Wind Induced Vibrations on the Humber Bridge

4th Year MEng Group Project

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Project Overview

- Long span bridges can be susceptible to wind induced vibrations
- The Humber Bridge was used as a case study

Overall Group

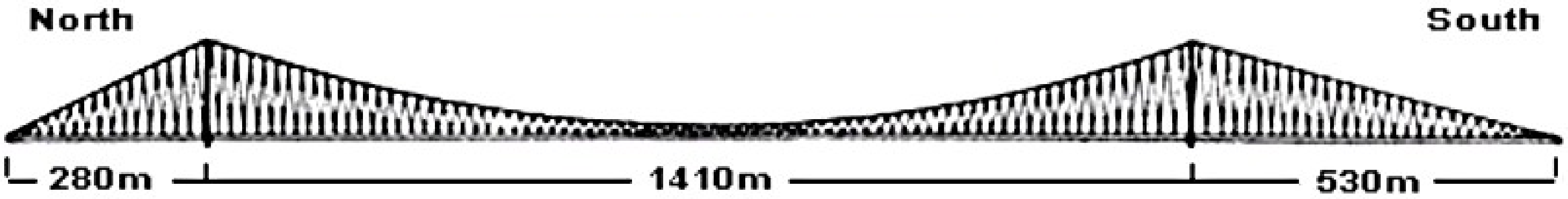
CFD Subgroup

James Richmond	Joshua Mullins	Joseph Morgan
Defining a CFD inlet condition using the synthetic eddy method	Inlet conditions for atmospheric boundary layer flow over terrain	Selection of an appropriate turbulence model and analysis of CFD results

Structural Subgroup

Patrick Lambton	Victoria Triay Jiménez	Damien Fieldhouse
Analytical approach to finding the vibrational characteristics of the bridge	Analytical analysis of flutter effects of the bridge cross-section	Computational approach to finding the vibrational characteristics of the bridge

Humber Bridge



- Steel box girder construction
- 2220m total length
- 7th longest single span bridge in the world
- Longest ever when constructed
- Length of bridge and relative low stiffness can lead to aero-elastic effects

Image Credit - The Humber Bridge Board, www.humberbridgeboard.co.uk/../technical_information, (1999)

Structural Sub-group

- Vibrational characteristics
  - Analytical Model
  - Computational model
  - Mode shapes
  - Natural frequencies
- Critical Flutter wind speed
  - Analytical Model
  - Aerodynamic Derivatives
  - Critical Wind Speed

Image Credit – Photo Answers www.photoanswers.co.uk/Facilities-Landing/Search-Results/England/East-Yorkshire/Humber-Bridge/ (2008)

Analytical Model

- Aimed to find the mode shapes and natural frequencies
- Inherent complexity of the structure doesn’t allow conventional analysis
- Direct stiffness method can be used to simplify the problem
- Breaking the problem down into elements of known stiffness
- Each element matrix combined into global matrix
- Global Mass matrix created from equivalent masses at each point

Analytical Model

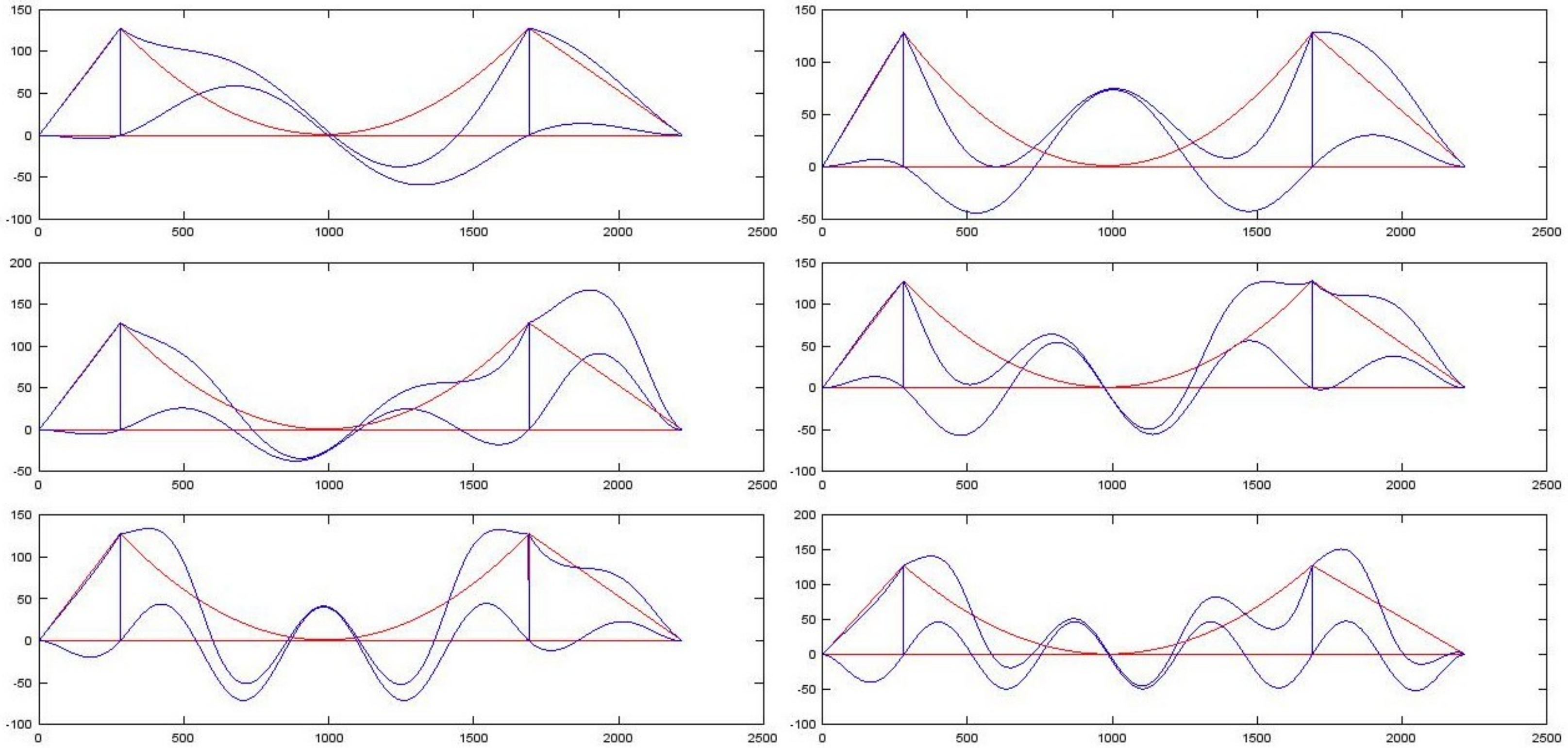
- Each model took into account different degrees of freedom for each element
- First model only took into account vertical degrees of freedom in the central span
- Simple model used to facilitate learning
- First vertical model 668 degrees of freedom
- Models became progressively more complex
- Final vertical model 1957 degrees of freedom
- All calculations carried out using GNU Octave

Issues

- Modelling of rotational inertia difficult
  - Non uniform rotation
  - Some rotations already accounted for by vertical deflections

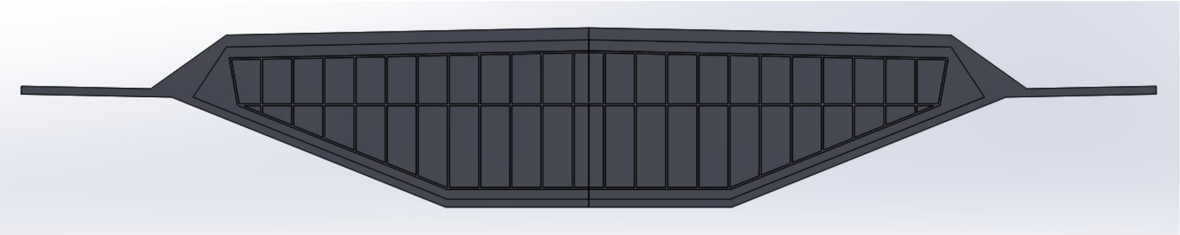
- For lateral and torsional vibrations a full 3D model was necessary
  - Taking into account main cable deflections properly
  - Too complex to model in given timeframe

Results

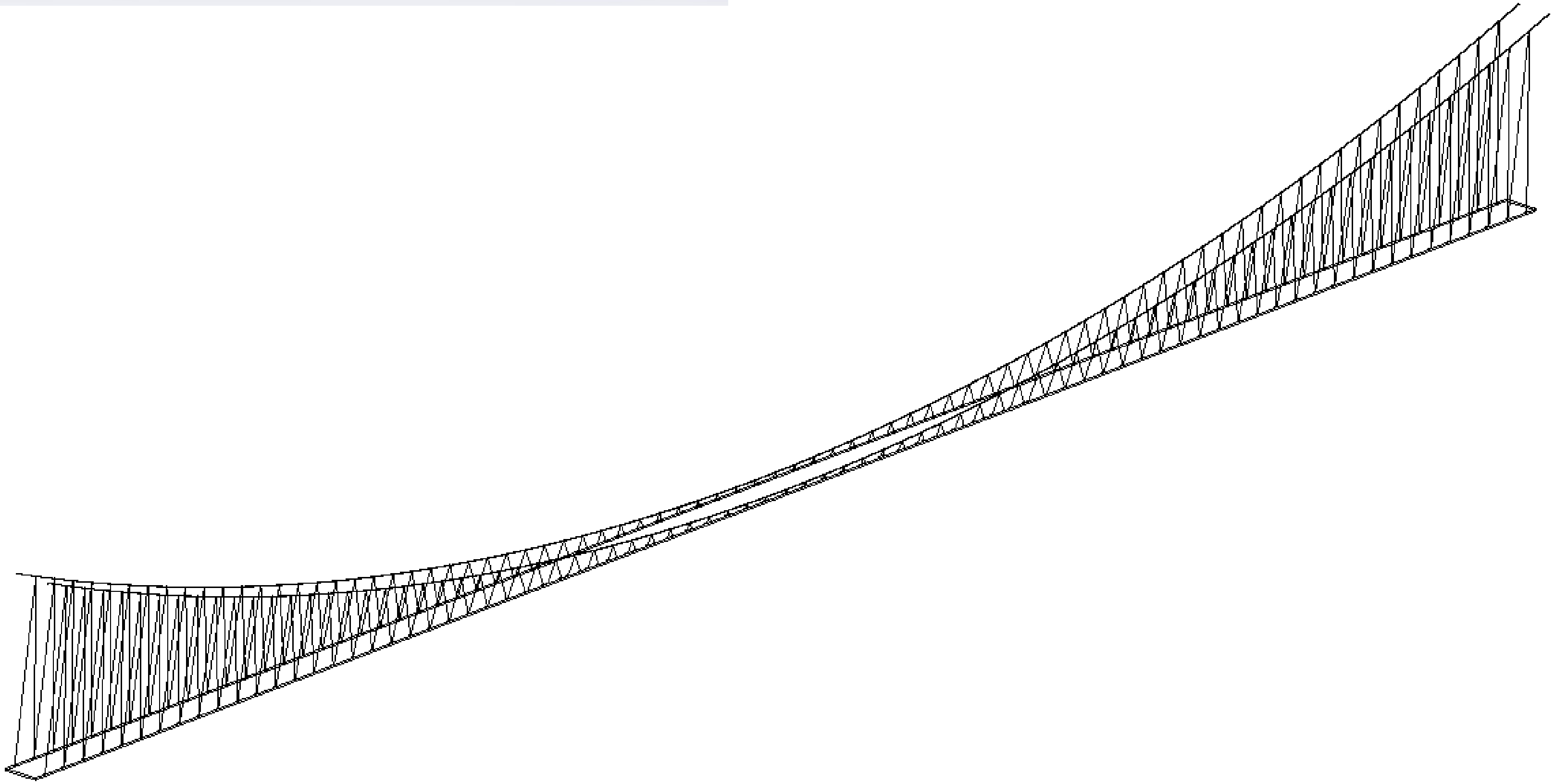


Mode number	Natural Frequency f_n (Hz)
1	0.125
2	0.171
3	0.204
4	0.238
5	0.282
6	0.333

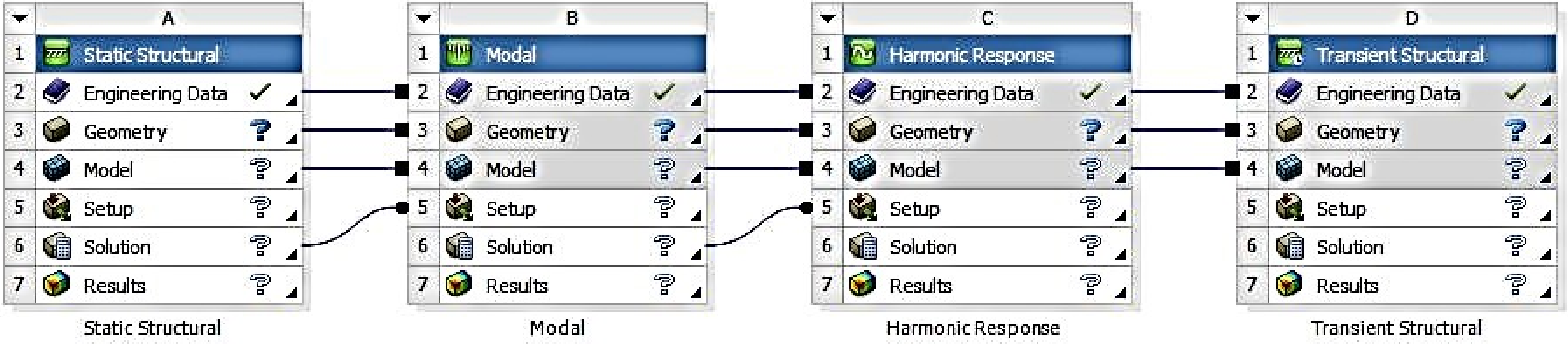
CAD Model



$$\delta_{\max} = \frac{Pl^3}{3EI}$$



Methodology



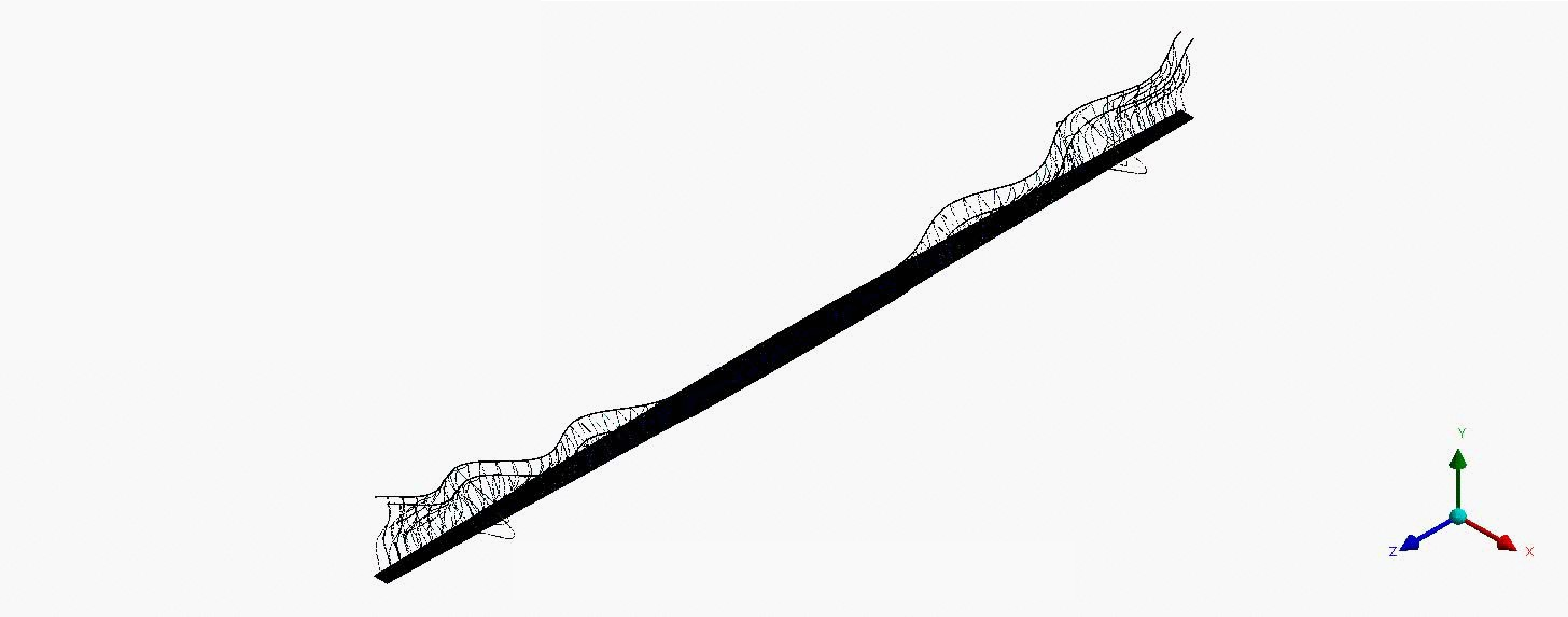
- Non-Transient
- Steady Loads

- Natural Frequencies
- Mode Shapes

- Frequency Response
- Phase Response

- Time Dependent Loading
- Dynamic Response

First Mode of Torsional Vibration



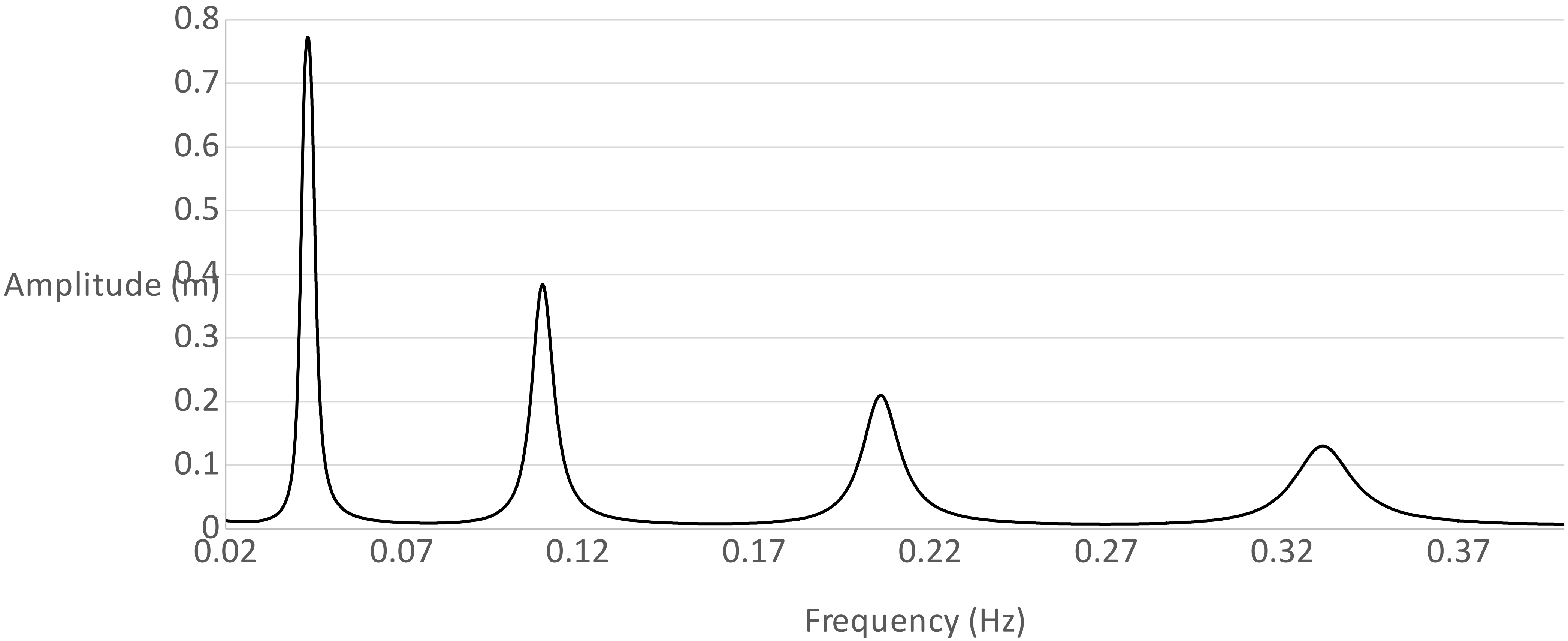
Natural Frequencies

Mode	Vertical			Torsional			Lateral		
	Lambton	Fieldhouse	Brownjohn	Lambton	Fieldhouse	Brownjohn	Lambton	Fieldhouse	Brownjohn
1	0.125	0.046	0.116	0.564	0.168	0.308	0.278	0.057	0.056
2	0.171	0.088	0.149	1.127	0.276	0.479	0.287	0.160	0.141
3	0.204	0.096	0.172	1.499	0.366	0.643			
4	0.238	0.099	0.215	1.691	0.422	0.848			
5	0.282	0.149	0.240						
6	0.333	0.175	0.309						

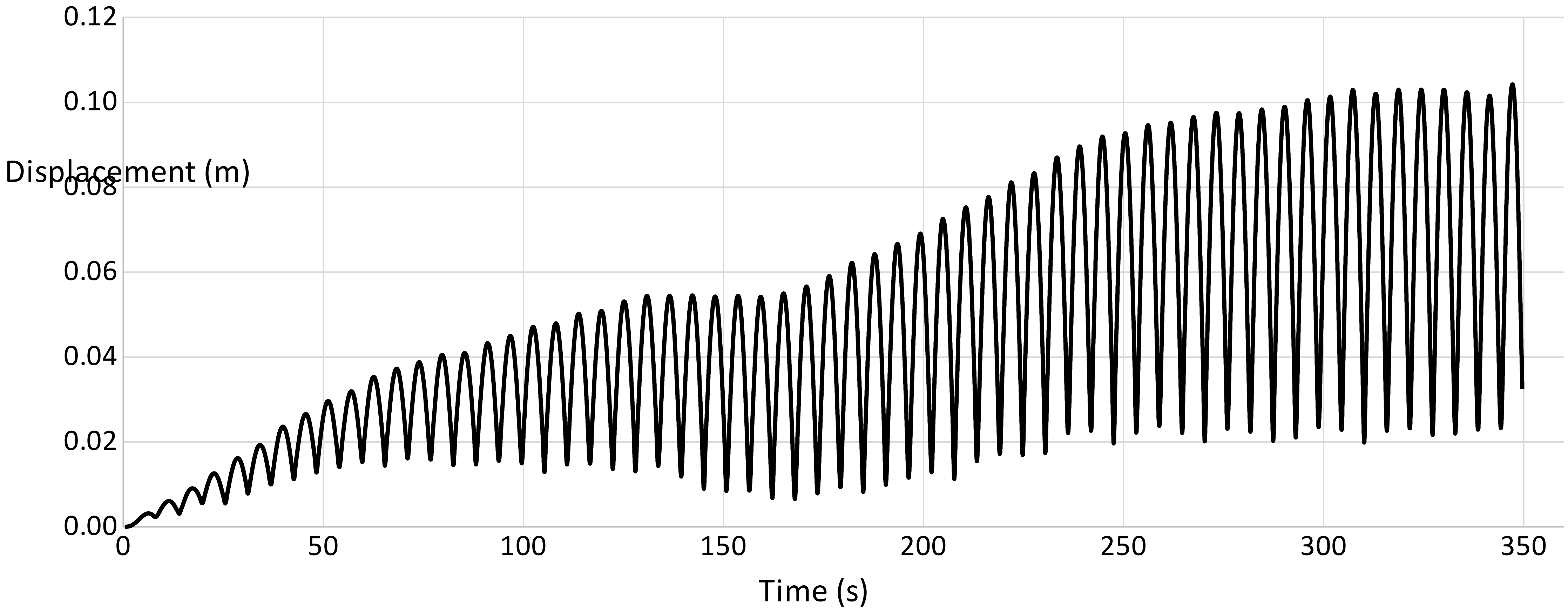
Calculated and experimental frequencies associated with each mode (Hz)

Experimental Data - Brownjohn, J.M.W. et al. 'Ambient Vibration Re-Testing And Operational Modal Analysis Of The Humber Bridge'. (1987)

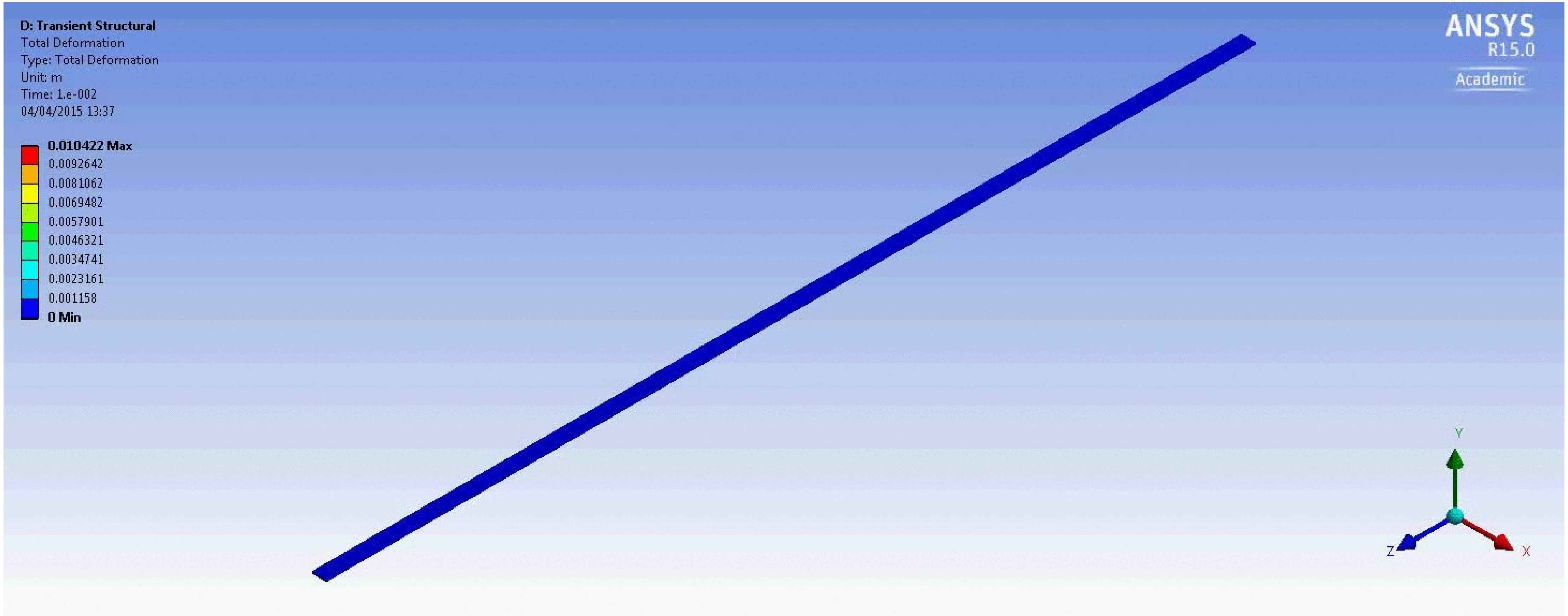
Frequency Response



Transient Response

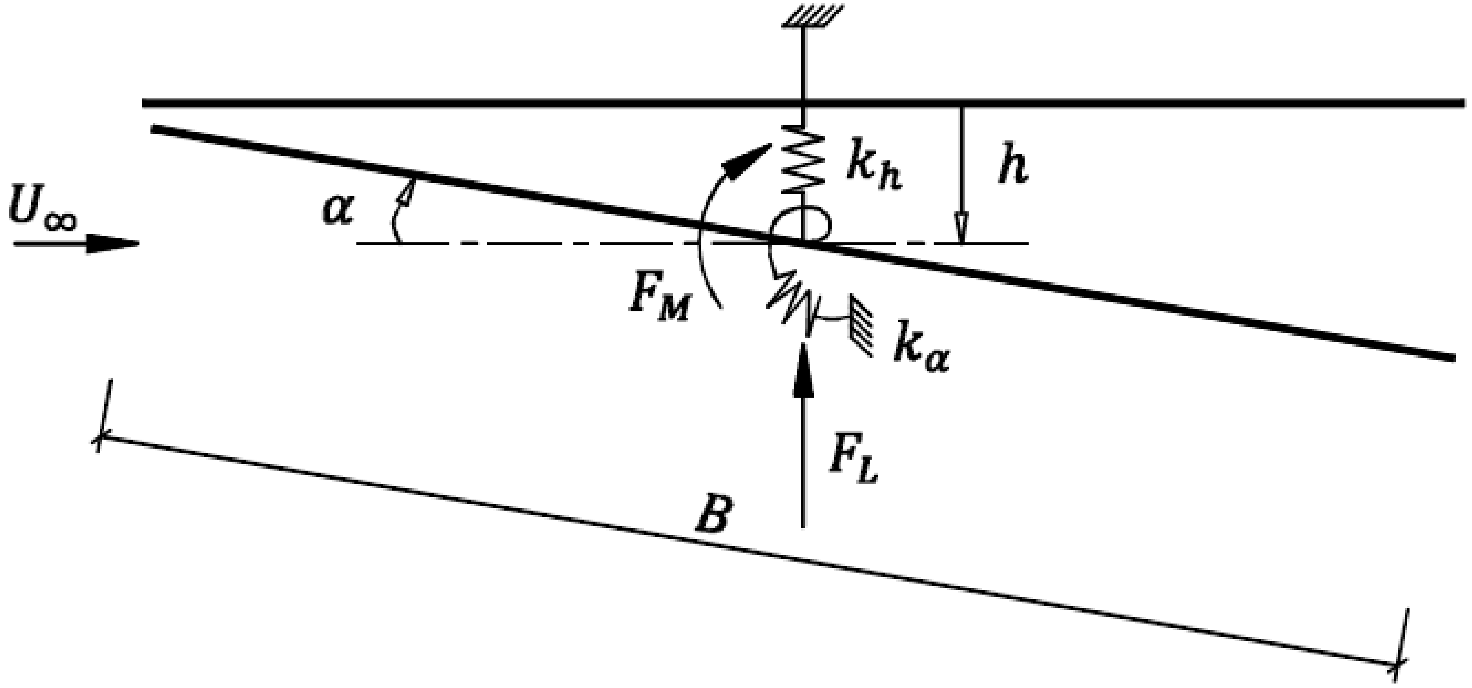


Transient Response



Flutter

- Type of aerodynamic effect on bluff bodies
- Coupled motion between vertical and torsional oscillations
- Critical condition occurs at zero damping



Analytical Approach

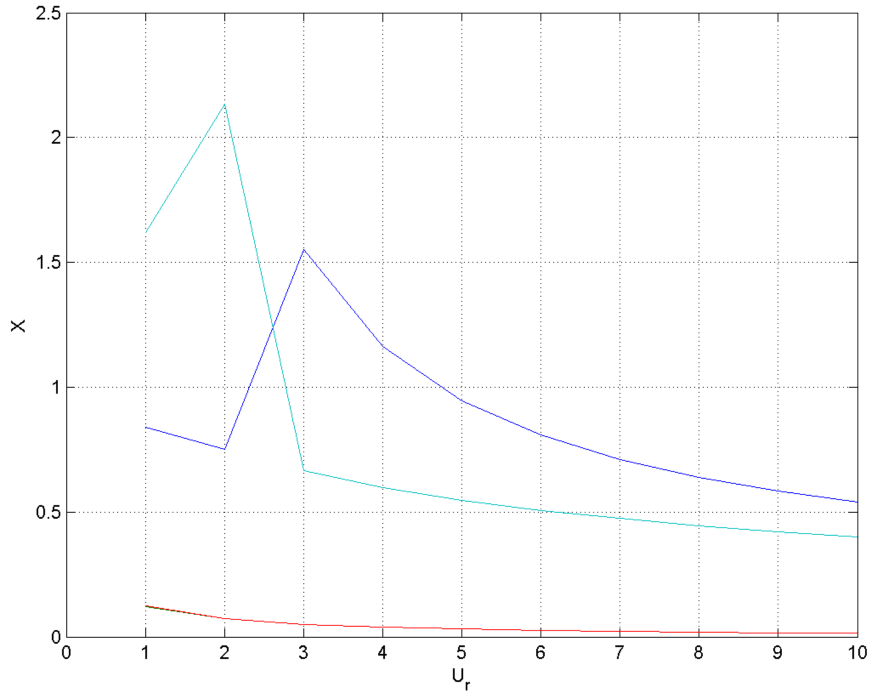
- Equation of motion
- Theodorsen theory
- Scanlan theory

Image Credit - T. Abbas and G. Morgenthal, "Hybrid Models for Assesing the Flutter Stability of Suspension Bridges," in The Seventh International Colloquium on BluffBody Aerodynamics and Applications, Shanghai, China, 2012.

Analysis and Results

Theodorsen Circulatory Function → Aerodynamic Derivatives → Critical Wind Speed

- Aerodynamic derivatives are obtained from equating Theodorsen and Scanlan theories
- Resolving the system of equations formed with the equations of motion and Scanlan self-excited force equations
- The solution for varying reduced frequencies is plotted and the critical wind speed is found where they intersect
- Obtaining a critical wind speed of 20m/s



Structural Concluding Remarks

- Produced both an analytical and computational model of the Humber Bridge
- For each model mode shapes and natural frequencies were found
- A transient response to wind induced vibrations was obtained
- A frequency and phase response of the bridge was calculated
- A flutter critical wind speed was found by using the first natural frequencies of the computational model

CFD Aim

- To accurately model wind flow in order to derive forces
- Vortex shedding is a cause of some wind induced vibrations
- Vortices impart a force on an object which they are shed from
- Vortex shedding can be periodic - causing oscillating forces
- Aim of the subgroup was to determine the frequencies of oscillating forces

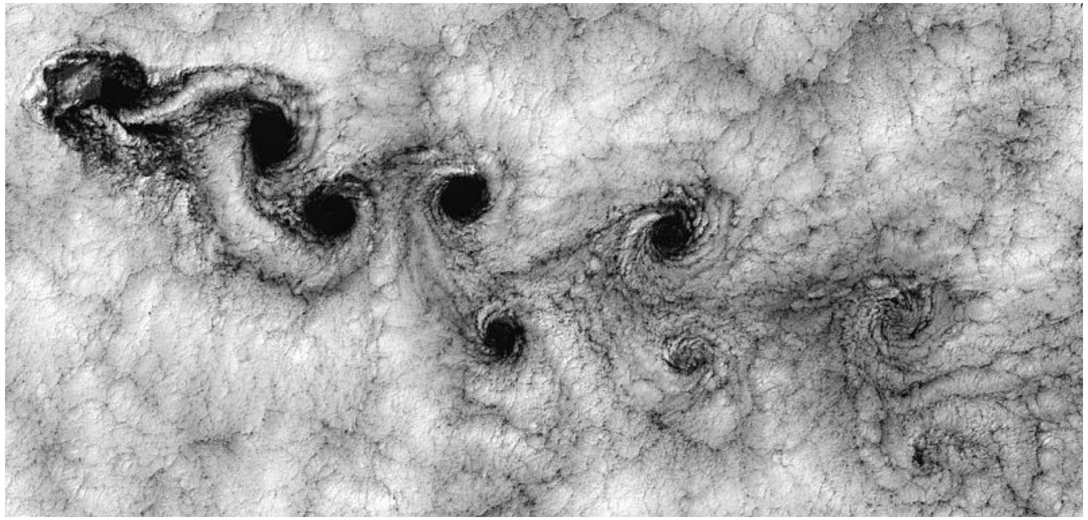


Image credit – Image by Landsat 7 of clouds off of the Chilean coast near Juan Fernandez Islands. The clouds are showing alternating vortex shedding. (1999).

Computational Fluid Dynamics

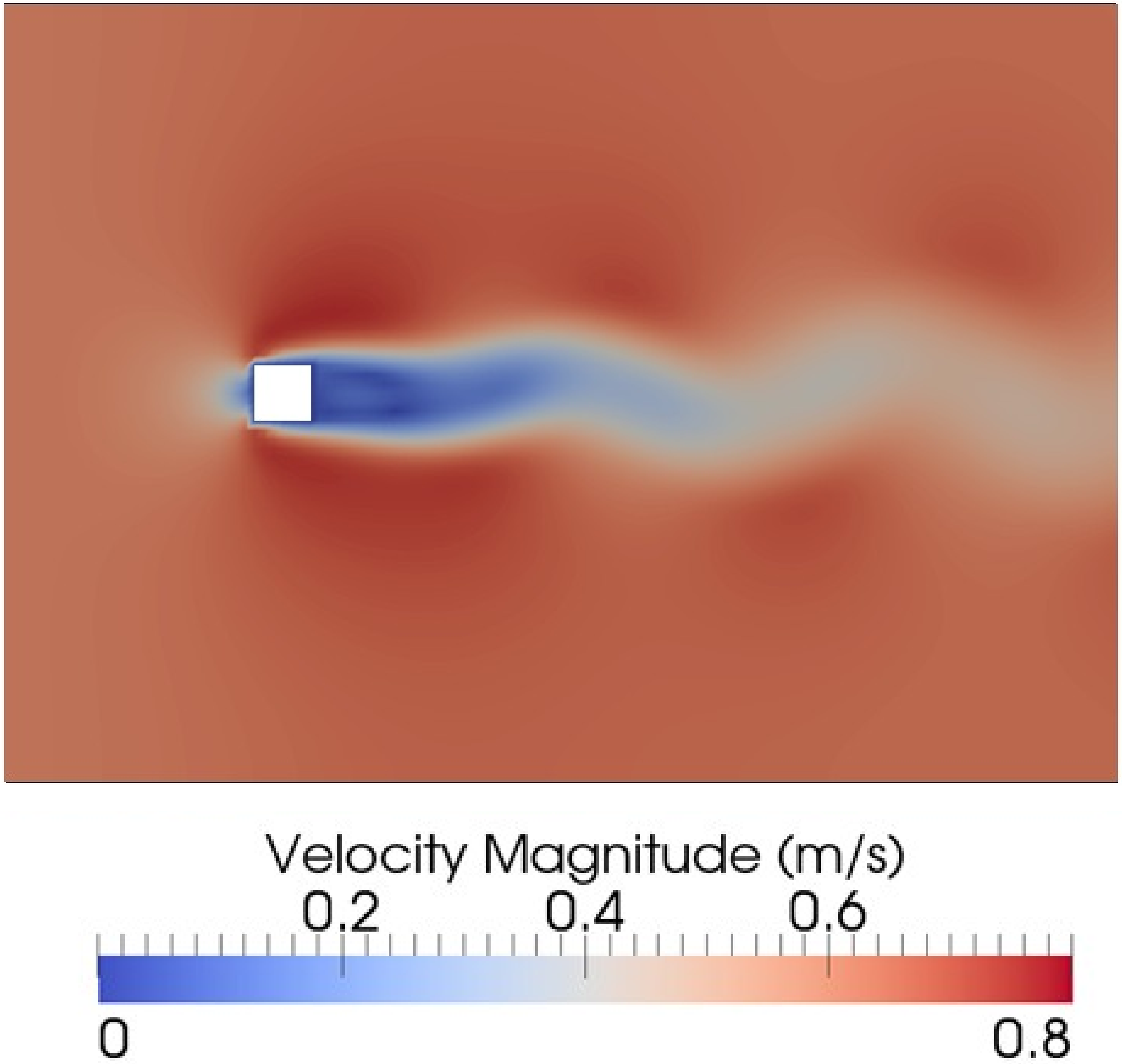
- Developed a CFD simulation of turbulent atmospheric wind flow over the Humber Bridge deck
- Used open source CFD software – OpenFOAM.

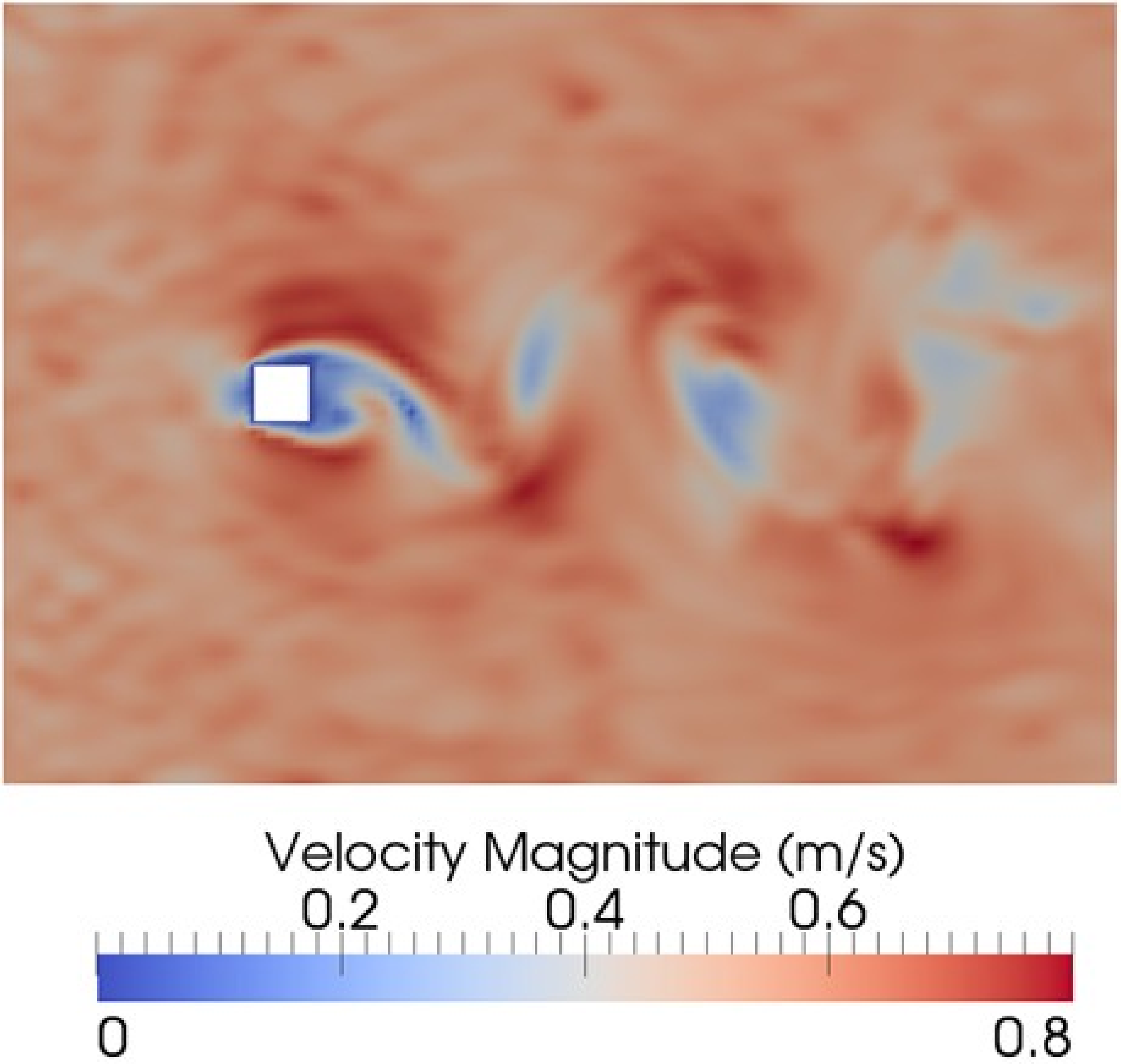
Parameters that were considered:

- Needed to capture time-dependent flow phenomena e.g. vortex shedding
- Required an inlet condition representing realistic atmospheric turbulence
- Required a mean inlet profile for realistic air flow

Turbulence Modelling

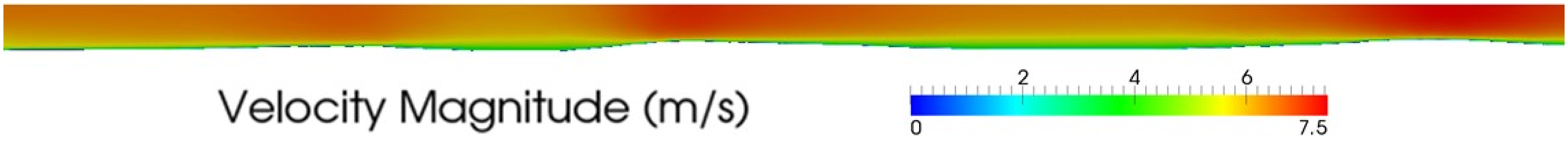
- Reynolds-Averaged-Navier-Stokes (RANS) models not appropriate
- Used a Delayed Detached Eddy Simulation (DDES) turbulence model
- DDES uses spatial filtering
- DDES requires a high resolution mesh
- Requires an explicitly defined turbulent inlet condition

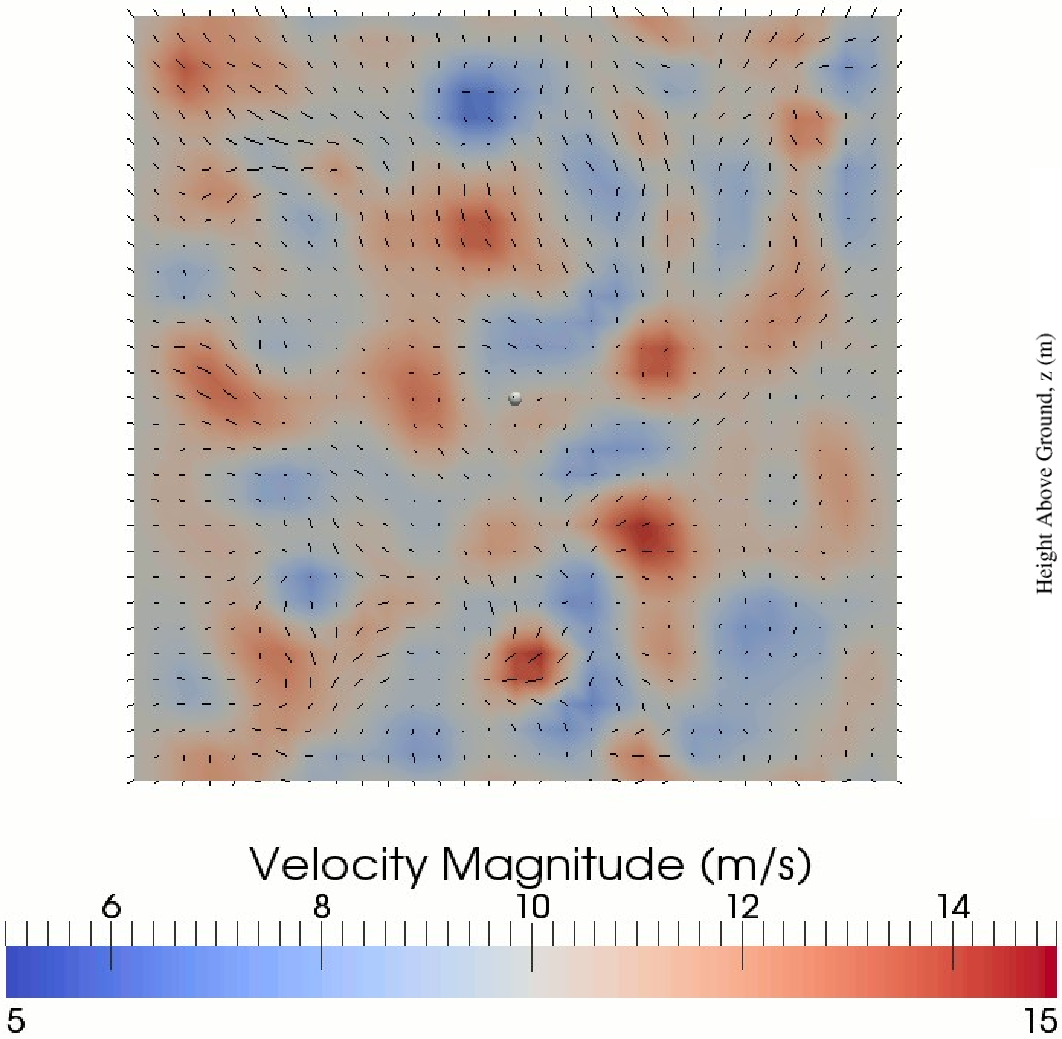

Velocity Magnitude (m/s)
0.2
0.4
0.6
0
0.8

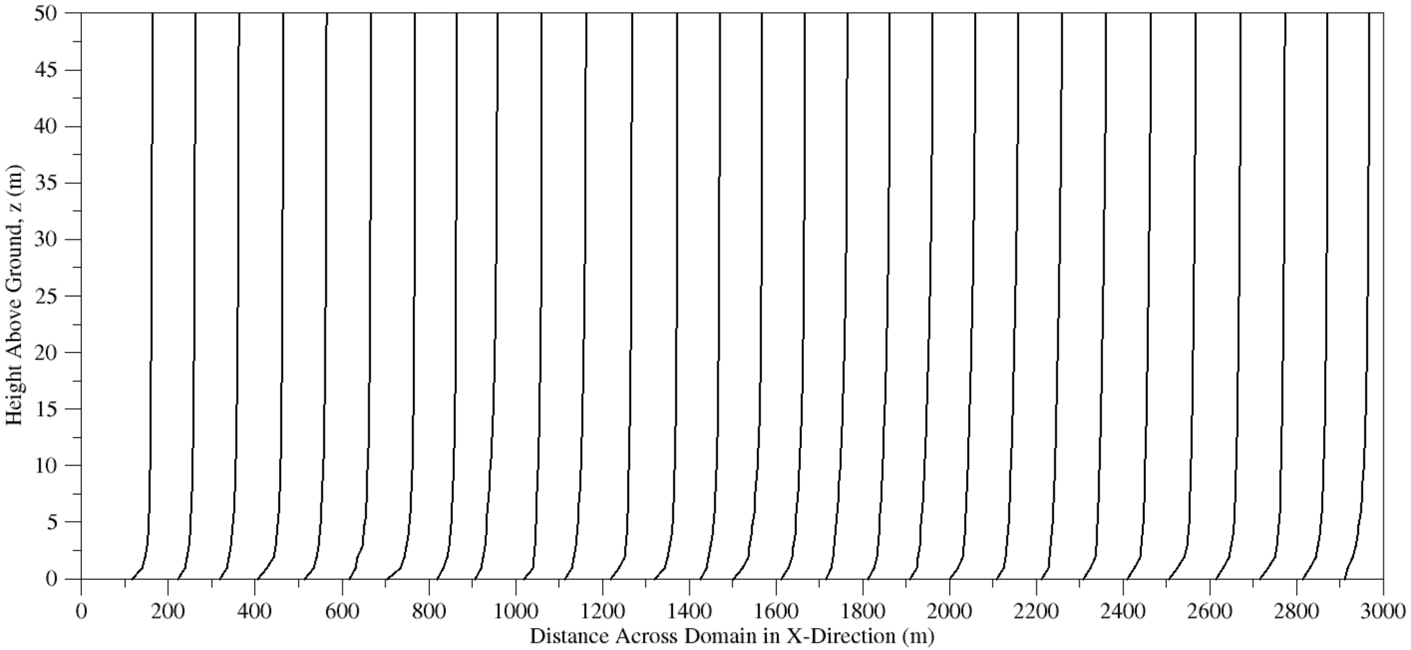

Velocity Magnitude (m/s)
0.2
0.4
0.6
0
0.8

Inlet Conditions

- Required a mean inlet profile superimposed with artificial turbulence
- A turbulent inlet was created using a synthetic eddy method (SEM)
- Flow over terrain used to develop a mean inlet profile

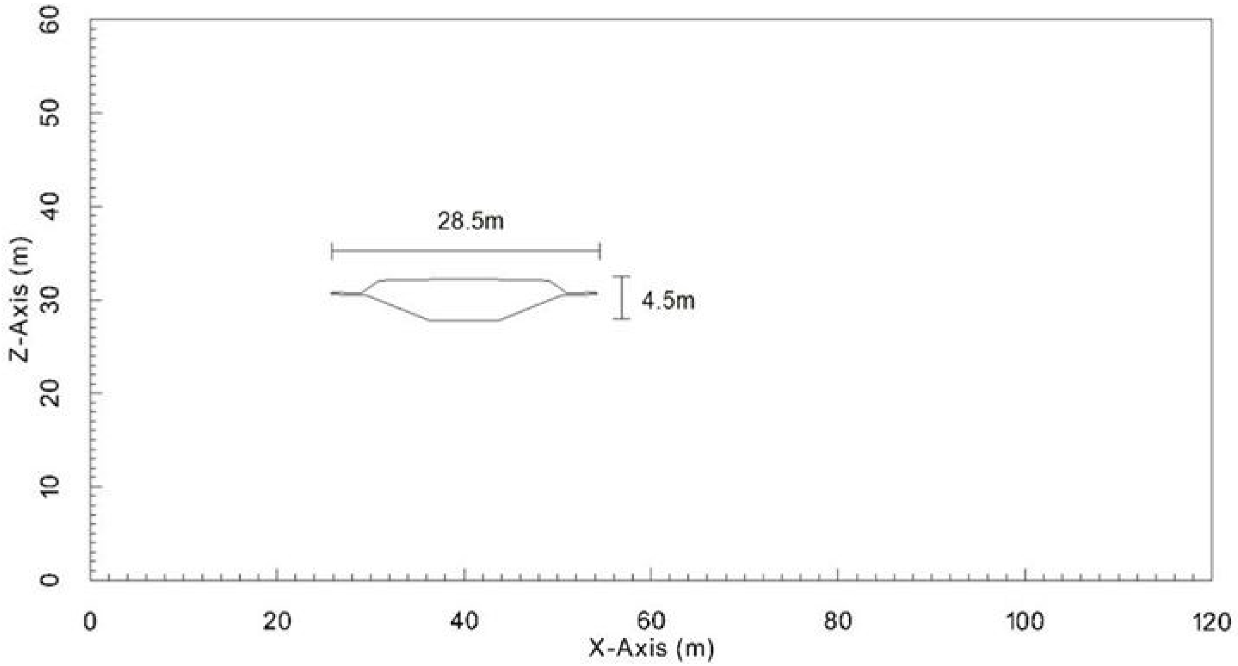


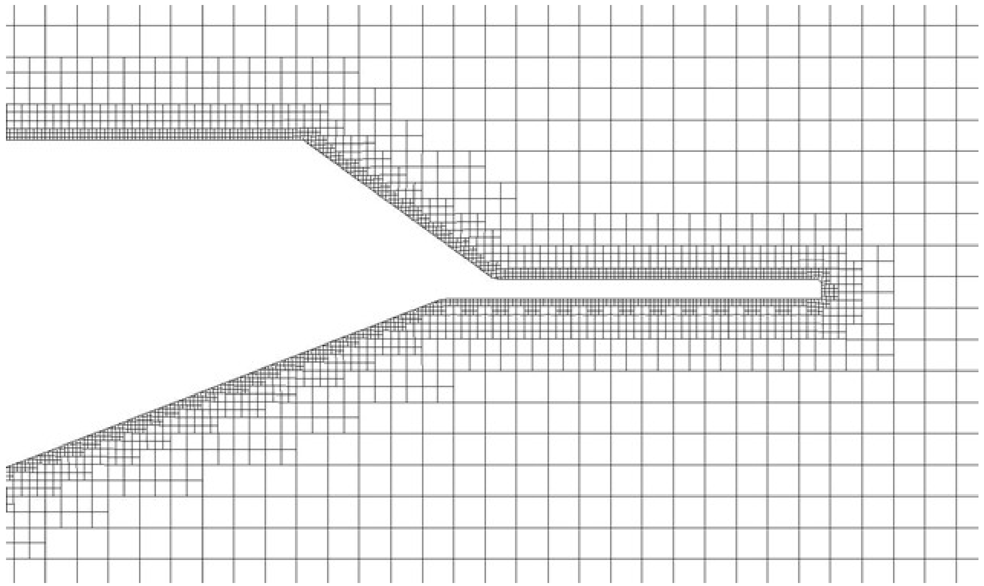

Velocity Magnitude (m/s)
6
8
10
12
14
5
15

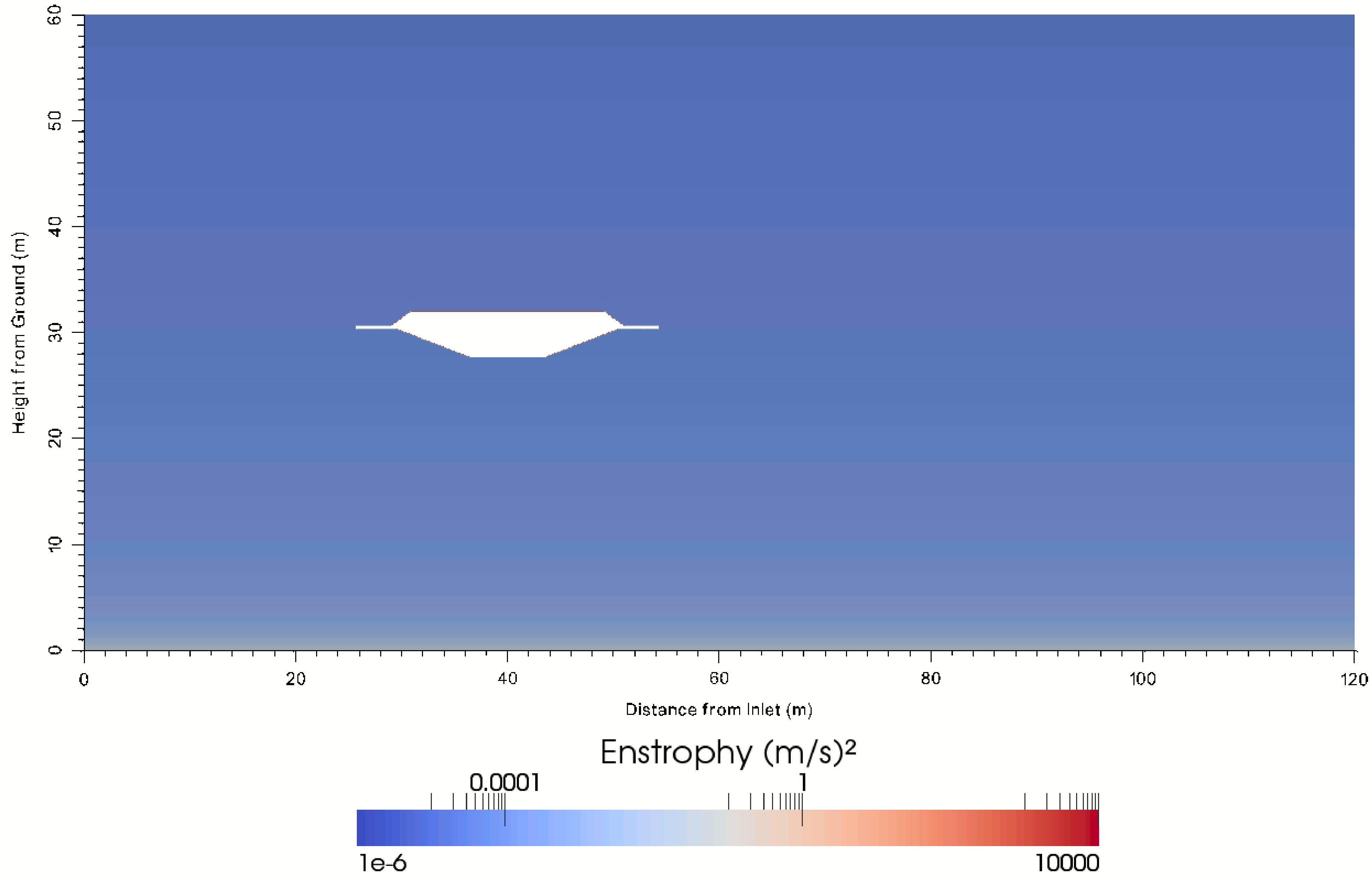

Height Above Ground, z (m)
Distance Across Domain in X-Direction (m)
0
5
10
15
20
25
30
35
40
45
50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000

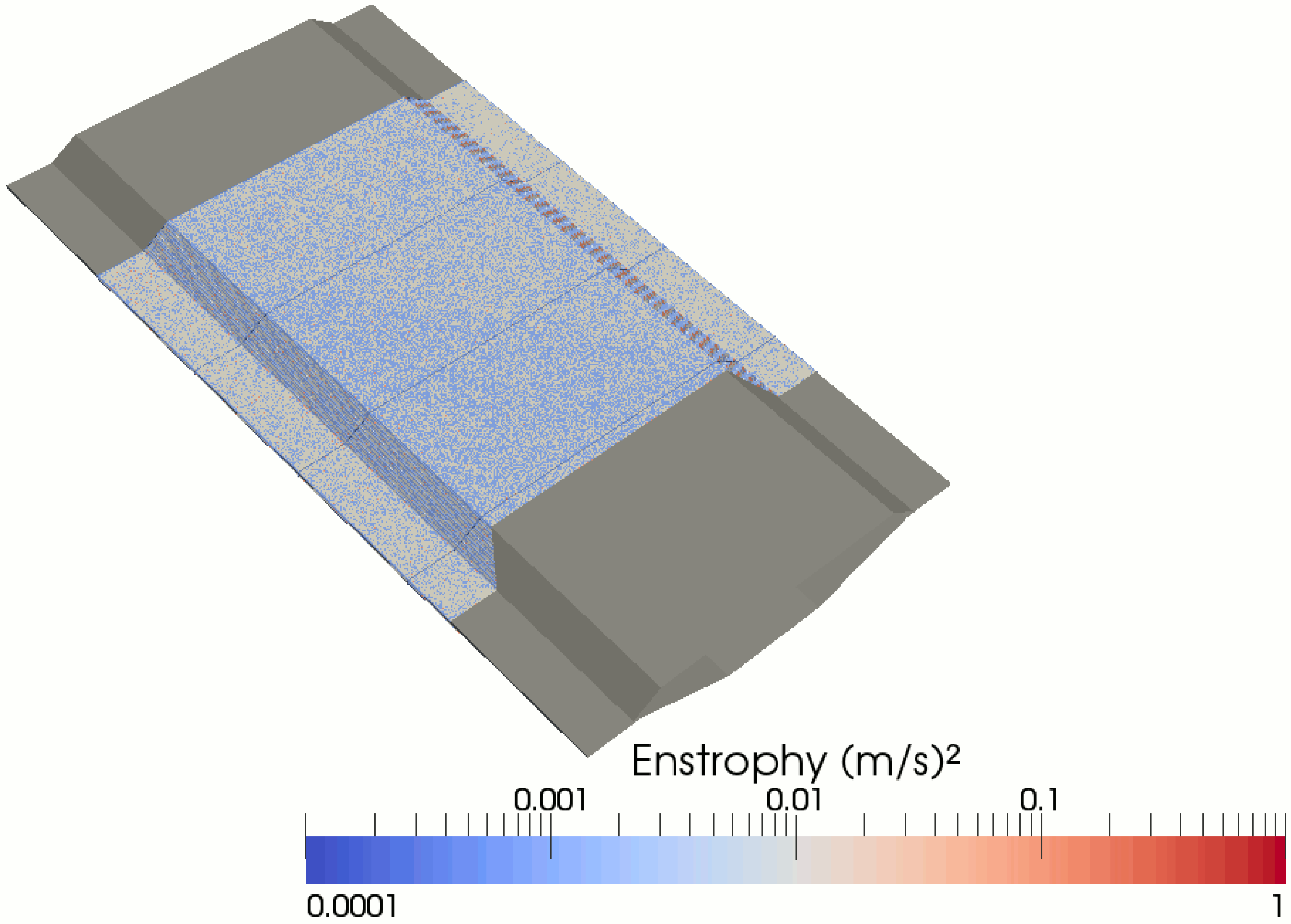
Simulation Setup

- Simulated flow over a 10m stretch of the bridge deck
- The velocity profile moved at 1m/s across the deck
- 12 minutes of air flow was simulated
- Simulation took 4 weeks to develop a wake



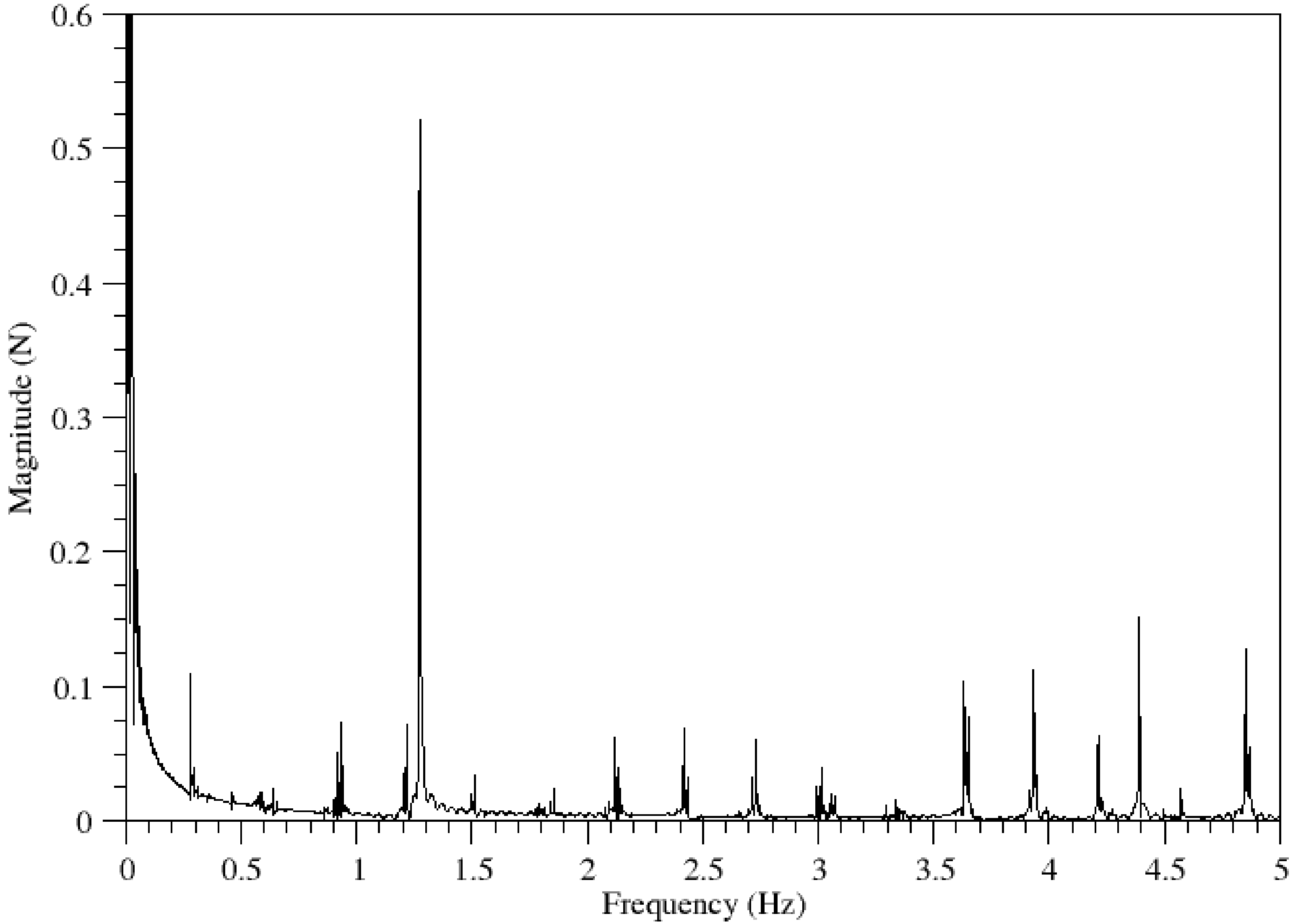


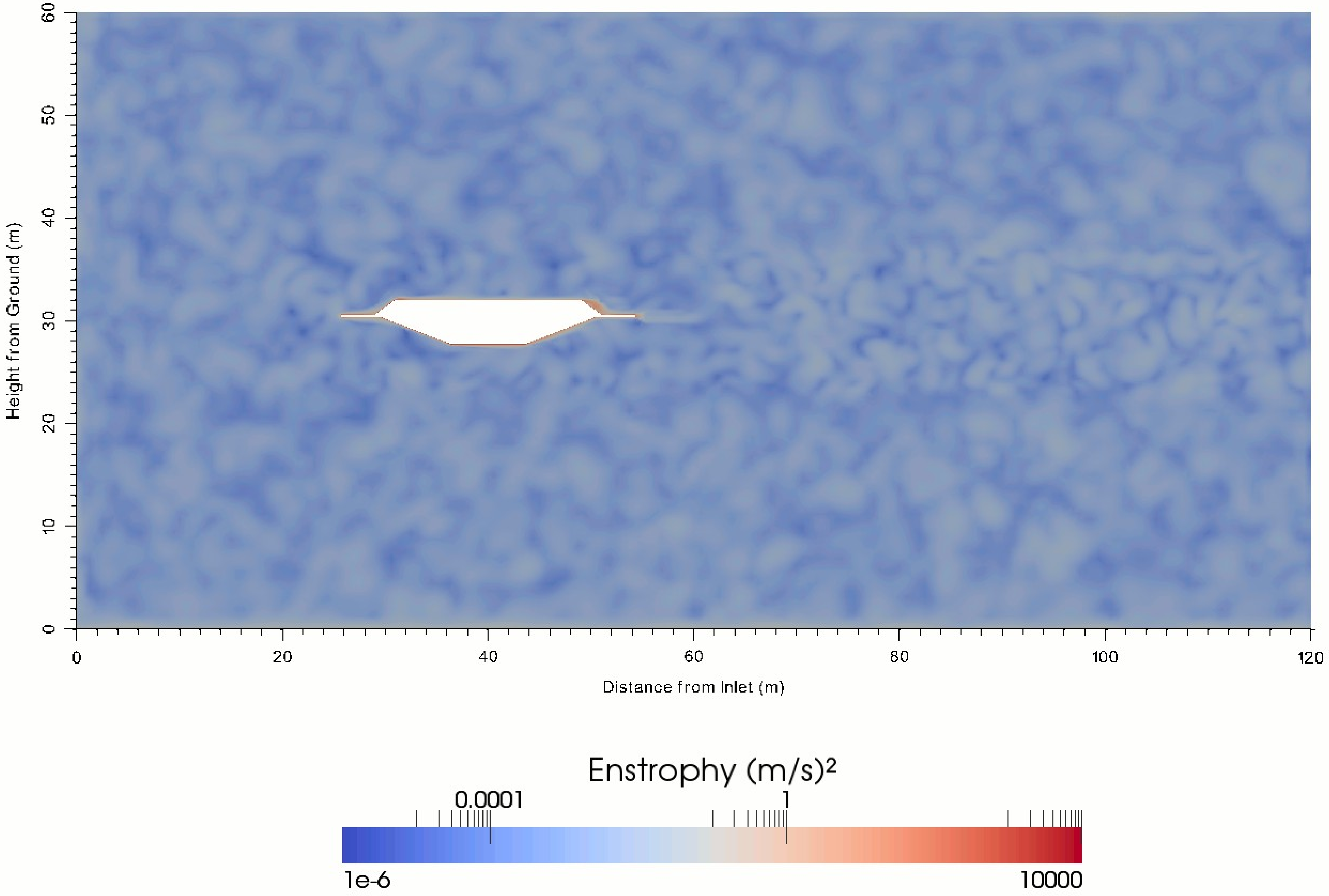

Height from Ground (m)
Distance from Inlet (m)
0
10
20
30
40
50
60
0
20
40
60
80
100
120
Enstrophy (m/s)²
0.0001
1
1e-6
10000



Enstrophy (m/s)²
0.001
0.01
0.1
0.0001
1

Fast Fourier Transform – Frequencies





Height from Ground (m)
60
50
40
30
20
10
0
0
20
40
60
80
100
120
Distance from Inlet (m)
Enstrophy (m/s)²
0.0001
1
1e-6
10000

CFD Concluding Remarks

- Produced a comprehensive model of wind flow over the Humber Bridge deck
- Included relevant parameters – atmospheric, transient flow with real turbulence
- Theoretically could be applied at other wind speeds and directions
- Compared with structural analysis group natural frequencies

Final Conclusions

- CFD simulation is capable of generating forcing frequencies and amplitudes
- Structural analysis enables the calculation of natural frequencies and dynamic response of the bridge
- The forcing and natural frequencies were different
- Resonance will not occur at this wind speed
- Further simulation of CFD testing would be prohibitively costly at higher wind speeds
- Wind tunnel testing is currently more appropriate

Any Questions?