Comparison of numerical and physical models for bridge deck aeroelasticity

Autor(en): **Frandsen, Jannette**

Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **79 (1998)**

PDF erstellt am: **12.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-59909

Comparison of Numerical and Physical Models for Bridge Deck Aeroelasticity

Jannette FRANDSEN
PH.D. Student
Cambridge Univ.
Cambridge, UK

Jannette Frandesen, born 1967, obtained her degree in structural eng. in 1991. After working for five years, at first as an offshore structural eng. and then as a bridge designer, she returned to research by first obtaining a degree in structural steel design and is at present a PhD student pursuing research within the field of bridge aerodynamics.

Allan McROBIE
Lecturer
Cambridge Univ.
Cambridge, UK

Allan McRobie, born 1958, obtained degrees in Physics in 1979 and Structural Eng. in 1985. After working for five years as a bridge designer in Australia, he returned to pursue research in nonlinerar structural dynamics and is now a Lecturer in Structural Eng. in Cambridge.

Summary

A finite element approach to the fluid-structure interaction of long-span bridges is described. Using an Arbitrary Lagrangian-Eulerian formulation for the fluid around a spring-supported section model, self-excited oscillations of bridge cross-sections can be modelled in the time-domain. The eventual aim is to verify or otherwise the validity of the approach. If verified, the method could provide additional insight into the effects of minor changes of cross-section geometry on the various aeroelastic phenomena and so provide an aid to design evolution. Two case studies are presented, both involving the Great Belt East project in Denmark. In the first we consider the vortex-induced oscillations of the approach spans and in the second we consider the coupled flutter of the main suspension span. The initial results are interesting.

1. Introduction

There has been much research into the application of computational fluid dynamics (CFD) to long-span bridge cross-sections. In this paper we describe some initial results of an Arbitrary Lagrangian-Eulerian code applied to two-dimensional section models. The bridge sections are spring-supported and self-excitation of the combined fluid-structure systems occurs naturally as the field equations are integrated forward in time. The first objective of the research is to ascertain whether or not this approach can accurately model the various aeroelastic instabilities, and if so, to see how such a facility may best be used to guide design evolution.

The code, a transient fully-coupled CFD/FEA code, is *Spectrum* [2] of Centric Engineering Systems Inc., based on the work of T.J.R. Hughes and coworkers to whose papers [1, 5, 6] the reader is referred for the finite element theory. Two case studies involving the Great Belt East project are described.

2. Computational Method

Spectrum is a fully three-dimensional code, but all analyses presented here are essentially two dimensional. The fluid is modelled by the isothermal incompressible Navier-Stokes equations. Although a number of turbulence modelling capabilities (such as Large Eddy Simulation) are available within *Spectrum*, no turbulence modelling is included in the preliminary analyses presented here. The fluid equations are obtained by a Streamline-Upwind Petrov-Galerkin formulation on unstructured meshes. In the Arbitrary Lagrangian-Eulerian formulation, the mesh is endowed with fictitious elastic properties such that the mesh evolution can be tracked in response to the moving fluid-structure boundaries. Automatic mesh adjustment is achieved by forward integration of the fictitious elasticity field equations, with the mesh velocity feeding into the convective term of the fluid equations at each time step. The structure, essentially a rigid body in the studies here, is modelled using stiff shell elements supported on springs and dashpots. *Spectrum* uses an implicit Hilber-Hughes-Taylor integrator. Typical boundary conditions here include a constant pressure outflow, an incident wind speed and zero normal velocity on the upper and lower boundaries (see Fig. 1c). At the fluid-structure interface, a no-slip condition is prescribed since viscous flow is being modelled. Further boundary conditions associated with the fictitious mesh elasticity problem are also specified to keep the fluid mesh in contact with the structure. A complete set of initial conditions is also required. These typically involve zero structural motion and a fluid velocity comparable to the incident wind speed everywhere. A variety of aeroelastic phenomena then naturally emerge as the field equations are integrated forward in time.

3. Case Study: Great Belt East Bridges

The CFD/FEA program *Spectrum* [2] was used in two case studies of bridge aeroelasticity, both involving the Great Belt East project in Denmark. In the first case study, the vortex-induced oscillations of the approach bridges were considered whilst the second focused on the flexural-torsional coupled flutter of the main suspension bridge.

3.1 Approach bridges - vortex-induced oscillations

From the original wind tunnel tests carried out by others at the Danish Maritime Institute [4], the 193 metre span approach bridges were known to be susceptible to vertical, vortex-induced oscillations at low wind speeds. A system of Tuned Mass Dampers (TMDs) were subsequently designed and fitted to alleviate this problem. In our initial numerical analyses we attempt to simulate the response without TMDs, leaving the complex problem of modelling the effects of TMDs on a continuous viaduct for future research. The two-dimensional full-scale numerical model of the approach bridge is illustrated in Fig. 1. The box-girder deck section is 25.8m wide and 7m high. It was modelled using four-noded isoparametric quadrilateral plate elements sufficiently stiff to create an essentially rigid structure. A 1m slice of the deck was supported on linear springs as shown in Fig. 1b. The section mass ascribed was the actual mass per unit length of the real bridge and the spring stiffnesses were proportioned to provide the correct natural frequencies. Owing to the high torsional rigidity of the box section, only the vertical motions are of significant interest in this study. Structural damping (corresponding to 1% logarithmic decrement) was applied via a pair of dashpots attached to the top of the middle flange. The surrounding fluid mesh has 1752 nodes and 854 eight-noded hexahedral elements. The control volume has a total size of 100×200m with unit thickness. Each simulation took approximately 6 hours on an HP C180, using a time increment of 0.05 seconds.

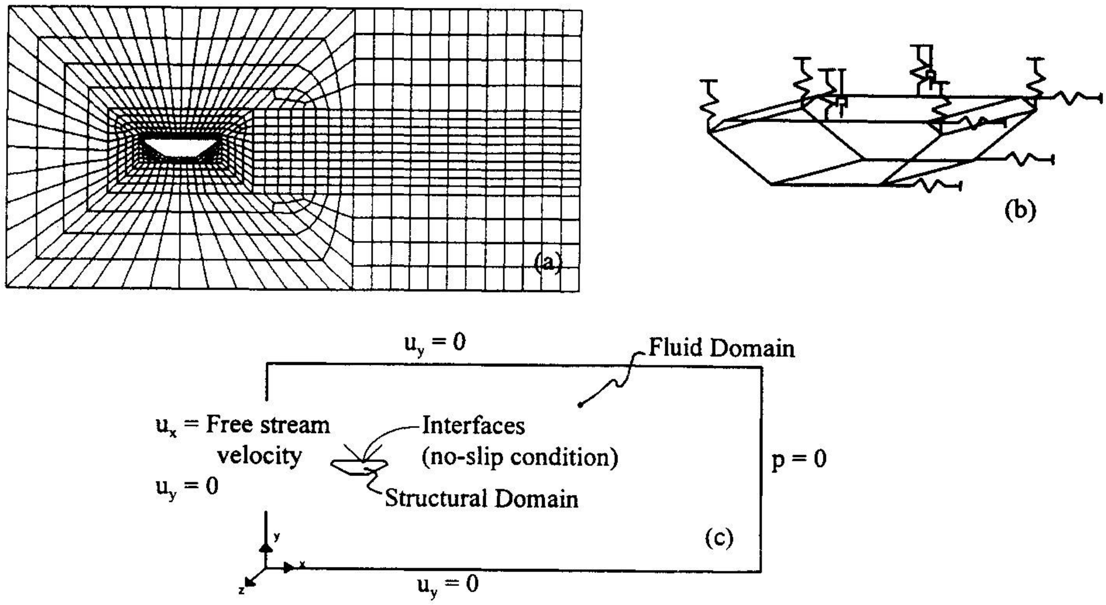

Fig. 1. *Computational model of the approach bridge. (a) Finite element mesh. (b) Location of springs and dashpots in the deck model. (c) Boundary conditions.*

Starting from initial conditions with no structural motion and the full inflow wind speed, the model self-excites into a vortex-induced oscillatory response. At the wind speed corresponding to resonance conditions the structure undergoes some transient motion before stabilising onto a large-amplitude periodic response. Fig. 2 shows two snapshots of the mesh movement (with displacements magnified) during a simulation at resonance. Fig. 3 shows the pressure contours at two similar instants, and a large-scale coherent vortex street is clearly visible downwind.

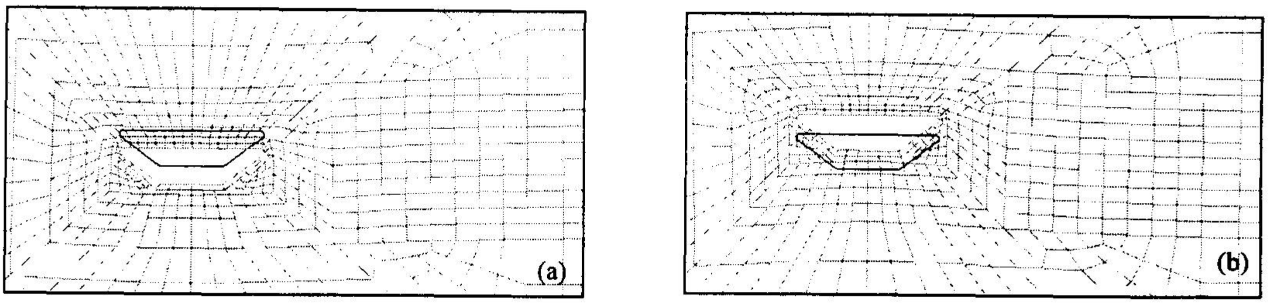

Fig. 2. *Mesh movement at resonance (vertical displacement magnified 5 times). (a) Maximum downwards movement. (b) Maximum upwards movement. Note: original position of bridge deck shown in black.*

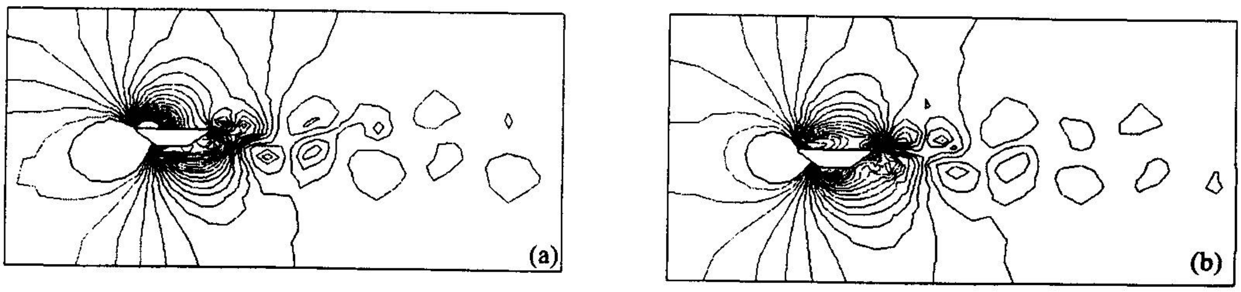

Fig. 3. *Pressure contours at resonance. A vortex street is evident downwind. (a) Maximum upwards movement. (b) Maximum downwards movement.*

Fig. 4 shows some typical displacement histories at and off resonance. Maximum displacements were extracted from a set of such histories and are plotted against wind speed in Fig. 5, together with the corresponding results taken from the original experimental investigations at the Danish Maritime Institute [4].

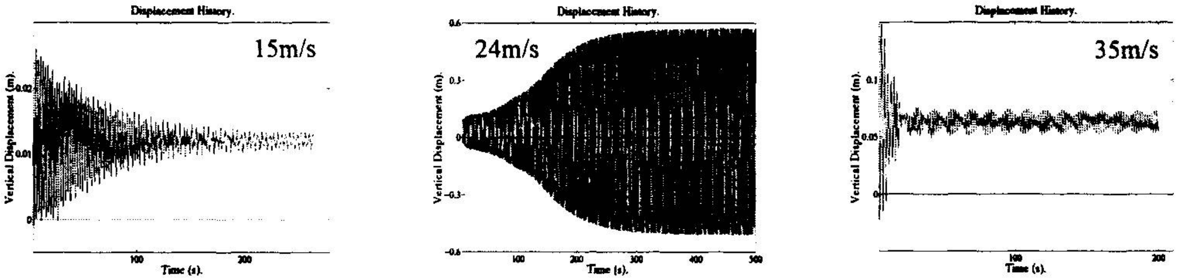

Fig. 4. *Displacement histories at and off lock-in.*

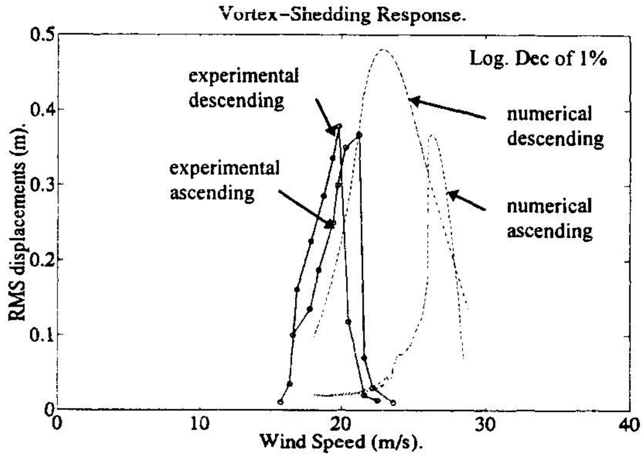

Fig.5. *Comparison of numerical (---) and experimental (o-o) RMS displacements.*

The first conclusion is that, qualitatively at least, the ability of the computational model to self-excite vortex-induced oscillations has been demonstrated. Quantitatively, although there is some degree of agreement between the predicted resonant response amplitudes there is an evident disparity in the predictions of the critical wind speed at which resonance occurs. The cross-section is comparatively bluff and although separation points are largely dictated by the various sharp corners of the section the fluid processes at these locations are complex. It is thus suspected that the crudeness of the mesh used in these preliminary investigations could be a major factor in this disagreement. Further research is required, needing additional physical modelling to provide detailed flow-visualisation data at and around the separation points during an oscillation cycle for comparison with the initial and improved numerical simulations.

3.2 Suspension bridge - coupled flutter analysis

The case study presented here describes a preliminary investigation into the stability of the 1624m main span of the Great Belt East suspension bridge. A full-scale two-dimensional cross-section with unit thickness is constructed from plate elements and supported on springs and dashpots. The model is given the mass and mass moment of inertia per unit length of the actual structure, and the spring stiffnesses and dampers are then ascribed to give the correct natural frequencies and damping ratios in the flexural and torsional modes. The torsional rigidity of the deck is sufficiently high that this required the vertical springs to be placed on 'out-riggers' outside the cross-section (see Fig. 6b). (Note that these outriggers do not interfere with the fluid flow: the fluid-structure interface is the boundary of the deck). Horizontal motion was restrained by a horizontal spring attached at the intersection of four stiff, massless struts meeting at the shear centre. The fluid mesh is illustrated in Fig. 6a and involved 7176 nodes and 3508 hexahedron elements. Preliminary analyses showed that the sudden application of the full wind speed to a stationary structure led to large transient disturbances from which, for much computational expense, it was difficult to extract definitive conclusions about the stability of small oscillations. Therefore, for the first few seconds real-time, the level of structural damping was increased to near-critical values, and after the structure had settled into a stable stationary onfiguration under the full wind-speed, the damping values were then set to their correct values. The subsequent motion under further forward integration could then be observed to see if self-excited oscillatory behaviour of the structure occurred.

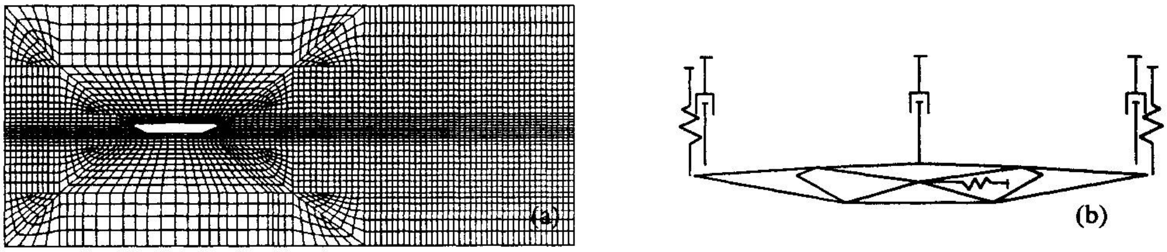

Fig. 6. Computational model of the suspension bridge.(a) Finite element mesh. (b) Location of springs and dashpots.

Fig. 7 shows typical mesh deformations and pressure contours in the vicinity of the bridge at an instant when significant oscillatory motion had occurred. (Displacements have been magnified for clarity). It is interesting to observe the pattern of vortices evident in the pressure contours downwind. By aeronautical standards the deck is comparatively bluff and has a number of sharp corners where separation can occur. Such vortex-shedding is thus to be expected at all wind speeds, even though most theories of flutter make no mention of its existence.

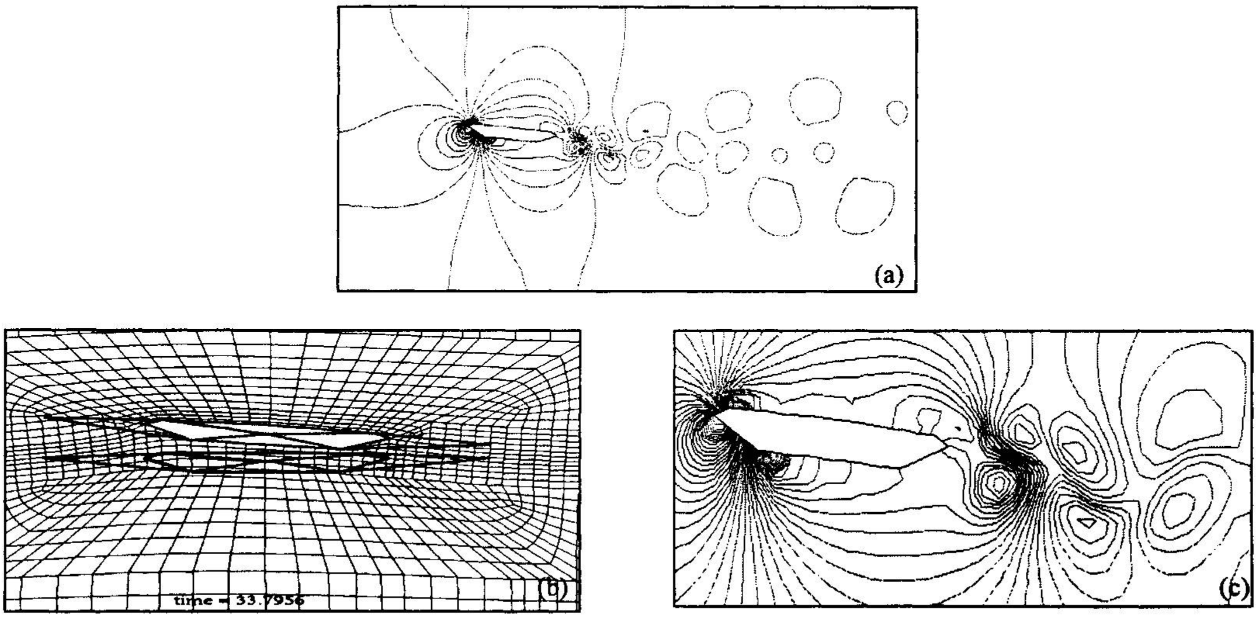

Fig. 7. Coupled flutter at 60 m/s. (a) Pressure contours in whole domain. (b) Mesh deformation (c) Pressure contours near deck. (displacements magnified 5 times).

Fig. 8 shows two displacement histories at 50m/s and 60m/s wind speed. The histories show the vertical displacement of the downwind out-rigger after the artificially-high structural damping has been switched to its correct values (1% and 0.6% logarithmic decrement for vertical and torsional modes respectively, in this case). At 60m/s, flexural-torsional oscillations self-excite at a frequency of about 0.24Hz, this comparing with 0.27Hz and 0.097Hz for the frequencies (still air) of the uncoupled torsional and flexural modes respectively. Each 35 second simulation took approximately 9 hours on an HP C200, using a time-step of 0.05 seconds. These preliminary results suggest a flutter velocity of around 50m/s, which is at some variance with the flutter limit of 73m/s predicted by the original wind tunnel tests conducted on the section models without windscreens at the Danish Maritime Institute [3]. Conclusions at this stage can only be tentative. In the first instance, the numerical method has demonstrated that under increasing wind speed it is capable of predicting self-excited flexural-torsional oscillations at a frequency close to that expected. However, the cause of the disparity in predicted flutter velocities between the physical and numerical experiments remains to be determined. An obvious source of concern is the poor mesh. Ascribing the no-slip boundary condition to the fluid at the structural interface implies that an attempt is being made to model the substantial wind-shear across the boundary layer, and yet the element dimensions in this region are clearly too large to accomplish this accurately. Future studies will aim to improve the meshing.

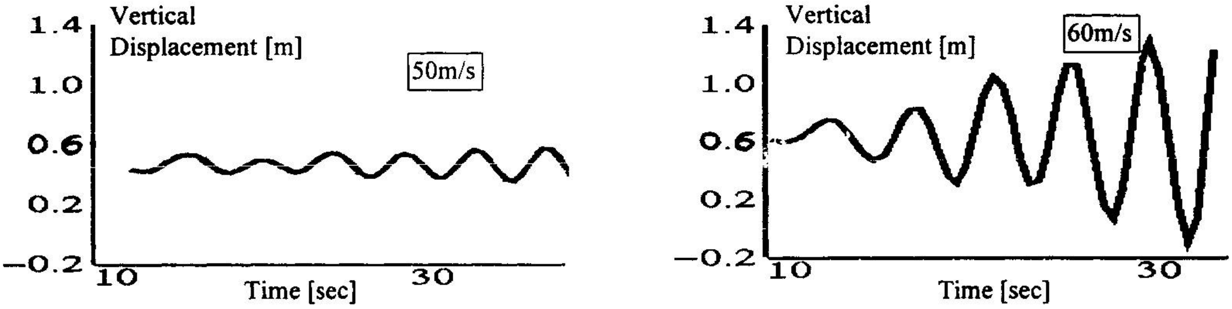

Fig. 8. *Histories of vertical displacements at the downwind outrigger.*

4. Conclusions and future work

The results of a preliminary investigation into the suitability of a finite element approach to bridge aeroelasticity have been presented. The ability of the numerical models to self-excite into vortex-induced vertical oscillations and flexural-torsional flutter were demonstrated on two case studies based around the Great Belt East project. Although a number of interesting qualitative phenomena were displayed, important quantitative predictions of critical wind speeds are somewhat at variance with the results of the original wind tunnel experiments. Further research is intended to discern the causes of these disagreements. If reliable quantitative predictions can subsequently be obtained by this method, then in tandem with the established physical testing procedures, it could provide a useful tool to aid the evolution of long-span bridge design.

5. References

[1] Brooks, A.N. and Hughes, T.J.R., Streamline upwind/Petrov-Galerkin formulations for convection dominated flows with particular emphasis on the incompressible Navier-Stokes equations. Comp. Meth. Appl. Mech. Eng., Vol. 32: 199-259, 1982.

[2] Centric Engineering Systems Inc., Sunnyvale, California. Spectrum Solver (ver. 2.0) Command reference and Theory Manual, May 1993. (Spectrum is the Registered Trademark of Centric Engineering Systems, Inc.)

[3] DMI report no. 90108.40.01: Section Model Tests to Determine Aerodynamic Derivatives, Vol. 1: Text, Storebælt East Bridge, August 1991.

[4] DMI report no. 92194.01: Detailed Design, Approach Bridges, Section Model Tests III, Storebælt East Bridge, March 1993.

[5] Hughes, T.J.R., Liu W.K. and Zimmerman T.K., Lagrangian-Eulerian Finite Element Method for incompressible viscous flows. Computer Methods Appl. Mech. Eng., Vol. 29, No. 1: 329-349, 1981.

[6] Nomura, T. and Hughes, T.J.R., An arbitrary Lagrangian-Eulerian Finite Element Method for interaction of fluid and a rigid body. Comp. Meth. Appl. Mech. Eng., Vol. 95, No. 1: 115-138, 1992.