G2 Report

The Causes and Effects of Wind Induced Vibrations on the Humber Bridge

Damien Fieldhouse, Patrick Lambton, Joe Morgan, Josh Mullins, James Richmond, Victoria Triay Jiménez

2015

4th year MEng Group Project

I certify that all material in this thesis that is not my own work has been identified and that no material has been included for which a degree has previously been conferred on me.

Signed...

College of Engineering, Mathematics, and Physical Sciences
University of Exeter

G2 Report

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1. Group objectives and deliverables

The aim of this project was to research the dynamic response of the Humber Bridge when subjected to atmospheric air flow. Project work was divided between two subgroups, focusing on Computational Fluid Dynamics (CFD) and structural analysis respectively. Using data from the computational fluid model, the rate of vortex shedding could be determined. Another aim was to analyse the structure of this bridge in terms of vibrational modes and natural frequencies. By evaluating the data generated by both subgroups, an understanding of the bridge's response to air flow could be obtained. The Humber Bridge was used as a case study because its structural characteristics are well documented [1]. The aims of the two respective subgroups are discussed in the sections below.

1.1. Structural subgroup

The aim of the structural subgroup was to develop numerical and analytical models in order to evaluate the vibrational and structural behaviour of the bridge deck. The natural frequencies obtained from these methods were compared to one another and to an experimental study in order to validate the results. Brownjohn [1] conducted an experimental study of the Humber Bridge in 1987 which was used as a benchmark throughout the project.

By considering the results generated by the CFD subgroup, the aerodynamic behaviour of the bridge could be predicted for phenomena such as flutter and vortex-induced vibrations. The degree to which vibrations are generated at a given air speed can be derived. Based on the vibrational modes calculated, an analysis of the flutter stability limit can be carried out and the critical wind speed found.

1 CFD subgroup

The aim of the CFD subgroup was to develop a CFD case within OpenFOAM [2] simulating turbulent wind flow around the bridge deck. This was undertaken using a Delayed Detached Eddy Simulation model (DDES). By using a DDES model, the turbulent fluctuations within the wake are solved explicitly, allowing accurate calculation of the vortex shedding frequency. This frequency of vortex shedding could be compared to the results from the structural subgroup in order to evaluate the response of the bridge. Set up of this model required proper definition of the mesh, turbulence model and inlet conditions. The CFD subgroup's work packages were focused around these tasks.

2. Work programme – individual work packages

The project was broken up into a number of sub-projects undertaken by the various group members. These individual projects had specific aims and objectives relevant to their area of research. A breakdown of the individual projects is shown in the sections below.

2.1. Victoria Triay Jiménez - Aerodynamic stability analysis of long-span suspension bridges

The aim of this individual package was to determine the critical wind speed through analytical assessment of the flutter instability. The program MATLAB was used to calculate equations that were too time consuming to solve manually.

Objectives

- To obtain the relevant structural, vibration and material properties of the Humber Bridge and produce a realistic aeroelastic study of the structure.
- To gain appropriate knowledge of coding so as to create a suitable MATLAB script for the given case study.
- To develop an analytical method to determine aerodynamic effects on a structure.

Deliverables

- A MATLAB script capable of calculating the critical flutter velocity of a bridge.
- A critical flutter velocity for the Humber Bridge.

2.2. Patrick Lambton – Calculating the dynamic characteristics of the Humber Bridge using analytical methods

The aim of this individual project was to develop a method to evaluate the dynamic characteristics of the bridge, using an analytical approach.

Objectives

- To model the bridge structure using mass and stiffness matrices for the three different types of vibration; lateral, vertical and torsional.
- To use these matrices to calculate the natural frequency of the structure at different modes and for horizontal, vertical and torsional vibrations and possibly combinations thereof.
- To compare the different models with other subgroup members and with experimental data.
- To hypothesise what effects different wind loads would have on the structure, based on the dynamic characteristics.

Deliverables

- A set of scripts that can be used to create and solve the mass and stiffness matrices for each model of the bridge.
- A set of mode shapes and natural frequencies for each model.
- A comparison of the results with known results from an experimental testing of the bridge and other structural subgroup members.

2.3. Damien Fieldhouse – The vibrational characteristics of the Humber Bridge

The aim of this project was to apply the CFD subgroup's wind data into a structural finite element (FE) model of the Humber Bridge to predict vibrational characteristics.

Objectives

- To use the finite element method to calculate the vibrational characteristics of the Humber Bridge.
- To obtain the lateral, longitudinal and torsional frequencies and mode shapes of the bridge.
- To obtain the transient response of the bridge deck to dynamic pressure distributions provided by the CFD subgroup.

Deliverables

- A Computer Aided Design (CAD) model of the Humber Bridge.

- A fully discretised FE scale model of the Humber Bridge which takes into account material properties and boundary conditions to predict the vertical, torsional and lateral natural frequencies.
- A FE model that generates the transient vibrational response of the bridge deck to time variant pressure distributions that represent vortex shedding.

2.4. Josh Mullins - The effects of topography on wind flow

The aim of this project was to study the effect of topography near the Humber Bridge on wind flow, and determine the feasibility of including topographic data in group CFD simulations.

Objectives

- To develop a method to integrate topographical data for analysis in OpenFOAM.
- To investigate the effect of topography on wind flow.
- To assess the effect of turbulent wind flow on the Humber Bridge deck.

Deliverables

- Fluid domains derived from topographic data with appropriate boundary conditions to accurately simulate the Atmospheric Boundary Layer (ABL).
- A CFD simulation of fluid flow over complex terrain and a validation of the results.
- A study on how topography affects wind flow over the Humber Bridge.
- A mean velocity inlet profile for CFD subgroup simulation of air flow past the Humber Bridge.

2.5. James Richmond – Inlet conditions for large eddy simulation of the atmospheric boundary layer

The aim of this project was to create a turbulent inlet condition suitable for simulating atmospheric air flow based on the Synthetic Eddy Method (SEM) [3].

Objectives

- To research the Synthetic Eddy Method and develop an implementation of it within OpenFOAM.

- To validate the inlet condition against common inlet conditions to ensure physicality of the solution.
- To aid in the setup of the group CFD simulation of flow past a bridge deck with regards to the inlet condition.

Deliverables

- An inlet condition using the Synthetic Eddy Method to generate coherent turbulence.
- A validation of the method against other common approaches.
- A set of inlet data to be used within the CFD subgroup for the group simulation.

2.6. Joseph Morgan – Modelling of turbulent effects on a bridge deck structure

The aim of this project was to investigate the different methods of modelling turbulence, with a focus on simulating vortex induced vibrations.

Objectives

- To investigate the interactions of fluid with a static object such as a bridge and to understand the effects that these interactions can have.
- To investigate the different methods of modelling turbulence.
- To aid in the creation of an accurate representation of air flow over the Humber Bridge.

Deliverables

- An appropriately chosen turbulence model for modelling flow past the Humber Bridge.
- A CFD simulation on a well-documented geometry which demonstrates wind induced vibrations, with analysis and comparison to pre-existing experimental data.
- Data extracted from the Humber Bridge simulation for use with the results of the structural subgroup.
- An analysis of the Humber Bridge simulation results.

3. Methodology and experimental design

3.1. Structural subgroup

The three individuals in the structural sub-group worked in parallel, with values such as the section properties being shared between the members throughout, to make sure the models were consistent within the group. The three members each worked on their own analysis and thus each individuals work will be described separately below.

1 Patrick Lambton

Initially, a preliminary model of the bridge was made, taking into account only the lateral, vertical and torsional stiffness of the box girder deck. This model assumed a sinusoidal mode shape. From the mode shape the maximum strain and kinetic energy could be calculated by integration of the mode shape. As these two quantities are equal, the frequency of vibration could then be obtained in this manner. This provided somewhat inaccurate results, as the main factor in the stiffness of a suspension bridge is the effect of the cables, rather than the deck itself, and this model took into account the latter and not the former.

In order that the cables could be taken into account for the model, a more complex method of analysis was required. This was done by using the direct stiffness method, in which the entire structure was broken down into a series of elemental stiffnesses, and lumped masses that link to each of the degrees of freedom. These elemental stiffness matrices were created and combined into a global matrix using Octave, an open source program with similar functionality to MATLAB. The Eigen solution of these matrices was calculated using a built in function in Octave. This provided both the mode shapes and natural frequencies of the bridge.

Each model took into account different degrees of freedom. The vertical vibration model took into account the following degrees of freedom:

- Vertical and rotational degrees of freedom for the deck nodes
- Vertical and translational degrees of freedom for the cable nodes
- Vertical, translational and rotational degrees of freedom for the tower nodes

The degrees of freedom were suitably selected for every model used. In total seven different models were made; four for the vertical vibration, one for lateral vibration and two for torsional vibration. Once the Eigenvector was found for each model, the relevant values were plotted to give an image of the mode shape. For each Eigenvector, a corresponding Eigenvalue represented the square of the natural angular frequency.

2 Victoria Triay Jiménez

To produce an adequate flutter analysis a detailed research on aeroelastic stability was necessary. To develop an accurate stability study, a clear understanding of the aerodynamic forces and coefficients was necessary. Initially, a MATLAB script was created to analyse flutter stability. Theodorsen and Scanlan [4] derived an analytical method to obtain the critical wind speed for flutter stability. This consists of resolving the equations for the coupling between lift forces and moments in order to calculate aerodynamic derivatives. These are described in terms of the circulatory Theodorsen function.

For further analysis of this coupled phenomenon, it is assumed that the bridge deck is a linear-elastic system. For this case, the equations of motion and the aerofoil forces were equated and the determinant of the amplitude coefficients set to zero. The critical flutter wind speed is obtained from the plot of the resultant values against the reduced wind speed [5]. An initial set of results is obtained from the vibrational properties inherent to the Humber Bridge [6]. The vibrational properties were obtained from the other structural subgroup members and further properties calculated, such as the aerodynamic derivatives.

3 Damien Fieldhouse

A scale model of the Humber Bridge was created from the reference drawings which are outlined in Figure 1 [7]. The dimensions were shared within the group to ensure compatibility of all models.

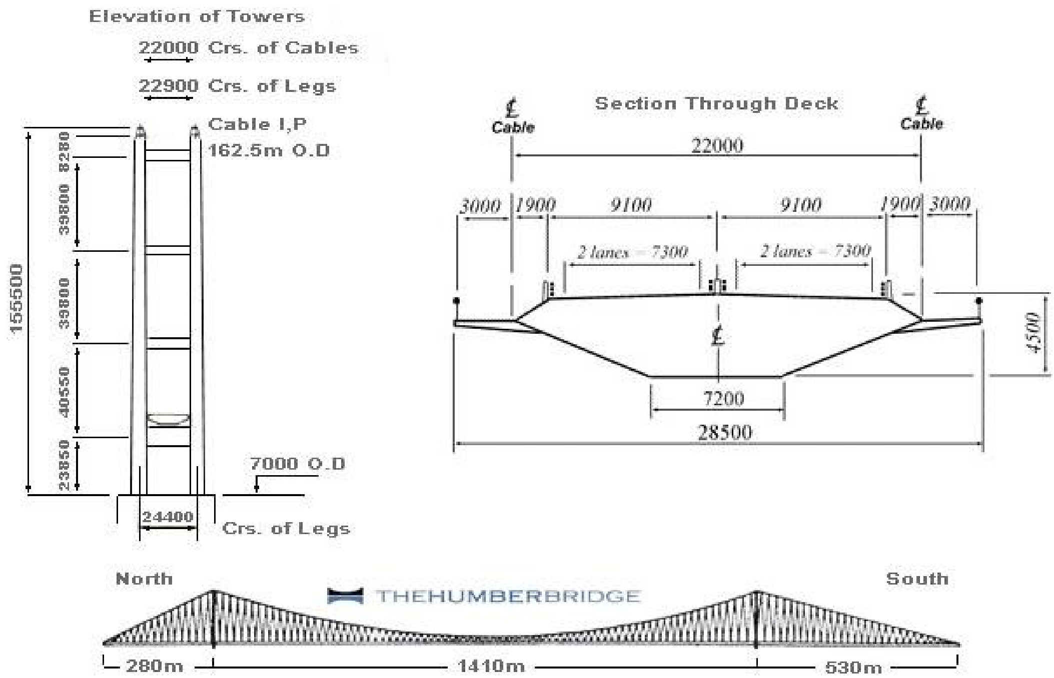

Figure 1. Structural dimensions of the Humber Bridge

The cables were modelled as 1D elements to reduce the computational requirements of the FE simulation. The vibrational effects of the towers were found to be negligible and so only the mid-span of the Humber Bridge was modelled. This provided a representation of the vibrational mode shapes of the bridge.

Upon importing the CAD model to ANSYS Workbench, different material properties were assigned to the hangers, cables and deck to accurately map the properties of the bridge. The Geometry module was then linked to the Static Structural, Modal Analysis, Harmonic Response and Transient Structural modules for full analysis. Fixed supports were applied at both ends of the deck because the bridge uses A-frame rocker bearings which constrain it in three degrees of freedom [1]. Due to the towers having negligible vibrational characteristics, the cable ends were set as fixed. The effect of gravity was applied to the model which was set up for non-linear deformations. Connections were used to link the 1D elements of the cables to the 3D elements of the deck. Zero damping was assumed for the Static analysis, the Modal analysis and the Transient analysis. The Harmonic Response used an estimated damping coefficient of 0.03 for the structure [8].

A mesh convergence study was run on the bridge and the optimal mesh that balanced computational time with accuracy was used for further analysis. The model was set to calculate the first 500 mode shapes of the structure. This was because the individual cables exerted similar frequencies to the main deck section which obscured the main vibrational mode shapes. The First 11 vertical, 4 torsional and 2 lateral mode shapes and frequencies were obtained. The frequency response plot of the bridge was calculated, highlighting the range of frequencies at which resonance could occur. The transient response of the deck to vortex shedding at the first torsional natural frequency was obtained.

The wind velocity that causes vortex excitation was predicted using the known linear relationship between velocity and shedding frequency. This is dependent on the Strouhal number (*St*) which is a dimensionless value used to describe oscillating flow mechanisms around bluff bodies. The relationship is outlined in equation 1, where D is the characteristic length scale, U is the freestream velocity, and ω_s is the shedding frequency.

$$St = \frac{\omega_s D}{U} \tag{1}$$

3.2. CFD subgroup

The aim of the CFD subgroup was to create a simulation of atmospheric air flow past a model of the Humber Bridge deck. This involved the contribution of several different design aspects which were created by the members of the CFD subgroup (Mullins, Morgan, Richmond). These included: creation of the mesh, the specification of the mean inlet profile, the specification of the turbulent inlet profile, the definition of the turbulence model, and the general setup and running of the case.

4 Mesh

To simulate wind induced vibrations, a turbulence model capable of capturing time variant phenomena was required. As the Reynolds number was very high (1.9 million), Delayed Detached Eddy Simulation (DDES) [9] was chosen as the turbulence model. This turbulence model requires the cells next to the wall to be small enough to resolve boundary layer flow ($y^+ \leq 1$). In a study of external aerodynamic flow over the bridge deck, simulating boundary layer flow and separation is important to achieve numerical accuracy of the solution.

The mesh was created using the OpenFOAM native mesher, *snappyHexMesh*. The deck was simplified (removal of guard rails, assumption of a solid deck) to reduce the complexity of meshing. The mesh was refined in the wake region to improve the resolution of downstream flow, and at the inlet, for a more comprehensive definition of inlet turbulence. *SnappyHexMesh* was found to be a robust meshing tool, however, it has some limitations. The addition of boundary layer cells (for resolving boundary layer flow near walls) was problematic. This meant that achieving a sufficiently high resolution mesh along the bridge deck, was hard to achieve. The upper limit for the number of cells in the mesh was limited by the computational resources and time available. Increasing the resolution of the mesh, and thereby the number of cells, would have dramatically increased the time taken to fully simulate vortex shedding in the wake.

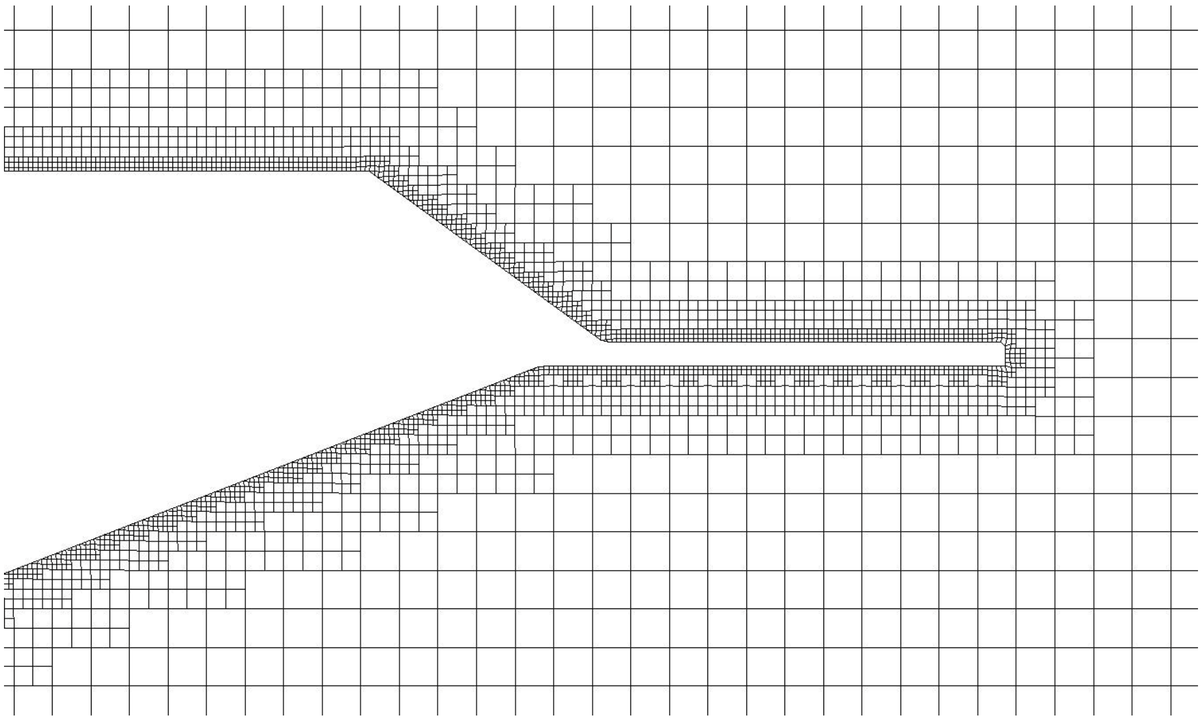

Figure 2. Close-up of boundary layer mesh

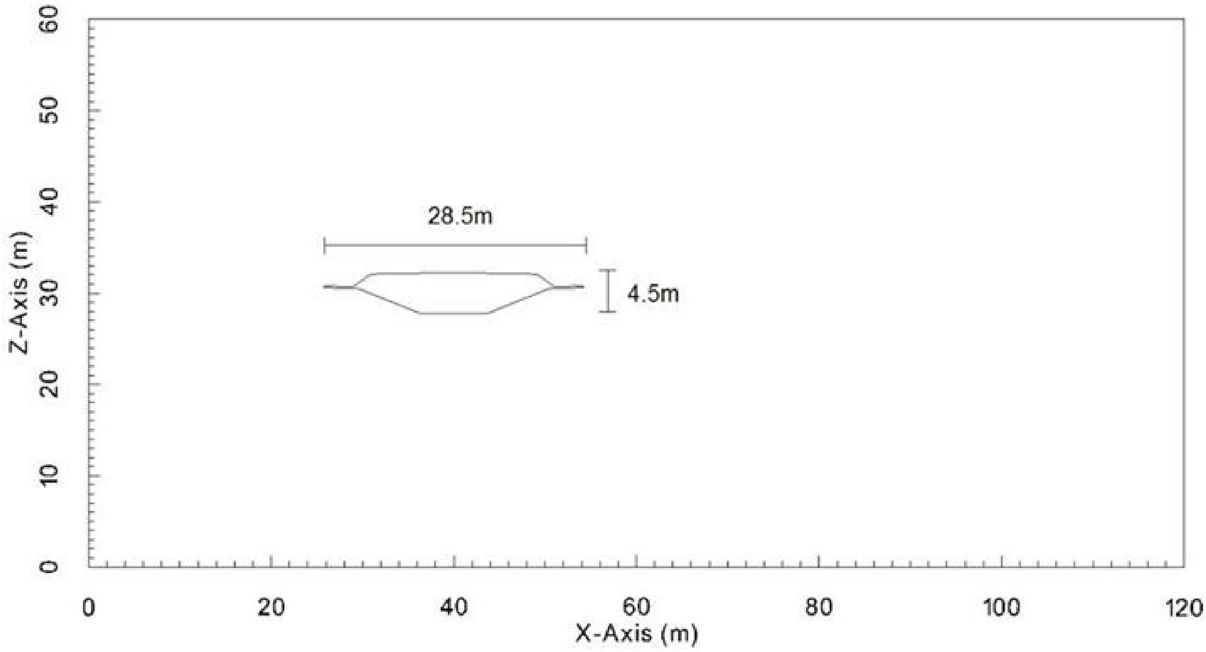

Figure 3. Schematic diagram of flow domain

Figure 2 shows the mesh refinement at the boundary layer of the deck. The cell decomposition method used in *snappyHexMesh* can be clearly seen. Figure 3 shows the layout of the domain. The deck was 8m long in the y-axis. The mesh was composed of 2,342,457 mostly hexahedral cells.

5 Mean Atmospheric Profile

The mean inlet was based on the study of flow over terrain. To evaluate wind flow over complex terrain, appropriate boundary conditions were used to accurately simulate the atmospheric boundary layer. As a mean flow profile was required for final CFD subgroup simulations, the k-epsilon turbulence model was used. This has been shown to produce accurate results in atmospheric flow over complex terrain [10]. Transient flow was captured using a time marching solver, PISO. Boundary conditions for k and epsilon were implemented using the methods proposed by Richards & Hoxey [10], with a top boundary shear stress condition based upon the work of O'Sullivan [11].

In producing geometry suitable for meshing in OpenFOAM, topographic Lidar data was obtained from the UK Environment Agency's Geomatics group. This data was converted to the appropriate Stereolithography (STL) geometry format using MatLab, GlobalMapper and MeshLab software packages. The realistic terrain geometry for the 9km^2 area near the Humber Estuary was meshed in OpenFOAM using the *snappyHexMesh* utility. The wind flow across this terrain was analysed using an inlet condition derived from the MET office wind map [12]. A mean velocity profile was extracted and used in the subgroup DDES bridge simulations. This made the flow over the Bridge deck as similar to real conditions as possible, including the effect of the local terrain on the wind flow. This implicit method was used because explicitly simulating terrain and a bridge deck with sufficient accuracy (using DDES) would have required a very large, high resolution mesh (likely in the order of 1×10^7 cells). Simulating this would have been prohibitively expensive in time and computational resources.

6 Turbulent Inlet Profile

In order to create turbulent inlet velocity data, an inlet had to be created capable of representing the turbulent behaviour of the flow as well as the mean flow profile. Research was initially done into an application of the Synthetic Eddy Method for use within an OpenFOAM solver. This method involves the definition of a number of eddies which are simulated on top of a Reynolds Averaged Navier-Stokes (RANS) simulation run prior to the simulation of the test domain.

This approach provides a much more physical representation of turbulence by replicating the definition of turbulence as a superposition of coherent structures. The eddies are defined with a random intensity within a fixed range and are assigned a random position within a sub-domain in which they are simulated. The eddies are used to create an altered velocity field based on their positions relative to the computational cell within the mesh and the Reynold’s stress tensor at the cell. An example of the inlet condition generated by this approach is shown in Figure 4. This shows a spatial coherence capable of representing multi-directional flows physically.

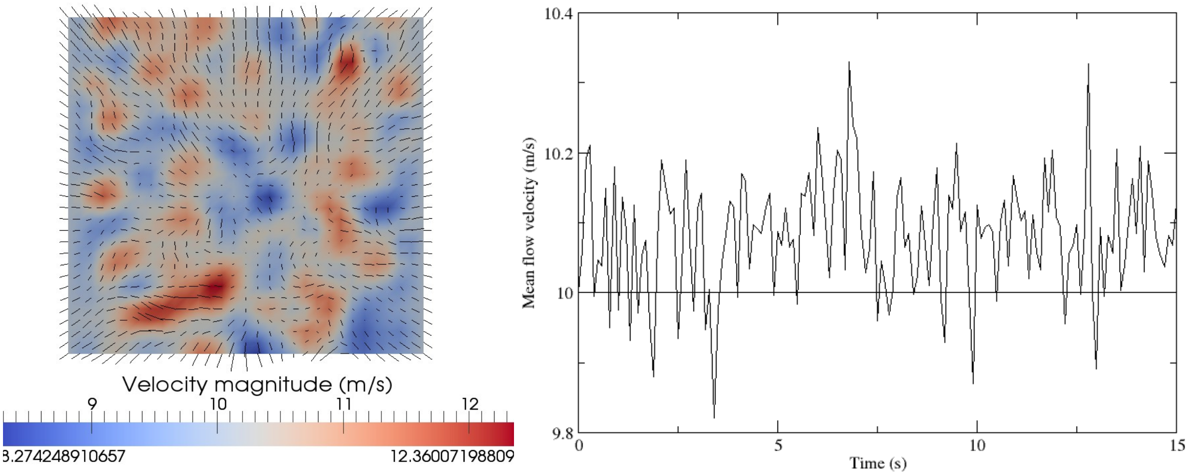

Figure 4: Velocity plot of SEM inlet (left) and average inlet velocity graph (right)

The specification of the method allows for the generation of eddies on top of a mean flow with a variable and specifiable length scale. The inlet generation method is shown to be suitable at representing turbulence physically and with a high degree of numerical accuracy. Use of this inlet condition within the group simulation of air flow past a bridge would yield better results than the default turbulence inlets present in OpenFOAM.

7 Modelling Choices

To simulate wind induced vibrations, a turbulence model that can capture time dependent phenomenon is required. As such, LES modelling was chosen as the most appropriate turbulence model. There are multiple different LES models. Due to the large Reynolds number and the cubic nature of the cells used, DDES was the most appropriate modelling choice.

The inlet of the domain was set to have a turbulent atmospheric profile with a maximum velocity of $1ms^{-1}$ at the height of 60m above the ground. The kinematic viscosity of air was $1.5x10^{-5}$ m^2s^{-1}. The outlet of the domain was set to have an average pressure of 0Pa across its face. The bottom face of the domain was set as a wall. The top face of the domain was set as a slip plane. Terrain topology was omitted from the domain since it was accounted for in the inlet condition. The side walls were set as cyclic boundaries, to preserve the larger turbulent structures.

4. Results and analysis

4.1. Final structural subgroup result comparison

Three main comparisons in the structural subgroup were undertaken. The natural frequency, mode shape and the critical flutter velocity were compared.

The results obtained by Fieldhouse and Lambton were in the form of a set of mode shapes and corresponding natural frequencies. In order to validate these results they were compared with a set of known mode shapes and frequencies that originated from an instrumented testing of the bridge [13]. Of the seven analytical models created, the most comprehensive for each form of vibration; vertical, lateral and torsional, was compared with each of the ones from the experimental data. The two different modelling methods were compared to each another. Figure 5 shows the comparison of these mode shapes with the experimental data. For conciseness, less significant mode shape comparisons are not presented. However, the all the models produced accurate mode shapes.

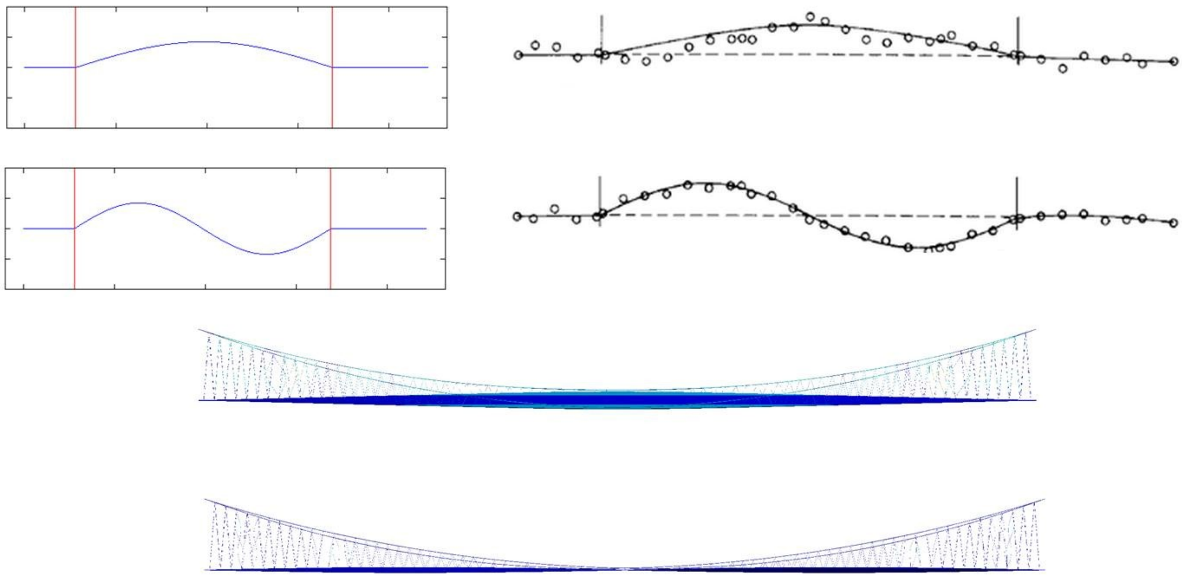

Figure 5. Comparison of modal shapes from analytical (top left), experimental (top right), and computational results (bottom)

For some of the analytical models erroneous extra mode shapes were obtained. This was due to assumptions made to improve the workability of the models. The natural frequencies obtained from the different modelling methods were compared to the measured values and are shown in Table 1.

Table 1. Comparison of modal frequencies with Brownjohn's[13] experimental data

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						

The percentage difference between the analytical results and the true values are, on average; 11.4% for the vertical, 141.7% for the lateral and 147.4% for the torsional model.

The percentage difference between the computational results and the true values are, on average; 45.4% for the vertical, 8.1% for the lateral and 45.2% for the torsional model.

These results show that the FE model was more accurate when predicting the lateral and torsional frequencies however the analytical approach proved better for the vertical modes.

The results obtained by Triay Jiménez and Fieldhouse allowed for the direct evaluation of the critical flutter velocity. From the generic aerofoil and Scanlan aerodynamic equations the determinant of the amplitude coefficients was equated to zero. Frequency values were obtained for a range of reduced wind speeds. The intersection point of the different plots determined the critical wind speed to be 13.13m/s. Given that the Humber Bridge deck is known to handle wind speeds up to 47m/s [13] it is likely that the critical wind speed is much higher.

8 Analysis of the analytical model accuracy

The frequencies obtained from the vertical model were close to the real values because the model accurately took into account every degree of freedom that could affect vertical vibration.

The inaccuracy of the torsional model was probably due to the fact that the warping constant was neglected during the modelling process. The lateral models gave a frequency that was too high, because the lateral deflection of the main cables was not modelled in three dimensions, due to the inherent difficulties in doing so.

9 Analysis of the computational model accuracy

The lateral vibrations of the bridge are accurate for this model due to interactions between the deck and cables having negligible effect on the results.

The inaccuracy of the vertical and torsional frequencies was due to the linear modelling of the connections between the cables and the deck. Inaccurate interactions caused errors to be accumulated for the vertical and torsional frequencies.

10 Analysis of the critical flutter velocity accuracy

The analytical approach produced a lower critical velocity than the computational method. This was due to the considering of coupled phenomenon between vertical and torsional motion which significantly decreases the critical velocity. The computational approach relied on the torsional natural frequency obtained by the model and an approximation of the Strouhal number.

The lack of accuracy of the results was due to the generalised approach undertaken by the analytical technique and the assumptions of the computational model.

4.2. CFD simulation

The results of the CFD subgroup are in the form of a set of simulations run over the course of several weeks. These simulations are representative of atmospheric air flow over the Humber Bridge deck. Basic sinusoidal turbulence was introduced because the SEM inlet was incomplete at the time of running. A secondary simulation was run later with the SEM inlet upon its completion, although time constraints meant that the flow of this simulation wasn't fully developed.

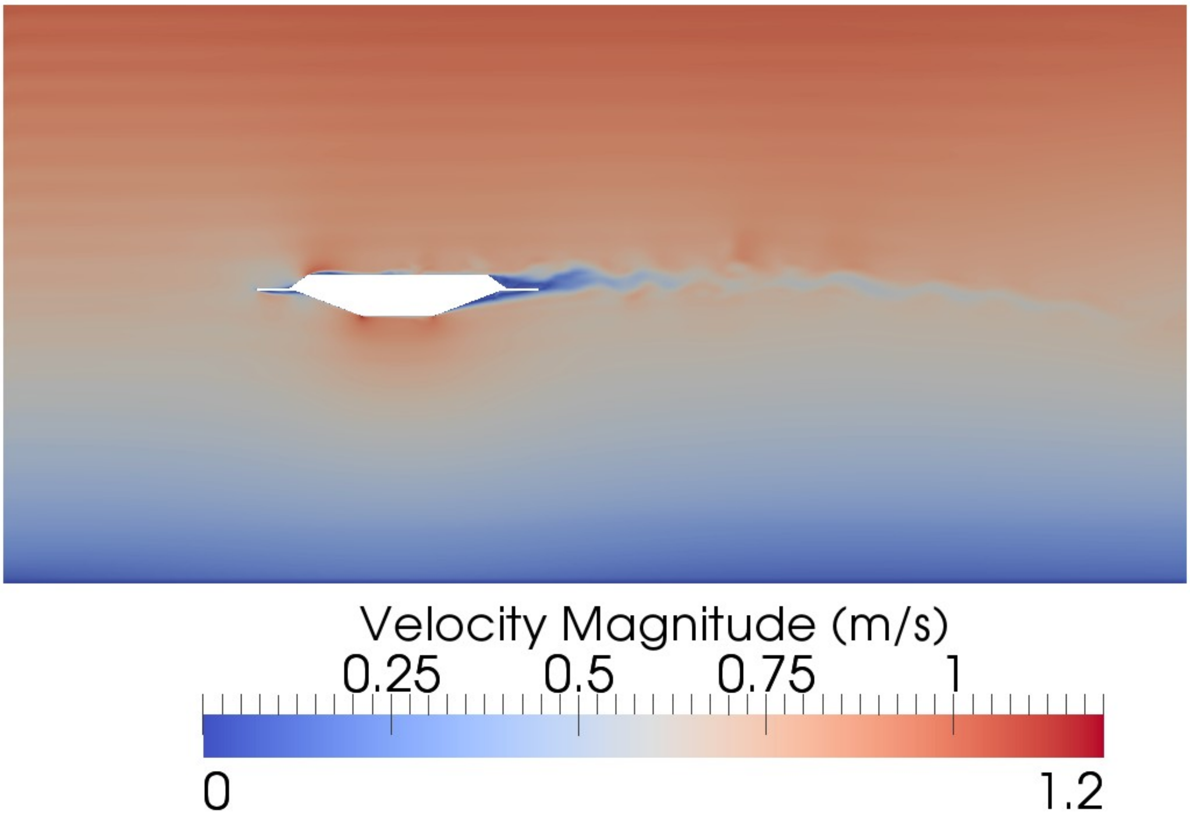

Figure 6: Plot of velocity magnitude of group simulation using sinusoidal inlet

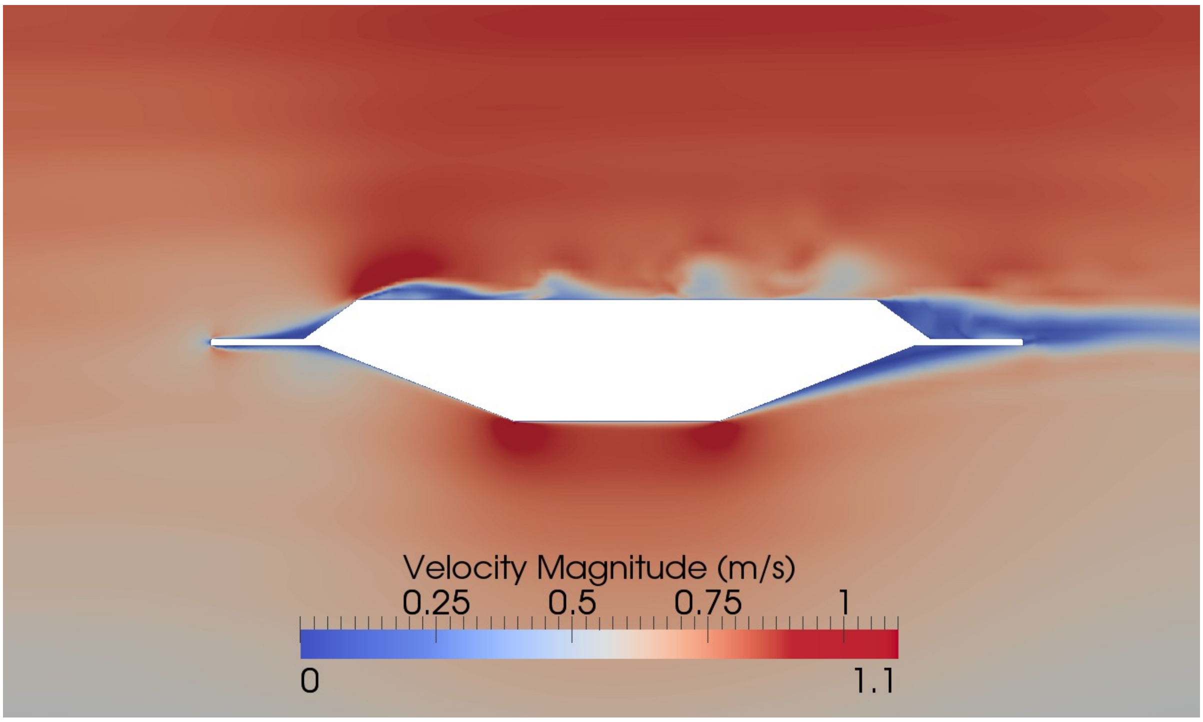

Figure 7. Detailed view of single shear layer vortices

The first simulation using the sinusoidal inlet developed a turbulent, oscillating wake. There is evidence of single shear layer vortices forming at the upper leading edge. These are convected along the upper surface of the deck to form the oscillating wake as shown in Figure 6. It was expected that the fins placed at the sides of the bridge would cause a zone of recirculation designed to delay the separation of the boundary layer. This suppresses the formation of a Von-Karmen vortex street. Such a recirculation zone can be clearly seen in Figure 7 showing the simulation to be accurate. The frequency and magnitude of these vortices can be used to compare against analytical calculation performed by the structural subgroup. A plot of the forces on the deck is shown in Figure 8.

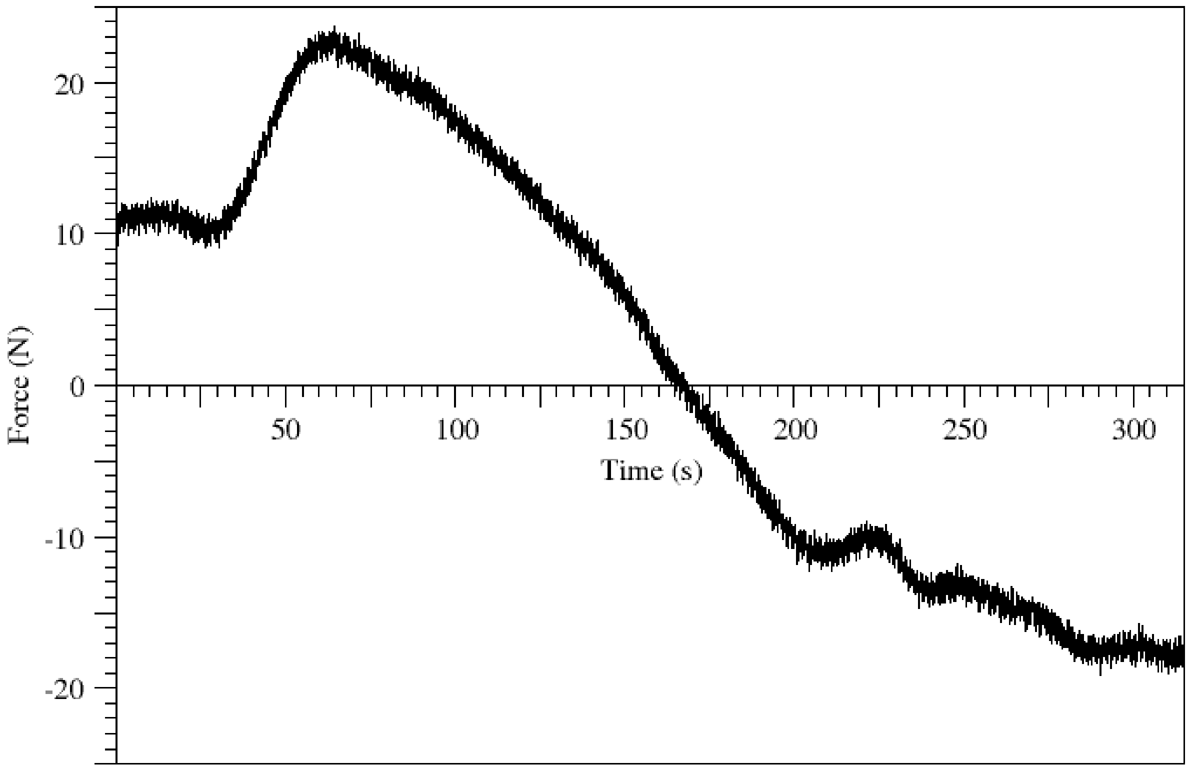

Figure 8: Plot of lift force on the bridge deck

A characteristic of the deck is its negative lift coefficient [6]. This property is successfully shown in Figure 8 after reaching a near steady-state turbulent flow. This occurs after 275 seconds of simulated flow. The lift force on the deck oscillates, indicating periodic fluctuations in the wake. By decomposing this response using a fast Fourier transform, the main shedding frequency was found to be 1.26Hz (Figure 9). These frequencies were compared with results from the structural subgroup.

In this simulation, the y^+ values of the cells adjacent to the wall were in the region of 10-30. This is higher than the requirements for accurate resolution of the boundary layer flow, introducing a degree of numerical error. An increased level of mesh refinement would solve this issue. However, this project was restricted by the available computational resources. As such, higher resolution mesh simulations of this nature would take an unreasonably long time to run.

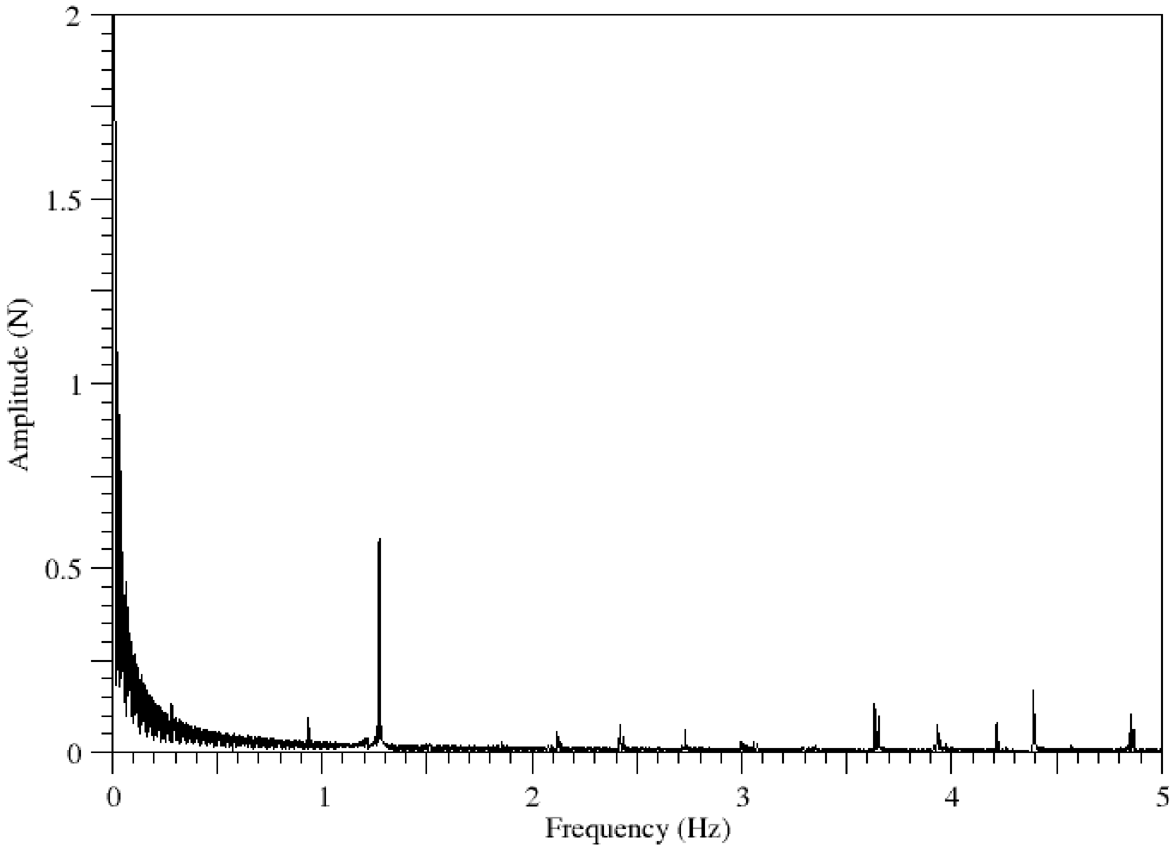

Figure 9. Fast Fourier Transfer Analysis of the Humber Bridge Simulation

A simulation run with the SEM inlet condition is shown in Figure 10. This simulation was not run long enough to develop a wake fully representative of the transient behaviour. However, the turbulent structures present in this simulations are more physically representative of atmospheric air flow and are more likely to produce a physically accurate solution. This shows that the SEM inlet was capable of producing a coherent turbulence pattern.

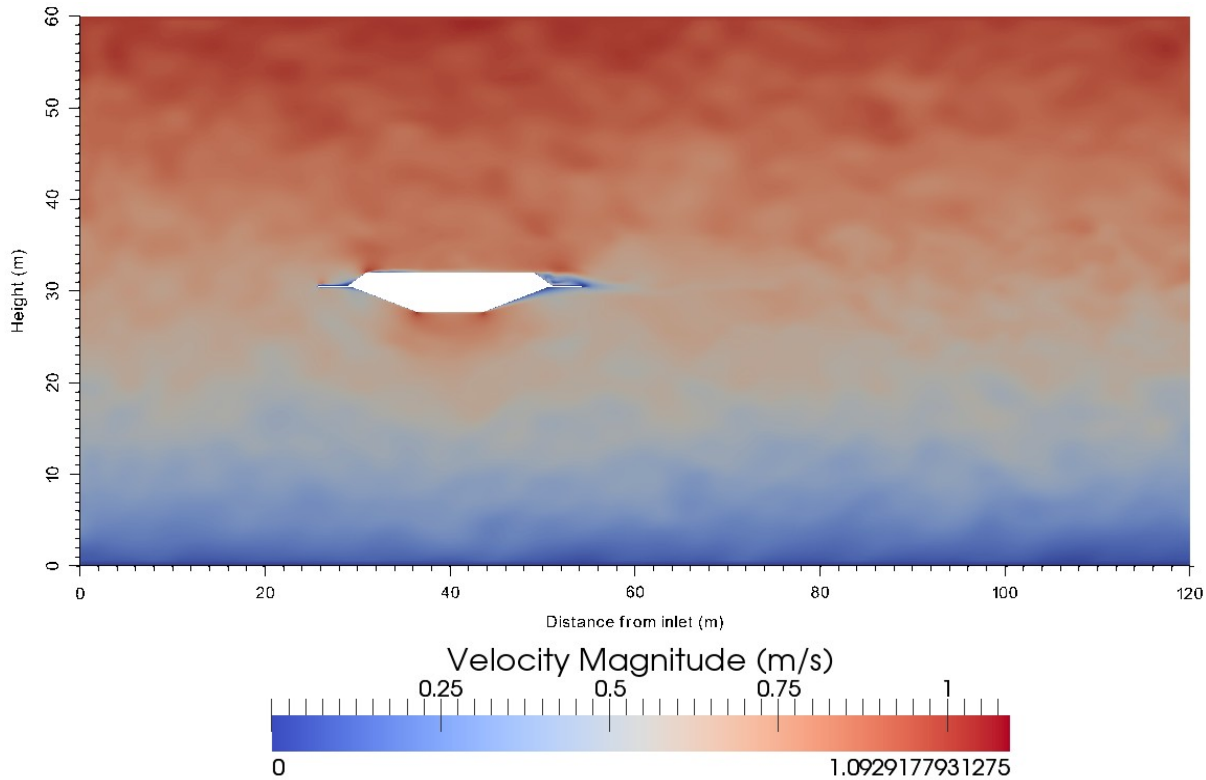

Figure 10. Plot of velocity on domain using SEM inlet

5. Conclusion and recommendations for further work

The simulations modelling the air flow past the bridge were able to generate a physical and accurate set of results. The simulations exhibited a negative lift coefficient, an oscillating wake relating to a characteristic frequency and zone of recirculation in the expected locations. A decomposition of the forces on the bridge deck using a fast Fourier transform was able to derive a set of frequencies corresponding to the oscillation of the bridge's wake. The calculation of such frequencies was the main objective of the CFD subgroup since the frequency and magnitude of the forces will correspond to an oscillatory physical response in the bridges structure. If this response characterises a positive feedback it is likely to cause significant damage to the bridge in terms of operational lifespan and fatigue failure.

The use of DDES turbulence models on a highly turbulent flow, such as those present in the atmospheric boundary layer, made the simulations highly computationally expensive. To reduce the length of time to run the simulations, and reduce the meshing resolution required, the Reynolds number was limited through the use of a 1ms^{-1} maximum inlet velocity.

Further work in the project would involve simulation of air flow past the bridge at various wind velocities. A Fourier transform could be performed on each of the wake profiles in order to determine the frequencies of vortex-induced vibration. These could be compared to the natural frequencies of the bridge and the resulting structural impact determined. For these simulations, given the higher velocities and correspondingly high Reynolds numbers, fully resolving boundary layer flow would require a set of significantly more refined meshes. Given the scope of this research project and the computational resources available, such simulations would be prohibitively costly to perform.

Both the analytical and computational models were able to produce a set of mode shapes and natural frequencies that corresponded to existing experimental data. The limitations of the numerical model were that the computational power available meant that the bridge deck had to be approximated to a rectangular cross section and the side spans could not be modelled. In order to attain the best possible representation of the bridges vibrational characteristics these factors would need to be accounted for.

Due to the complexity of the modelling process, it was necessary to limit the analytical approach to analysing only certain degrees of freedom for each model. This meant that some of the models could not provide a fully representative model of the bridge, and as such the results obtained from them were restricted in their accuracy. This also meant that combinations of different vibrations types, were not able to be evaluated simultaneously. Further development of these models is required to produce a set of results with a high degree of accuracy.

Approximate values for critical flutter wind speed were obtained from the natural frequencies of the numerical models. The approach chosen to study flutter stability is limited by the available facilities leading to undertaking a generic investigation. A better accuracy of results could be obtained with wind tunnel testing. This would provide the necessary values to calculate flutter derivatives dependent on the structural motion.

6. Economic, environmental, and other factors

6.1. Cost of Project

This project was primarily carried out using computational methods using various software tools. In the case of OpenFOAM, Octave and MeshLab, the software was free to use and as such has no licencing costs associated with it. When performing fluid simulations it is common for licences to be assigned per processor which makes parallel processing rather costly on licenced software. This was an advantage of using OpenFOAM as opposed to other commonly used fluid solvers such as ANSYS Fluent. Several programs used during this project did have a cost associated with them, namely: MATLAB, ANSYS Workbench, SolidWorks, GlobalMapper and Microsoft Office. The costs associated with these programs were covered by the University.

If obtained for commercial use, the cost of Lidar data for topography at the Humber Bridge ($83.98km^2$) would have a cost of £7535.53. This is a large cost associated with accurately producing a terrain mesh for local air flow conditions.

6.2. Sustainability

When modelling fluid flow in a project such as this one, there are two options available; CFD modelling or wind tunnel testing. The simulation of the Humber Bridge took just over two weeks to run. Assuming that the computer uses 250 Watts when running simulations, the modelling of the Humber Bridge will have used 96KWh of electricity. Comparatively, wind tunnels use huge amounts of energy. The 10ft x 10ft wind tunnel owned by NASA uses between 20,000 - 200,000 kW of electricity per hour [14]. Wind tunnel tests can be run for hours at a time. Consequently CFD simulations are a more sustainable approach to fluid flow problems than wind tunnel testing.

6.3. Health and Safety

There are a number of concerns to the health and safety of group members which are addressed in a risk assessment shown below. While this project primarily involves the use of computers with minimal physical experimentation, this has a number of hazards associated with it. These are shown in Table 2.

Table 2. Risk Assessment for group project

Hazard	Risk (1-5)	Severity (1-5)	Index (1-25)	Reduction of Risk
Repetitive Strain Injury	3	3	9	Caused by long periods spent typing. Take breaks every hour and stop if any discomfort persists.
Eye Strain	4	3	12	Ensure rooms are well lit and there is no glare on the screens. Regular breaks should be taken and any physical discomfort should be reviewed.
Damaged Work Equipment	2	2	4	Equipment should be reviewed for damage and maintained regularly. Damage should be reported immediately.
Trips, Slips and Falls	3	3	9	The workspace should be kept clear of loose cables and examined for trip hazards.

7. References

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