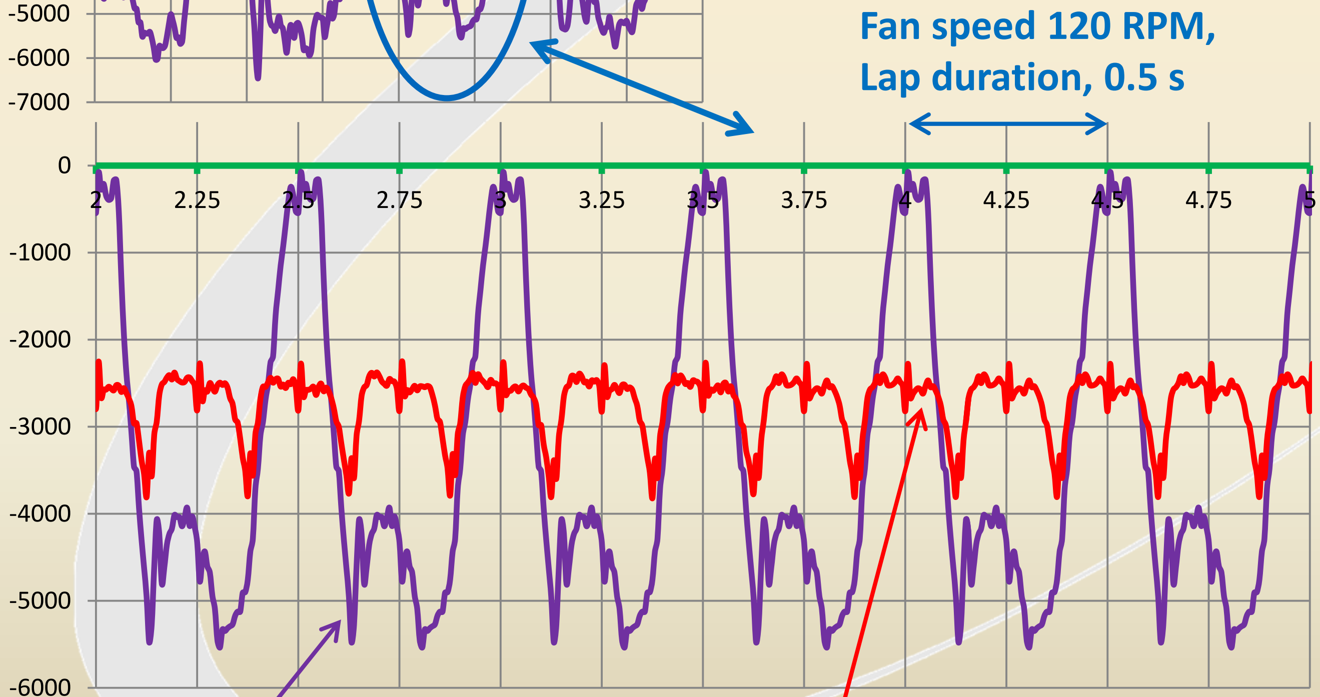
WS = 0 m/s
Vertical load spectrum
The 2 peaks/revolution are evidenced by the 2X load

WS = 25 m/s
Vertical load spectrum
The presence of the 1X is an evidence of the single prevailing peak/revolution

Loads (9): Loads patterns



In order to avoid “random perturbations”, a load pattern has been selected from each load time history, then replicated periodically with the same period as the original one. This was necessary to investigate the behavior of the blade clearing it from the influence of random load pulses



WS=25: Total Dynamic 5458 N (214% of NL)

WS=0: Total Dynamic 1557 N (61% of NL)

Nominal load (NL), N	-2550
Min @ WS=0, N	-3822
max @WS=0, N	-2265
Dynamic +, N	285
Dynamic -, N	-1272
min @ WS=25, N	-5536
max @ WS=25, N	-78
Dynamic +, N	2472
Dynamic -, N	-2986

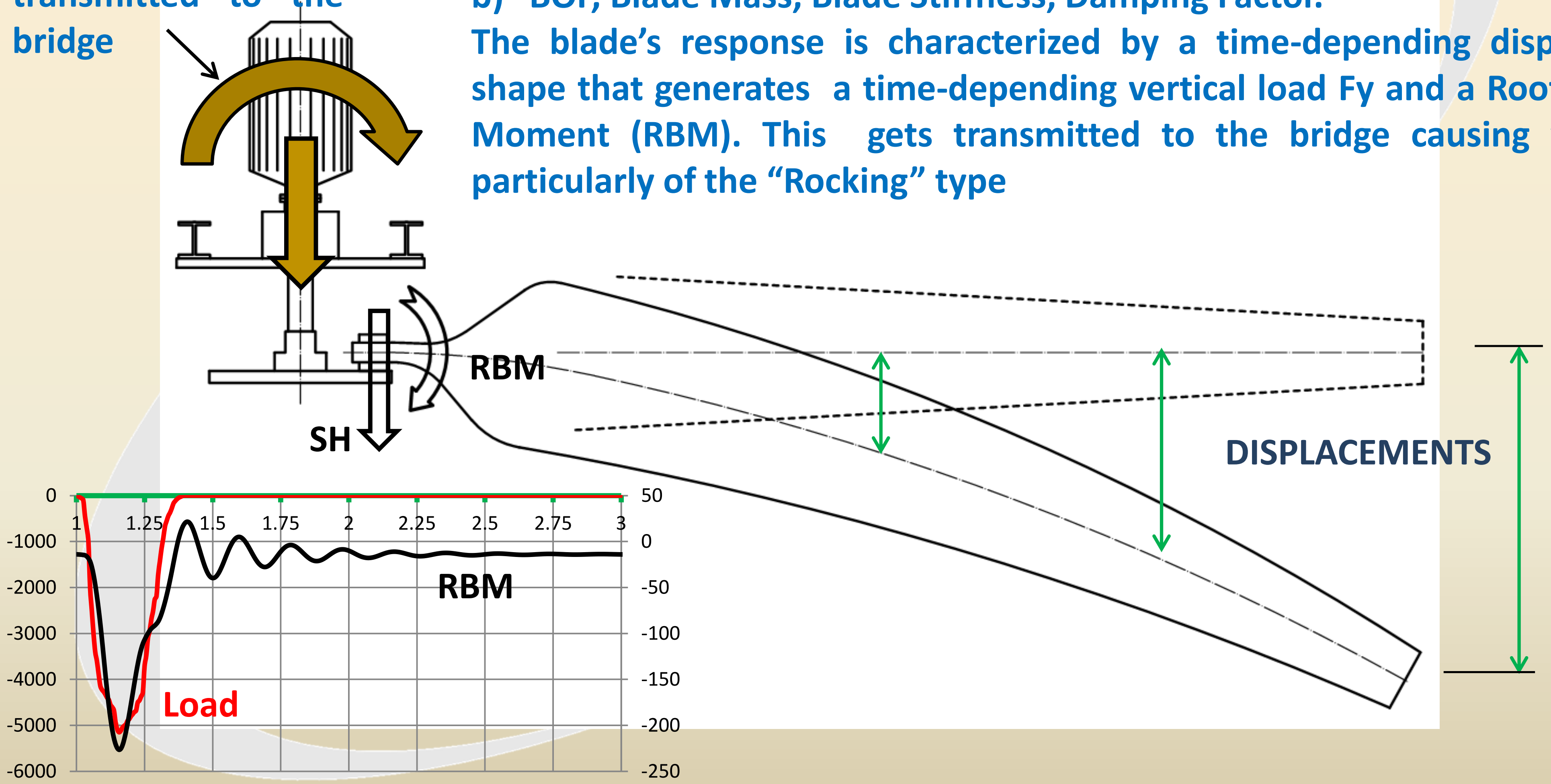
Loads (10): RBM origin

Bending Moment and Vertical Load transmitted to the bridge

As an elastic structure, a blade responds to a time-depending load according to several parameters:

a) Load characteristics (Pulses' shape, Pulses' duration, Pulses' frequency)
b) BOF, Blade Mass, Blade Stiffness, Damping Factor.

The blade's response is characterized by a time-depending displacement shape that generates a time-depending vertical load Fy and a Root Bending Moment (RBM). This gets transmitted to the bridge causing vibration, particularly of the "Rocking" type

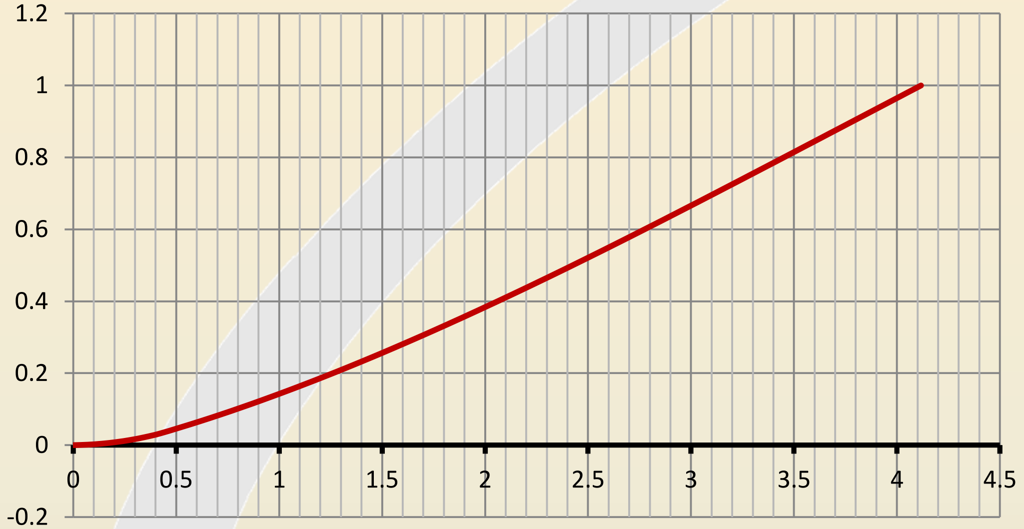


Dynamics

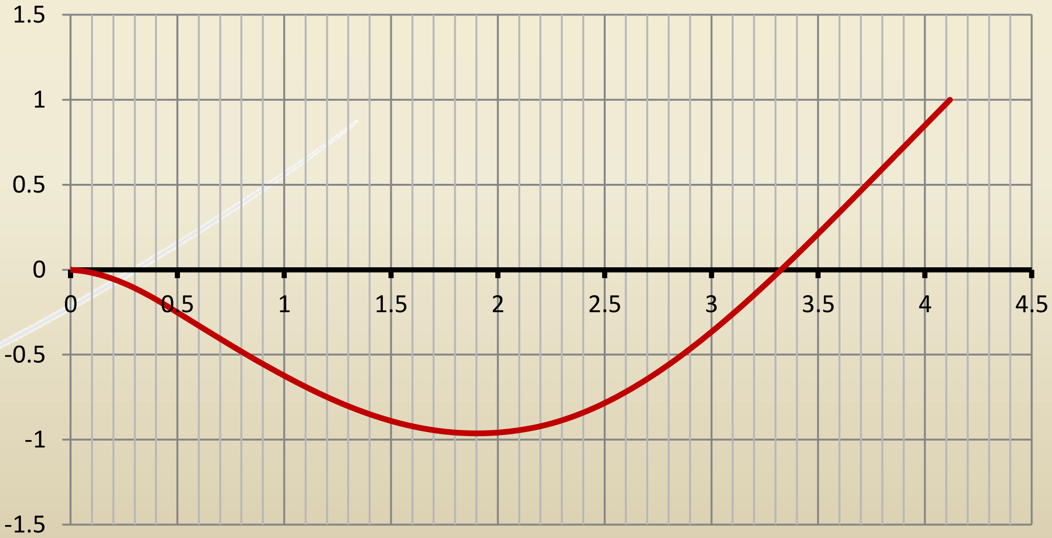
Dynamics (1): Modal analysis

Each blade's response has been determined by modal analysis. The first and the second modes only have been considered for the calculation.

Mode shape 1

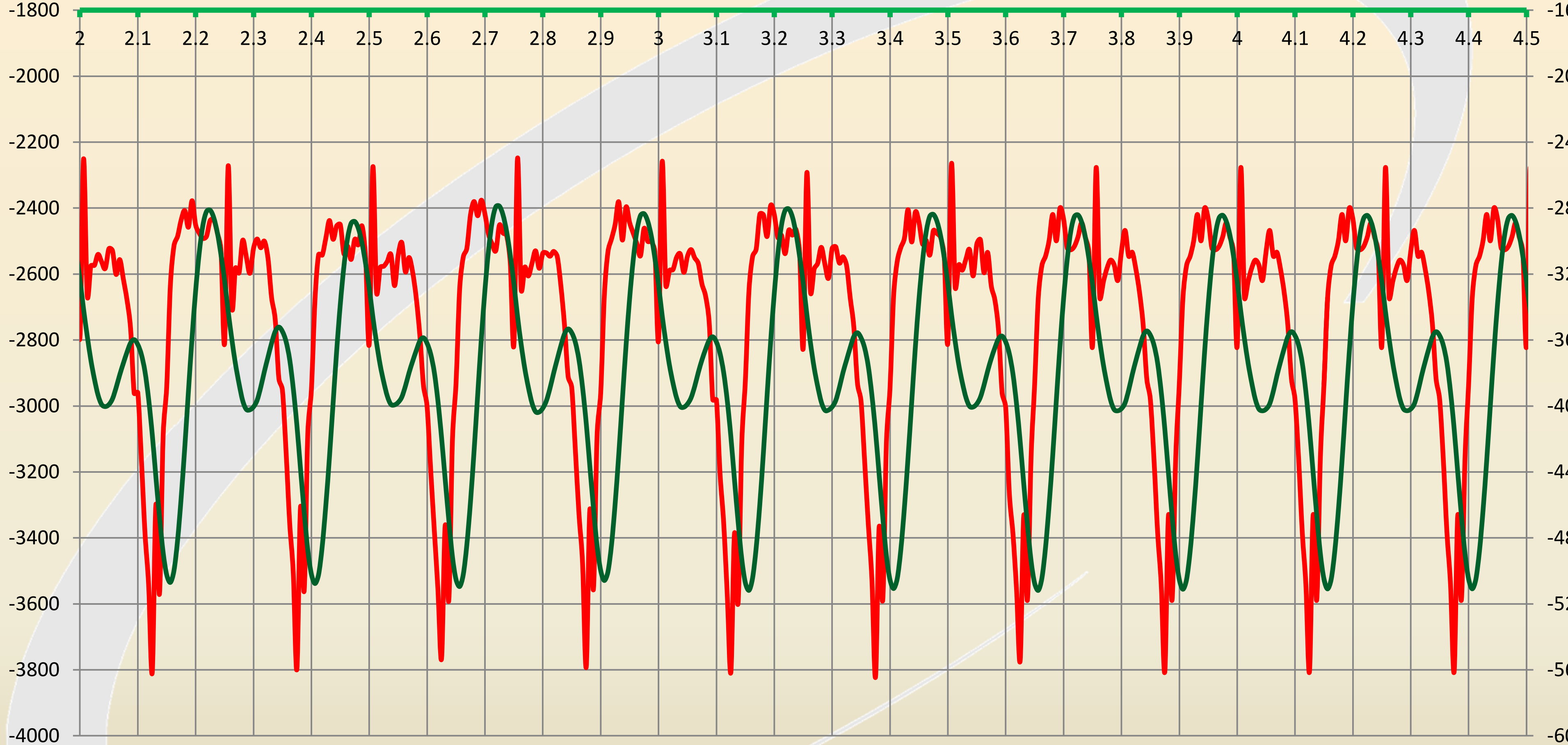


Mode shape 2



Dynamics (2): Blade A @ WS=0

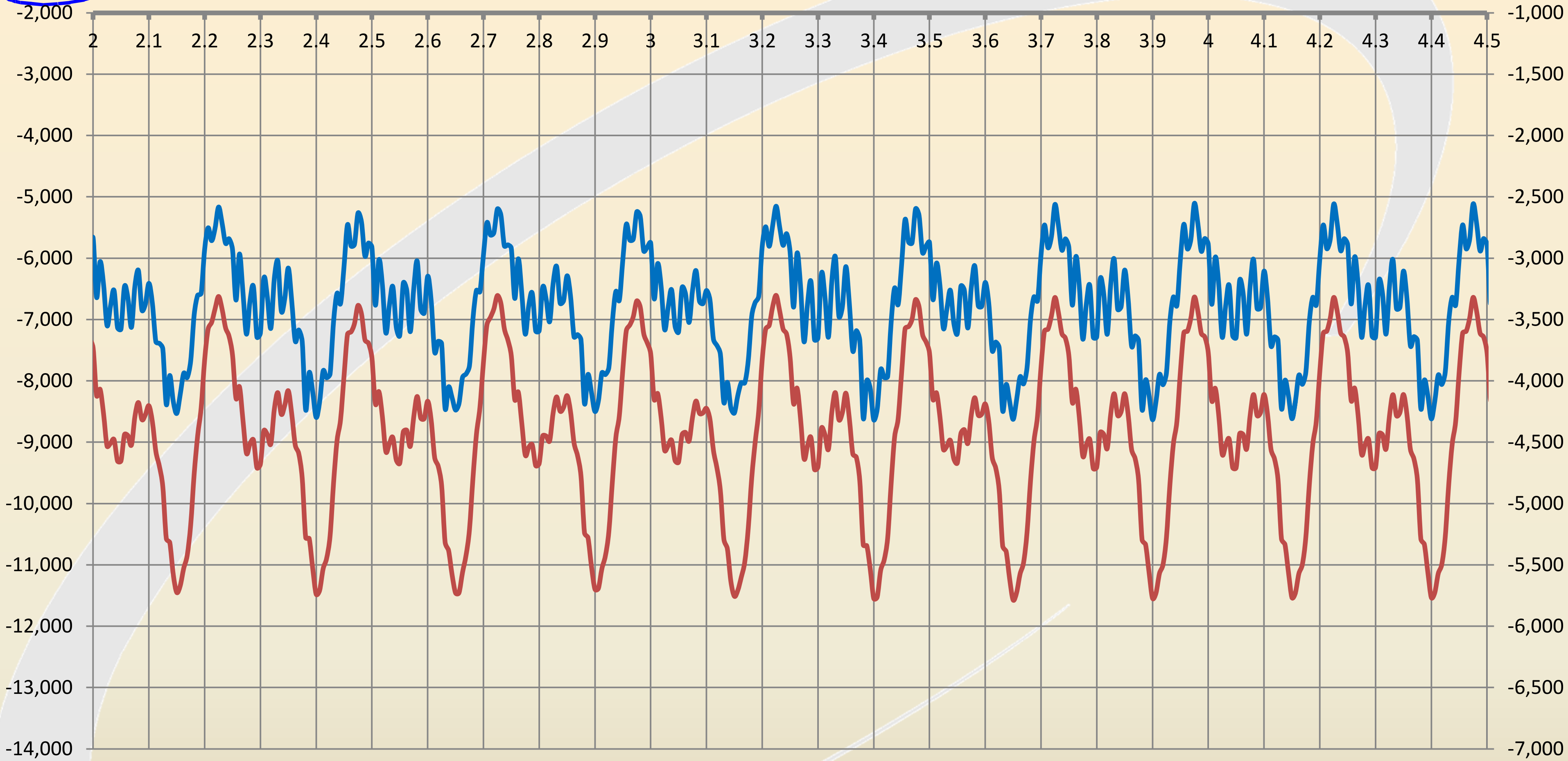
Fy (N) - Tip displacement (mm)



BLADE A	Mass	FN1 =	6.68	RBM	SH	Y des
	112.6	FN2 =	39.5	-8437.2	-3224.6	-36.4

RBM	Δ RBM	Δ RBM %	-59%	SH	Δ SH	Y tip
-11572.5	4965.8	Δ SH %	-55%	-4333.1	1778.8	-51.2
-6606.7		Δ Y %	64%	-2554.4		-27.9

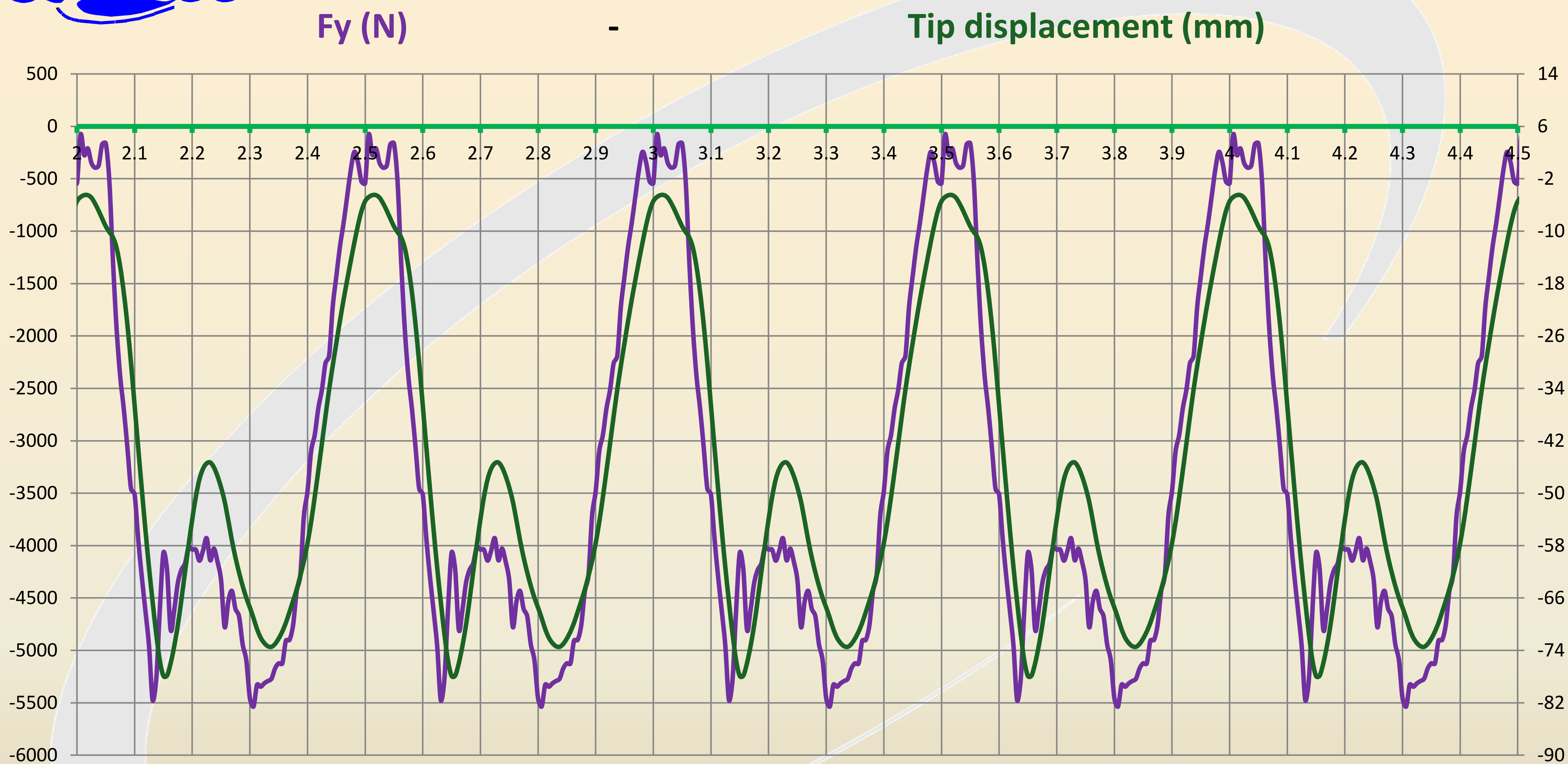
Dynamics (3): Blade A @ WS=0



BLADE A	Mass	FN1 =	6.68	RBM	SH	Y des
	112.6	FN2 =	39.5	-8437.2	-3224.6	-36.4

RBM	Δ RBM	Δ RBM %	-59%	SH	Δ SH	Y tip
-11572.5	4965.8	Δ SH %	-55%	-4333.1	1778.8	-51.2
-6606.7		Δ Y %	64%	-2554.4		-27.9

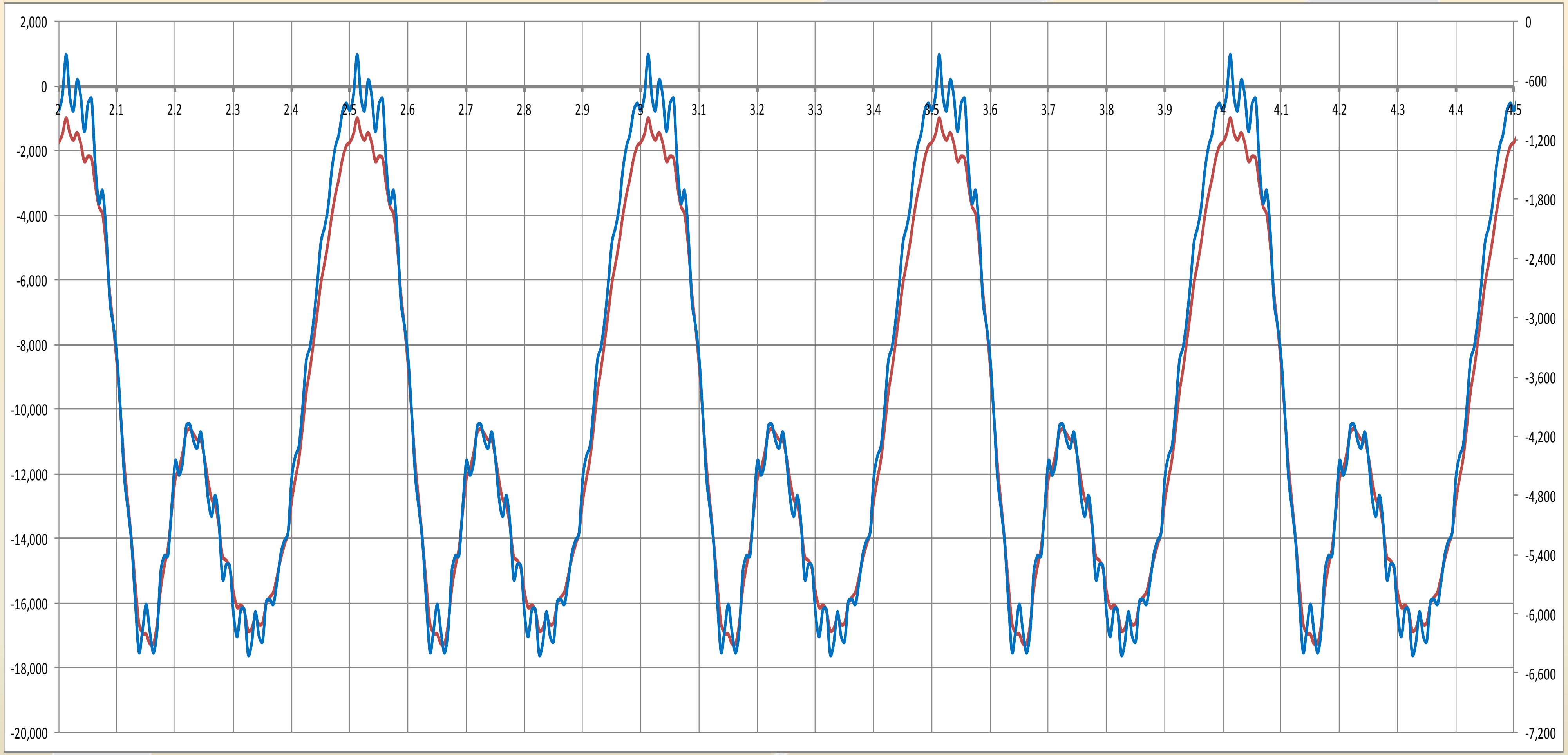
Dynamics (4): Blade A @ WS=25 m/s



	Mass			RBM des	SH des	Y des
BLADE A	112.6	FN1 =	6.68	-8437.2	-3224.6	-36.4
		FN2 =	39.5			

RBM	Δ RBM	Δ RBM%	-193%	SH	Δ SH	Y tip
-17274.5	16294.5	Δ SH %	-188%	-6417.2	6076.7	-77.9
-980.0		Δ Y %	202%	-340.5		-4.5

Dynamics (5): Blade A @ WS=25 m/s



BLADE A	Mass	FN1 =	6.68	RBM des	SH des	Y des
	112.6	FN2 =	39.5	-8437.2	-3224.6	-36.4

RBM	Δ RBM	Δ RBM%	-193%	SH	Δ SH	Y tip
-17274.5	16294.5	Δ SH %	-188%	-6417.2	6076.7	-77.9
-980.0		Δ Y %	202%	-340.5		-4.5

Dynamics (6): Load /Response summary

		WS = 0			WS = 25		
LOAD	Minimum, N	-3822			-5536		
	Maximum, N	-2265			-78		
	Dynamic +, N	285			2472		
	Dynamic -, N	-1272			-2986		
	Pulse duration, s	≈ 0.09			≈ 0.38		
	Spectrum	2X; 4X; NX			1X; 2X; 4X		
RESPONSE		Min	Max	Δ	Min	Max	Δ
	Tip Displacement, mm	-51.2	-27.9	23.3	-77.9	-4.5	73.4
	RBM, N*mm	-11572.5	-6606.7	4965.8	-17274.5	-980.0	16294.5
	Δ RBM / RBM0, %	59%			193%		
	SH, N	-4333.1	-2554.4	1778.8	-6417.2	-340.5	6076.7
	Δ SH / SH0 %	55%			188%		

Design conditions: Load = -2550 N TD = -36.4 mm VL0 = -3224 N RBM0 = -8437 Nm

Load Mitigation

Load Mitigation (1): Blade A -Wind Screen

Screen Tunnel Test CFD simulation

The screen is defined by the so called

PRESSURE DROP COEFFICIENT:

$$K = 2 * \Delta P / (\delta * V^2)$$

For this simulation, a value of

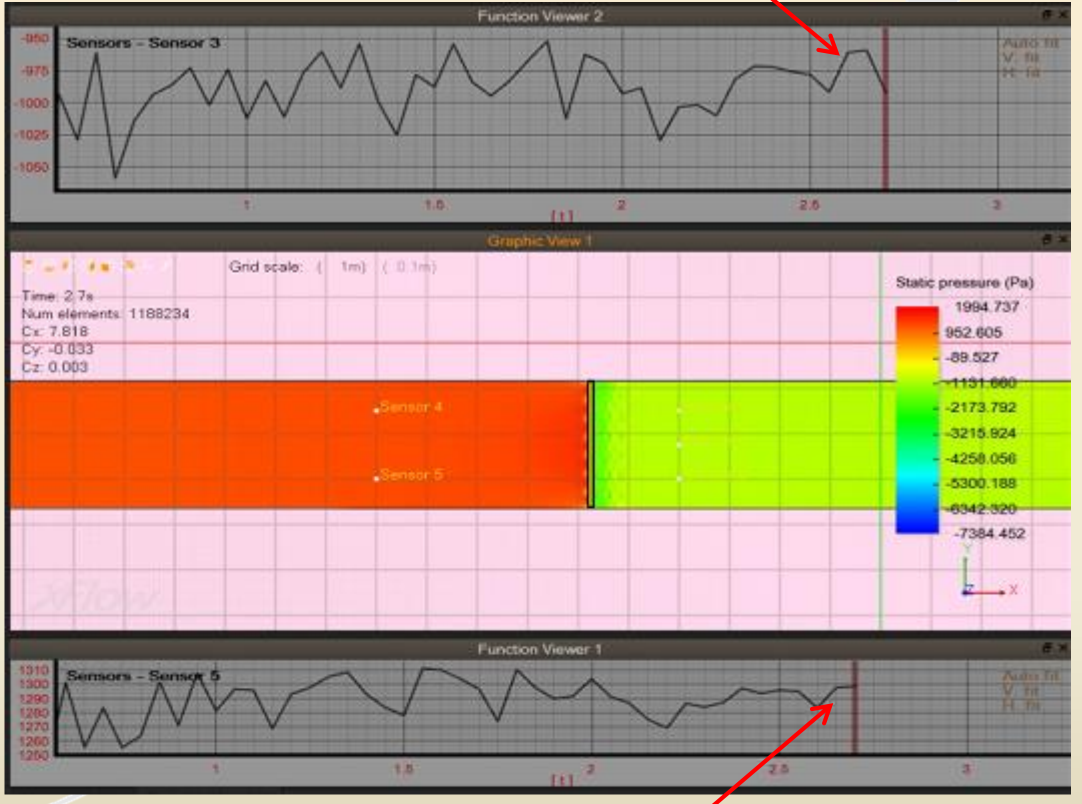
$$K = 6.2$$

was selected from the several sizes available on the market.

Therefore, at 25 m/s, the expected Pressure Drop is

$$\Delta P = 2363 \text{ Pa}$$

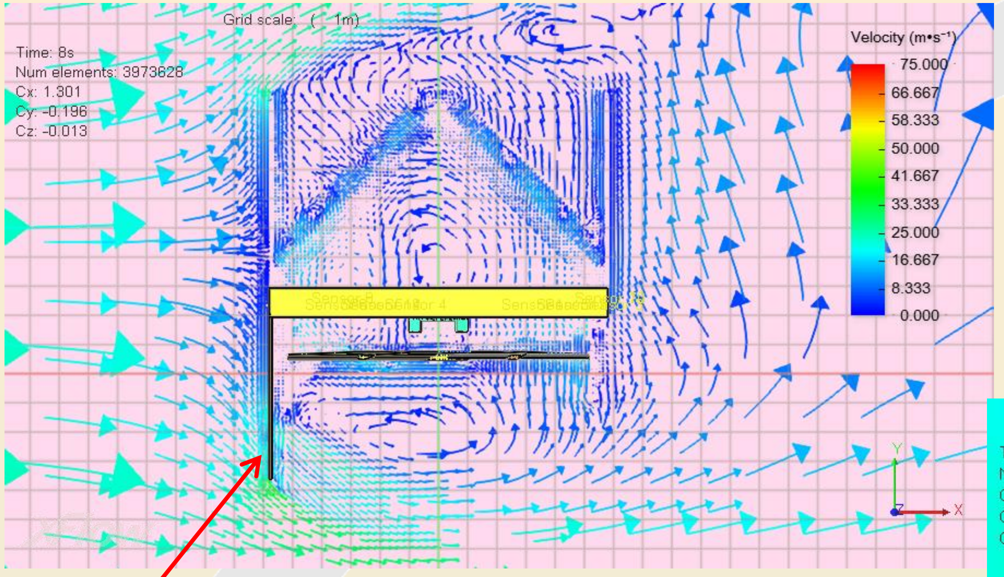
Downwind pressure ≈ - 1000 Pa



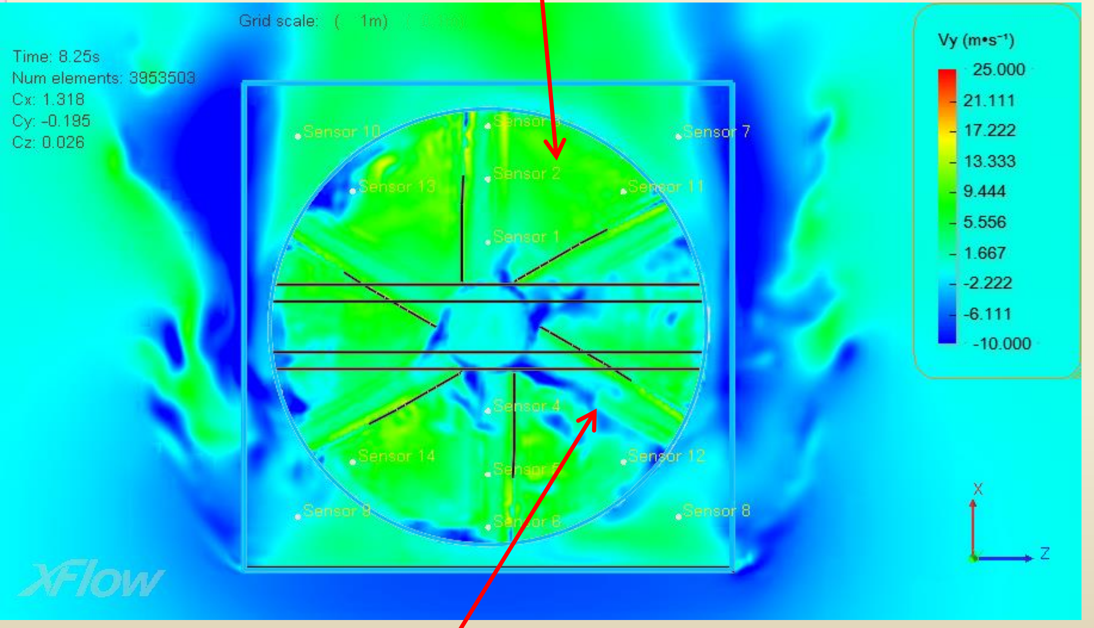
Upwind pressure ≈ 1300 Pa

Total ΔP from CFD simulation ≈ 2300 Pa

Load Mitigation (2): Blade A -Wind Screen



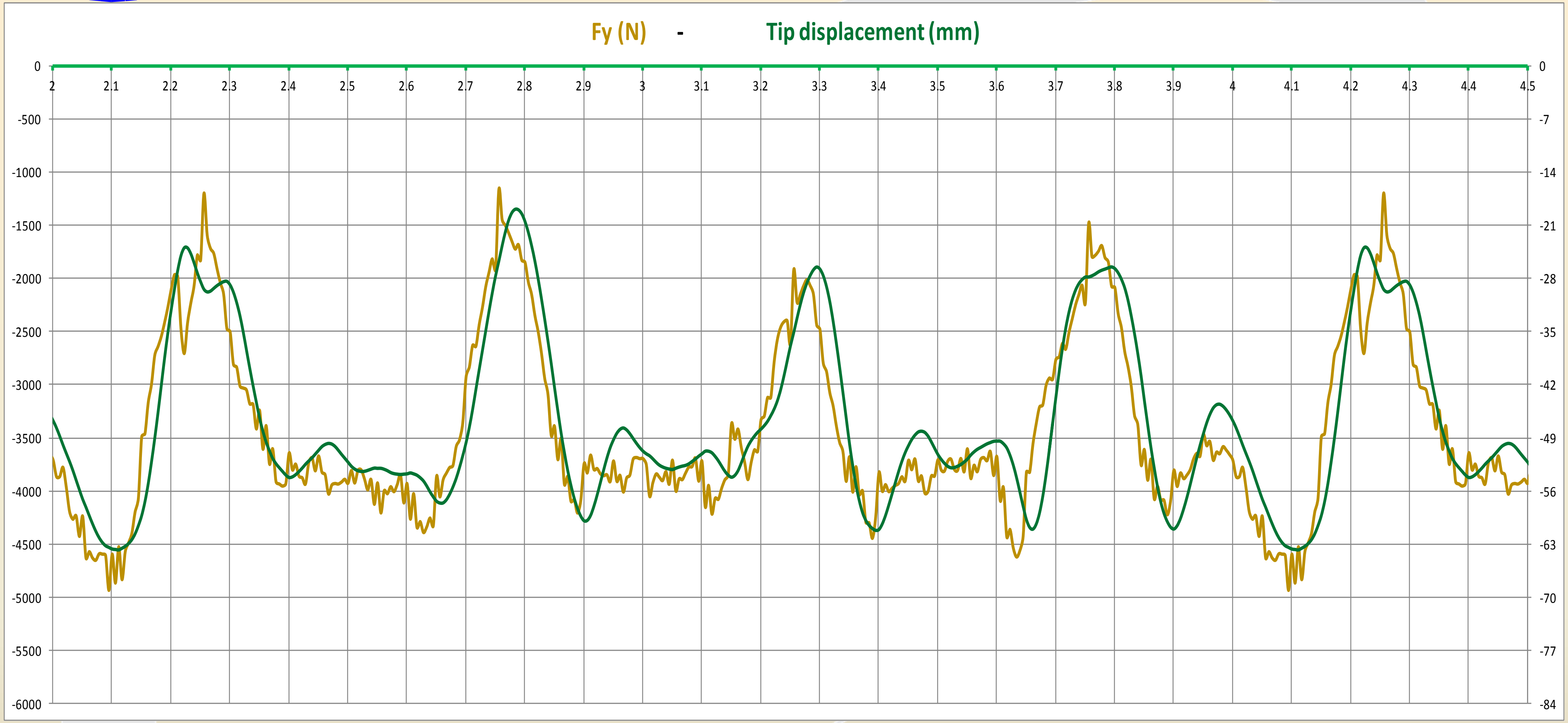
More regular distribution of the flow vertical component (Vy)



Wind Screen:
2.5 m below the fan inlet

Reduced perturbated areas

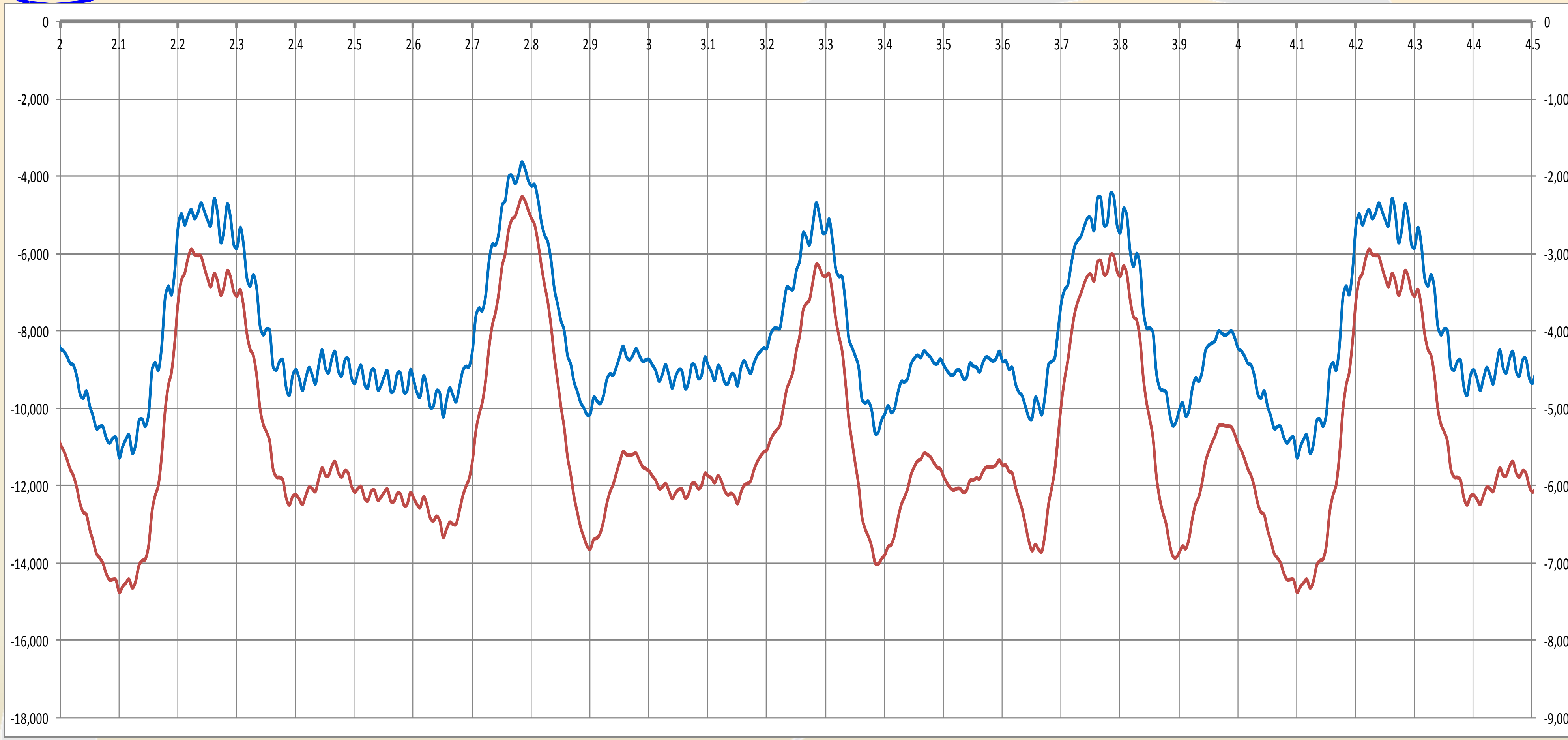
Load Mitigation (3): Blade A - Wind Screen



	Mass	FN1 = 6.68	RBM	SH	Y des
BLADE A	112.6	FN2 = 39.5	-8437.2	-3224.6	-36.4

RBM	Δ RBM	Δ RBM%	-121%	SH	Δ SH	Y tip
-14760.7	10219.4	Δ SH %	-118%	-5638.7	3817.8	-63.7
-4541.3		Δ Y %	123%	-1820.8		-18.9

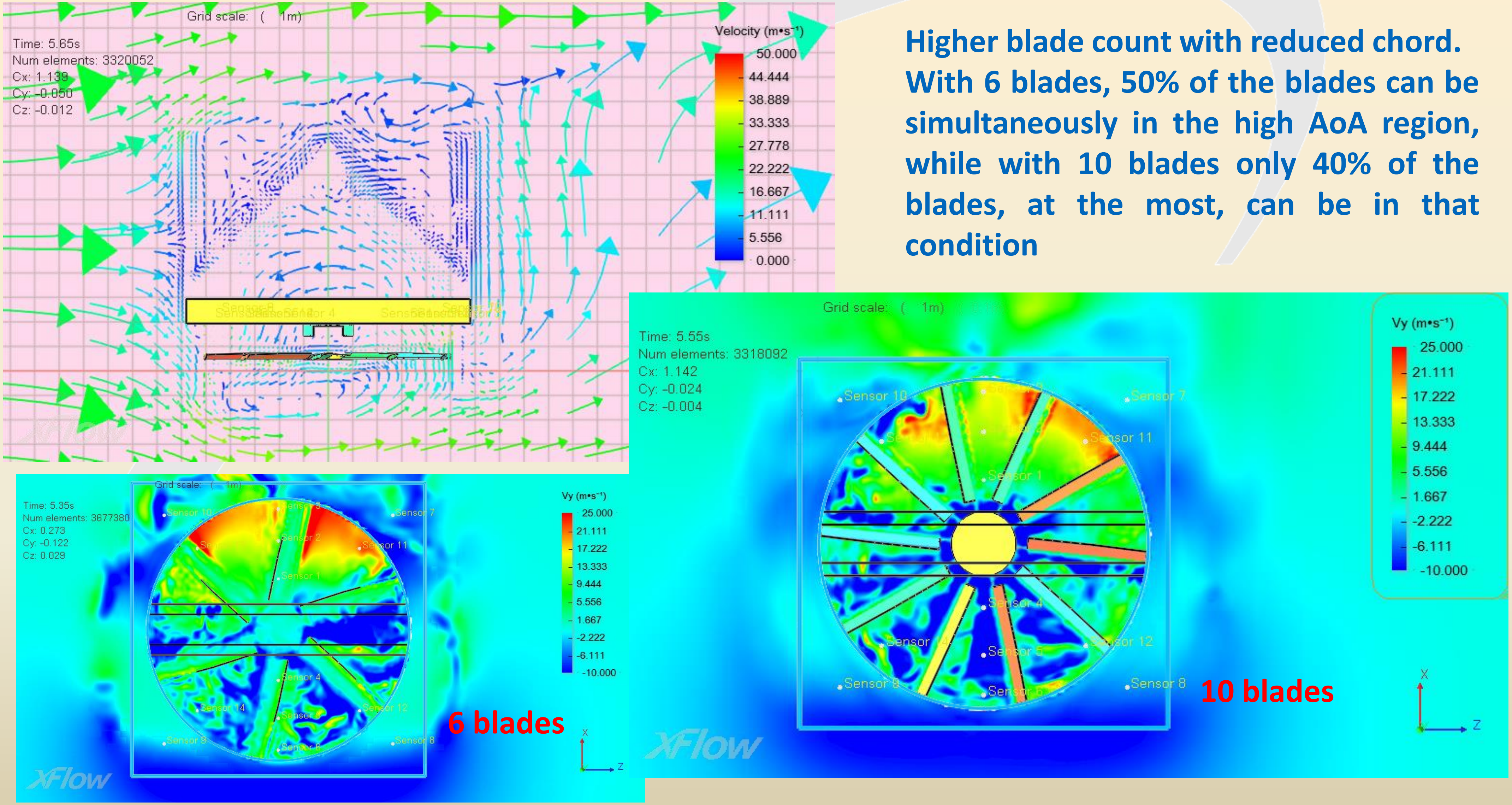
Load Mitigation (4): Blade A - Wind Screen



BLADE A	Mass	FN1 = 6.68	RBM	SH	Y des
	112.6	FN2 = 39.5	-8437.2	-3224.6	-36.4

RBM	Δ RBM	Δ RBM%	-121%	SH	Δ SH	Y tip
-14760.7	10219.4	Δ SH %	-118%	-5638.7	3817.8	-63.7
-4541.3		Δ Y %	123%	-1820.8		-18.9

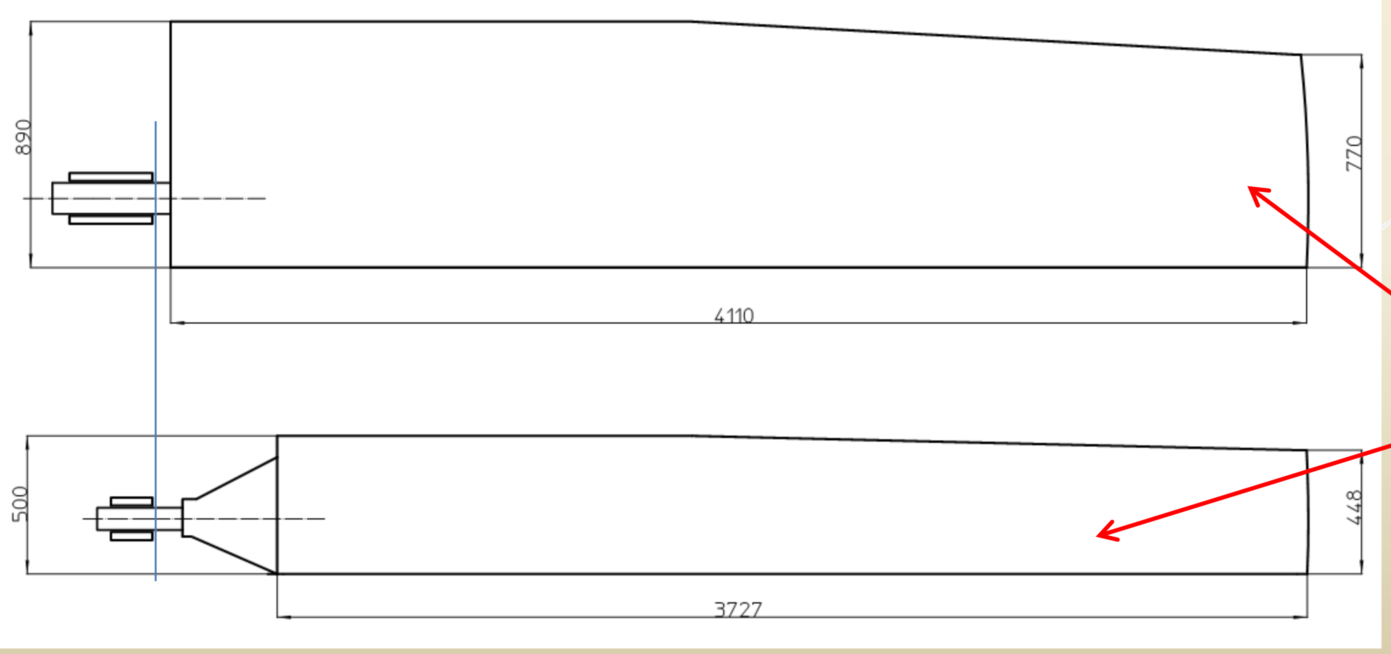
Load Mitigation (5): Blades B @ WS=25



Higher blade count with reduced chord. With 6 blades, 50% of the blades can be simultaneously in the high AoA region, while with 10 blades only 40% of the blades, at the most, can be in that condition

Load Mitigation (6): Blades B Features

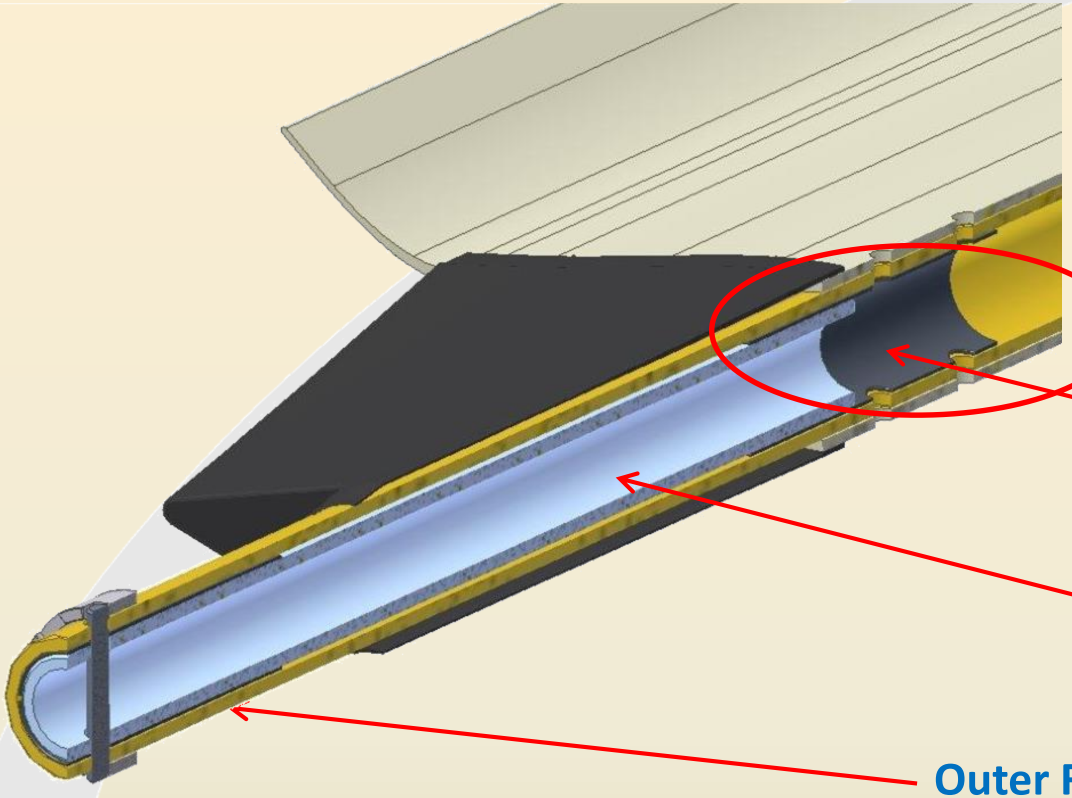
Two blades from blade family B with the following properties:	Blade B1	Blade B2 (35F)
Chord at root, mm	500 (1.64 ft)	
Chord at tip, mm	448 (1.47 ft)	
Blade Mass, Kg	89 (196 lbs)	41.5 (92 lbs)
Blade count	10	
BOF mode1 & mode 2, Hz	4.1 – 15.7	2.2 – 14.2
Main features	Lighter, stiff, medium BOF	Very Light, very low BOF, high damping effect (*)



(*) Double FRP shaft with inner friction-based damper

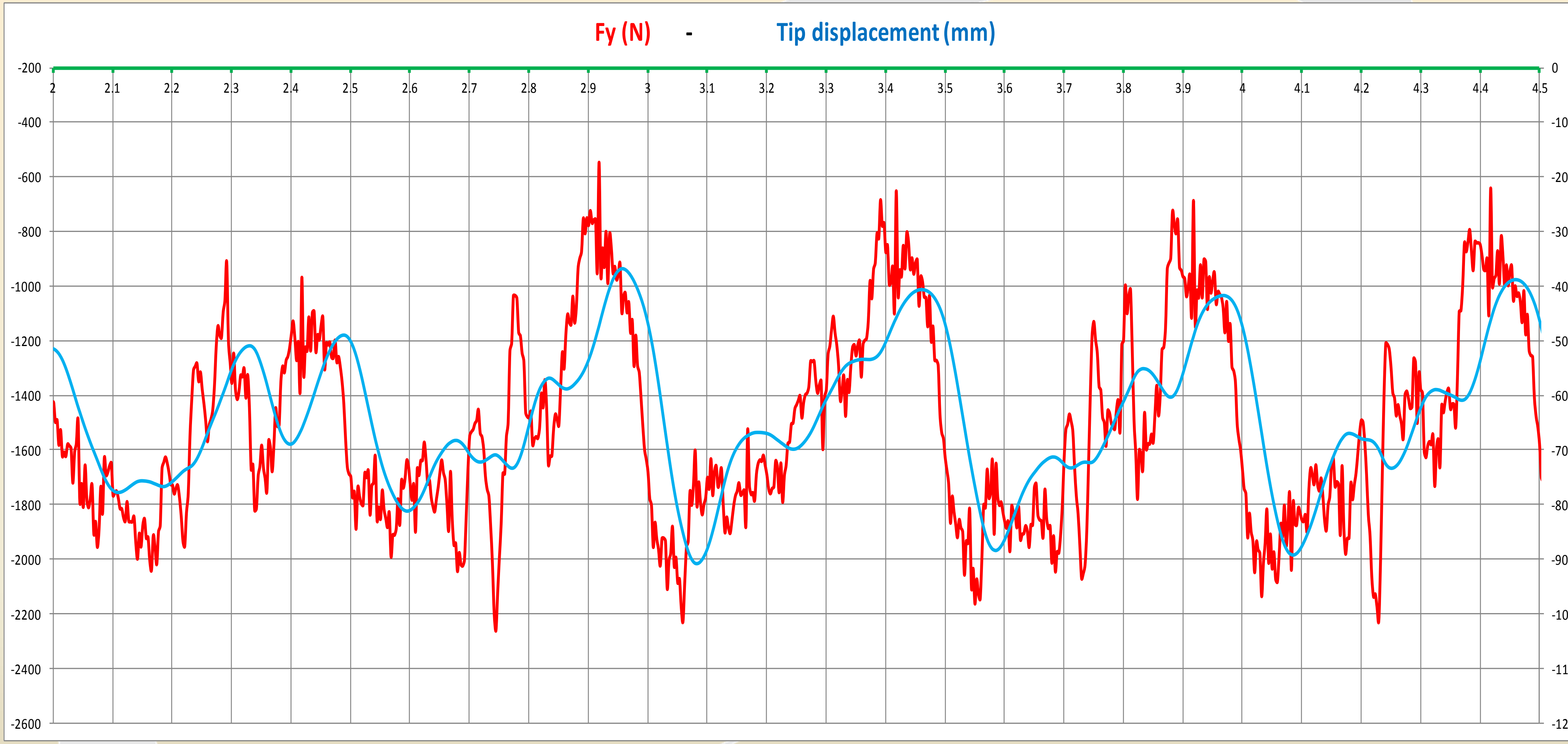
Shape and size comparison:
- Blade A
- Blades B1 & B2

Load Mitigation (7): Blade B2 Features



Blade B2
35F type

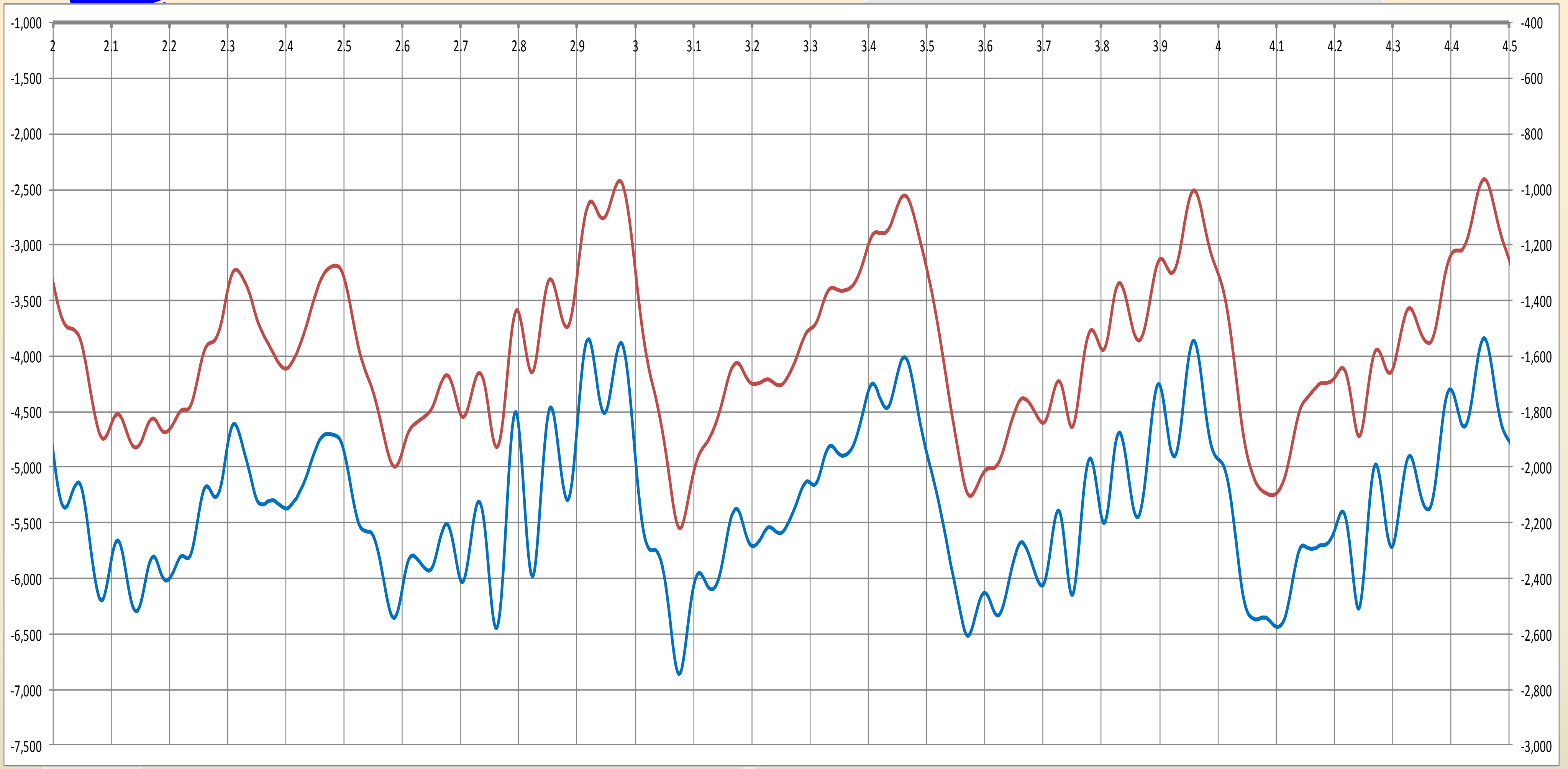
Load Mitigation (8): Blade B1 @ WS=25



BLADE B1	Mass		RBM	SH	Y des
	89.0	FN1 = 4.13	-4031.2	-1567.4	-65.3
		FN2 = 15.7			

RBM	Δ RBM	Δ RBM%	-78%	SH	Δ SH	Y tip
-5545.6	3140.3	Δ SH %	-50%	-2742.0	1207.0	-90.9
-2405.3		Δ Y %	83%	-1535.0		-36.9

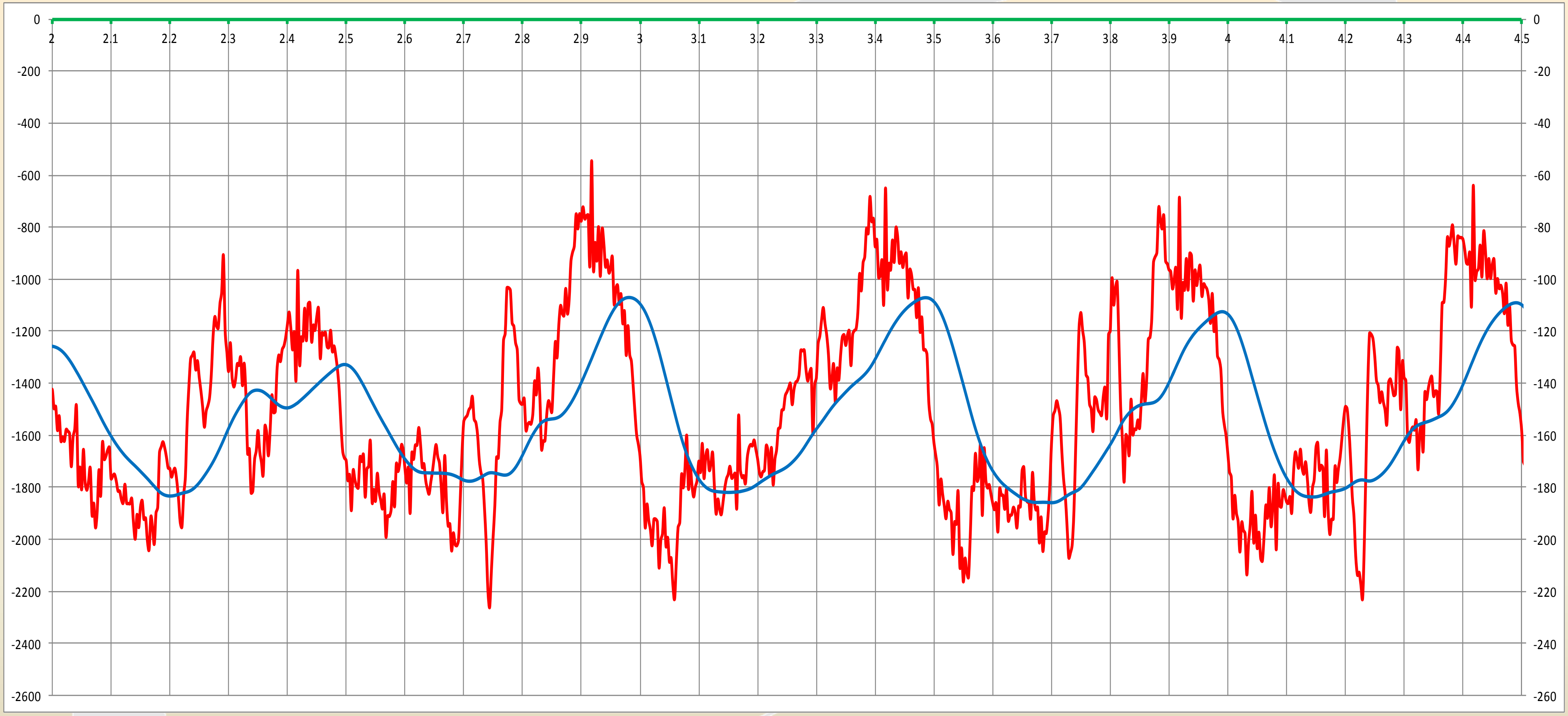
Load Mitigation (9): Blade B1 @ WS=25



BLADE B1	Mass	FN1 = 4.13	RBM	SH	Y des
	89.0	FN2 = 15.7	-4031.2	-1567.4	-65.3

RBM	Δ RBM	Δ RBM%	-78%	SH	Δ SH	Y tip
-5545.6	3140.3	Δ SH %	-50%	-2742.0	1207.0	-90.9
-2405.3		Δ Y %	83%	-1535.0		-36.9

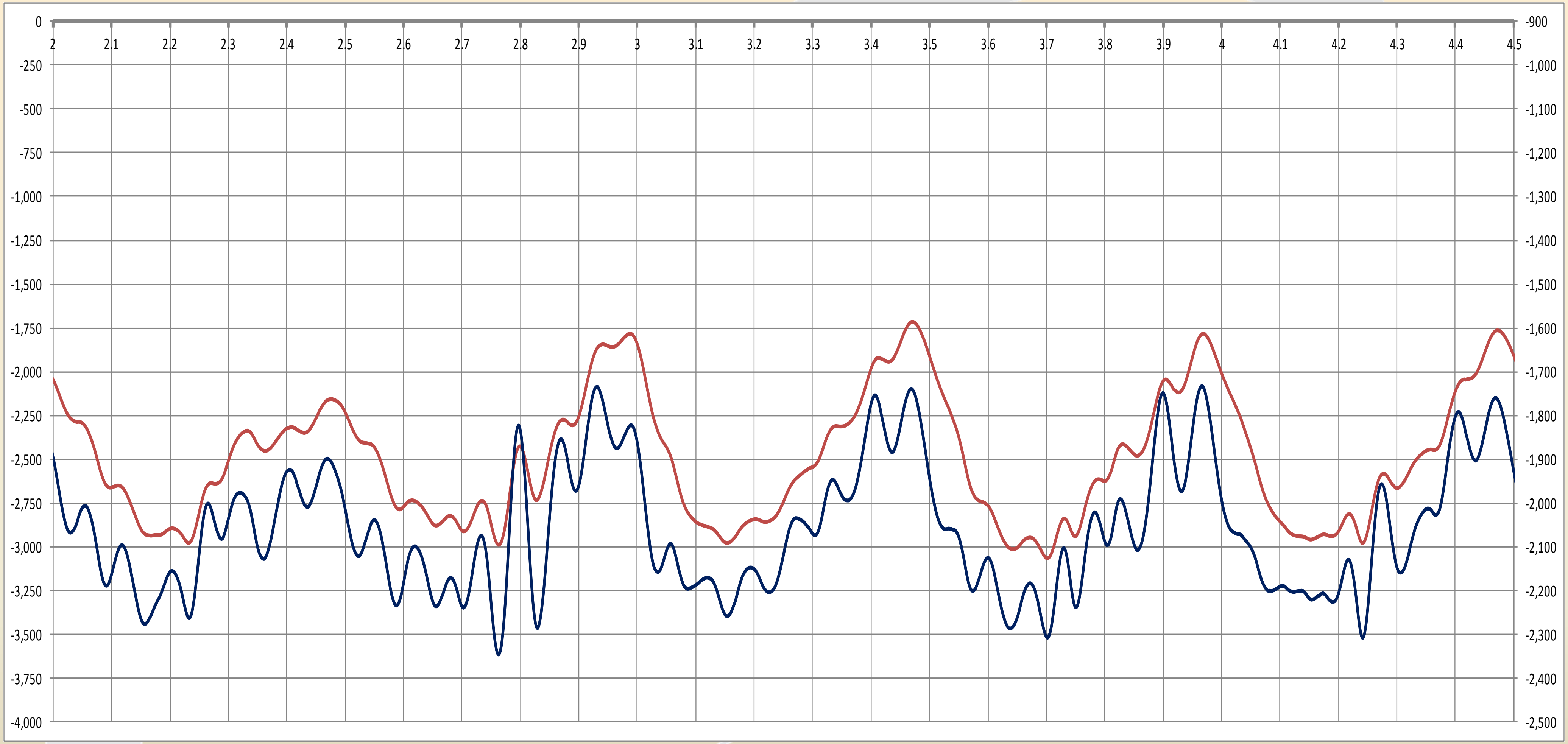
Load Mitigation (10): Blade B2 (35F) @ WS=25



BLADE B2	Mass	FN1 = 2.16	RBM	SH	Y des
	41.5	FN2 = 14.2	-2548.4	-1957.3	-157.0

RBM	Δ RBM	Δ RBM%	-53%	SH	Δ SH	Y tip
-3068.7	1350.7	Δ SH %	-31%	-2333.6	612.6	-186.0
-1718.1		Δ Y %	50%	-1721.0		-107.1

Load Mitigation (11): Blade B2 (35F) @ WS=25



BLADE B2	Mass			RBM	SH	Y des
	41.5	FN1 =	2.16	-2548.4	-1957.3	-157.0
		FN2 =	14.2			

RBM	Δ RBM	Δ RBM%	-53%	SH	Δ SH	Y tip
-3068.7	1350.7	Δ SH %	-31%	-2333.6	612.6	-186.0
-1718.1		Δ Y %	50%	-1721.0		-107.1

Load Mitigation (12): Load summary

		Blade A WS = 0 (REFERENCE)	Blade A WS = 25	Blade A WS = 25, Wind Scr.	Blade B1 WS = 25	Blade B2 (35F) WS = 25
LOAD	Minimum, N	-3822	-5536	-4936	-2250	-2250
	Maximum, N	-2265	-78	-1160	-530	-530
	Dynamic +, N	285	2472	1390	1030	1030
	Dynamic -, N	-1272	-2986	-2386	-670	-670
	Pulse duration, s	0.09	0.38	0.36	0.25	0.25
		Variation of tip displacement and RBM				
RESPONSE	Δ Tip Displacement, mm	23.3	73.4	44.9	54	79
	Δ RBM, N*mm	4966	16295	10220	3140	1351
	Δ RBM / RBM0, %	0.59	1.93	1.21	0.78	0.53
	SH, N	1779	6077	3817	1206	613
	Δ SH / SH0 %	0.55	1.88	1.04	0.5	0.31
	RBM mitigation with ref. to Blade A, WS = 0	N.A.	328%	206%	63%	27%

Blade A - Design conditions: Load = -2550 N TD = -36.4 mm SH0 = -3224 N RBM0 = -8437 Nm

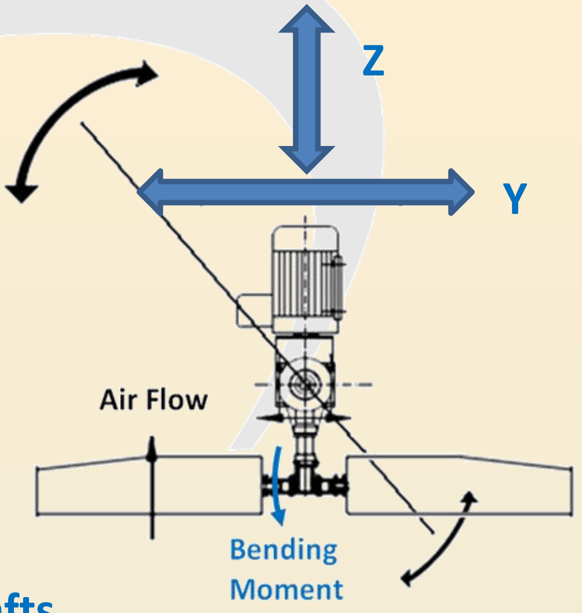
Blade B1 - Design conditions: Load = -1530 N TD = -65.3 mm SH0 = -2424 N RBM0 = -4031 Nm

Blade B2 - Design conditions: Load = -1530 N TD = -157 mm SH0 = -1957 N RBM0 = -2548 Nm

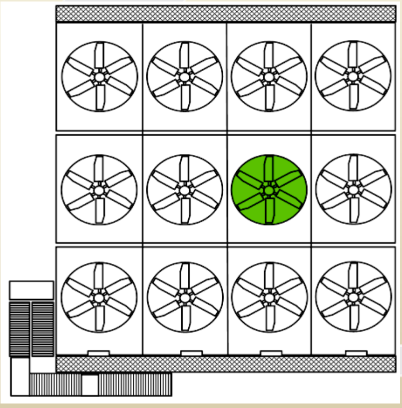
Load Mitigation (13): Blade B2 (35F) on-site test

Test carried out @ WS ≈ 0

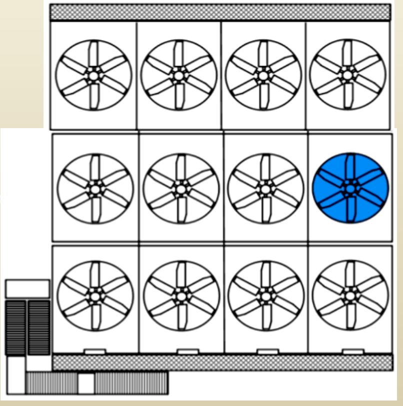
Fan type:	Gearbox, Direction			Motor Top
32ft - 6 blades	X	Y	Z	Y
	mm/s RMS			
Hand Laminated	3.1	4.2	7.8	12.2
FRP - Carbon Shaft 35F	2.8	2.1	2.7	6.1



Vibration amplitudes were greatly reduced using the new FRP-Carbon shafts.
On top of the motor, a huge vibration reduction was achieved compared to a standard FRP blade with rigid connection to the hub, evidencing a great reduction in the BM transmitted to the bridge.



Hand Laminated
Blades



FRP-Carbon shafts

Conclusions

Conclusions (1)

- Wind can dramatically increase the RBM variation transmitted to the bridge and, consequently, the vibration level, up to more than three times the nominal value in the conditions simulated in this report (120 rpm, WS=25 m/s)

- For the above reasons, the loads and stress on the drive chain components can reach up to three times the nominal level (in the conditions simulated in this report)

- While, at nominal conditions, the geometry (layout) of the cell defines the harmonic components of the loads (2X and 4X mainly), with strong wind other harmonic components can appear. The simulation of blade A at 90 rpm showed a relevant value of the 3X harmonic component.

Conclusions (2)

- Wind screens can reduce the wind effect significantly, both in terms of vibration level and performance (reduction of 37 % in the conditions simulated in this report)

- Using a fan with reduced-chord blades and increased blade count can reduce the wind effect as well in terms of vibration level.

- Generally, “softer” blades (low BNF like the 35F) can significantly mitigate the vibrations induced on the structure

- <u>The introduction of an enbedded damping device can take under control the blade displacement and the related loads even close to resonance conditions, increasing the blade safety margin and mitigating furtherly the vibrations induced to the structure</u>

Conclusions (3)

➢The reduction of the blade chord, together with the soft shaft and the embedded friction-based damping system, will have a great beneficial effect on the duty life of the cell but cannot avoid the lack of performances of the cell due to the wind

➢The combination of all the above means (reduced blade chord, low-natural frequency blade and damping system and Wind Screens) will likely achieve the optimum task of mitigating the wind effect on the performance reduction and on the vibration level, increasing the drive system life and reducing the maintenance requirements

NOTE: the different BPF and BOF MUST be taken into consideration. The above conclusions are true under the condition that the BPF and BOF don’t match with one of the bridge NFs or resonance components

THANK YOU FOR YOUR ATTENTION!