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Numerical simulation of induced hydrofoil vibration

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Summary

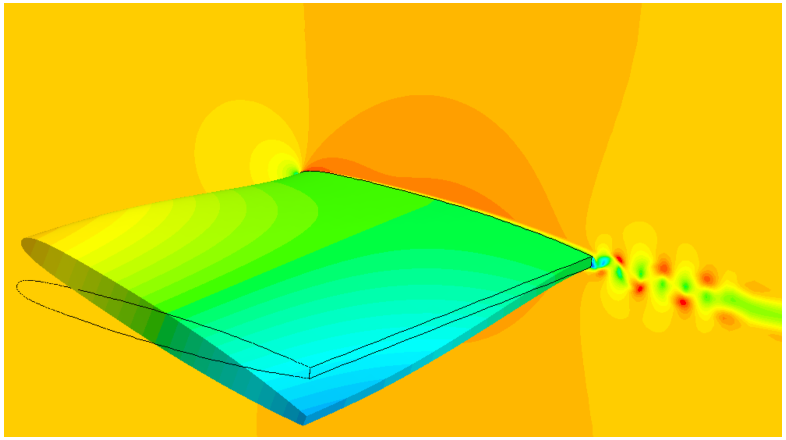
- Introduction: Blade singing and simulation requirements
- The model problem: NACA009 hydrofoil
- Fully-coupled FSI simulation results in Star CCM+
- Simulation difficulties and an alternative simulation approach
- Conclusions

Blade singing

Blade singing is a strong tonal noise component which is thought to be generated by unsteady hydrodynamic loads interacting with propeller blade structures.

Under specific flow conditions, the shedding frequency of the flow passing over the trailing edge of the blade can excite one of the structural modes of the blade.

This produces a 'lock-in' phenomenon during which the blade vibration is amplified at a fixed frequency over a significant range of flow velocities.



This phenomenon has been of interest to the maritime defence community for some time due to the potential <u>signature and fatigue implications</u> for platforms but is not yet fully understood.

Simulation: aims and benefits

The occurrence of blade singing has proved to be difficult to predict and alleviate.

- Model scale testing may fail to predict blade singing occurring at full scale due to the change in flow Reynolds number and different model frequencies of the full size blade structure.

- This has lead to the need to develop Anti-Singing Trailing Edge (ASTE) modifications to reduce or shift the frequency of in service vessels.

Numerical simulation can be used as a tool to:

- Develop a greater understanding of the underlying physics causing blade singing,
- Reduce reliance on model tests / sea trials,
- Support upfront blade design to reduce the possibility of blade singing,
- Improve future ASTE designs.

Cost
Risk ↓

↑ Platform capability
Component lifespan

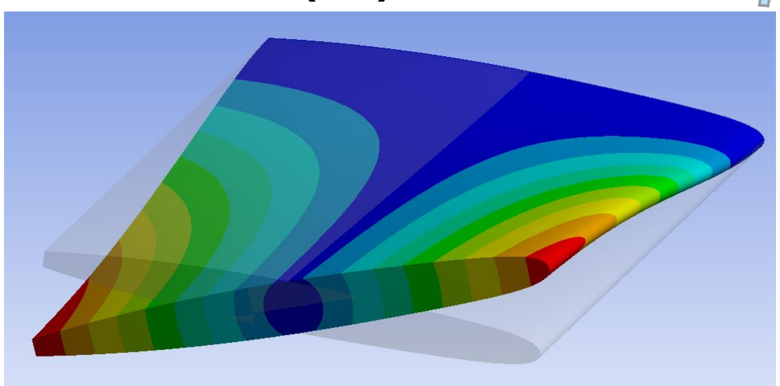
Simulation: challenges

The blade singing phenomenon is an example of a dynamic response of a tightly coupled complex system.

It is only recently that computational tools capable of modelling both the complex three-dimensional fluid flow around the trailing edge and the high frequency response of the structure required to accurately predict blade singing have become available.

Displacements

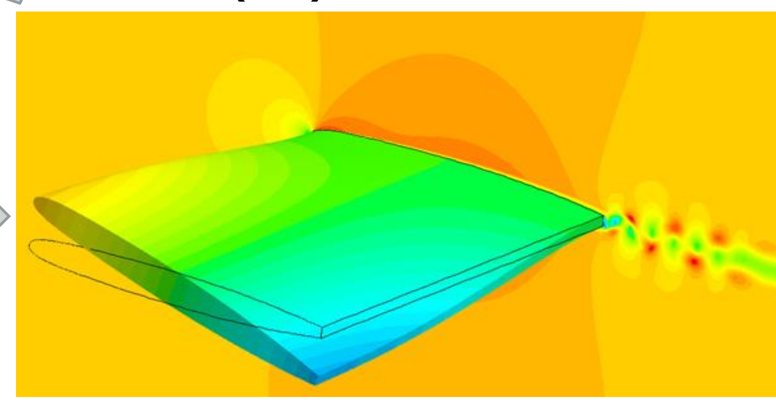
Structural model (FEA)



Two – way

coupling

Fluid model (CFD)



Forces

FEA simulation requirements:
- **Material properties / boundary conditions**
- **Predict the correct natural frequency of the structure**
- **Accurately calculate structure deformation (small magnitudes)**

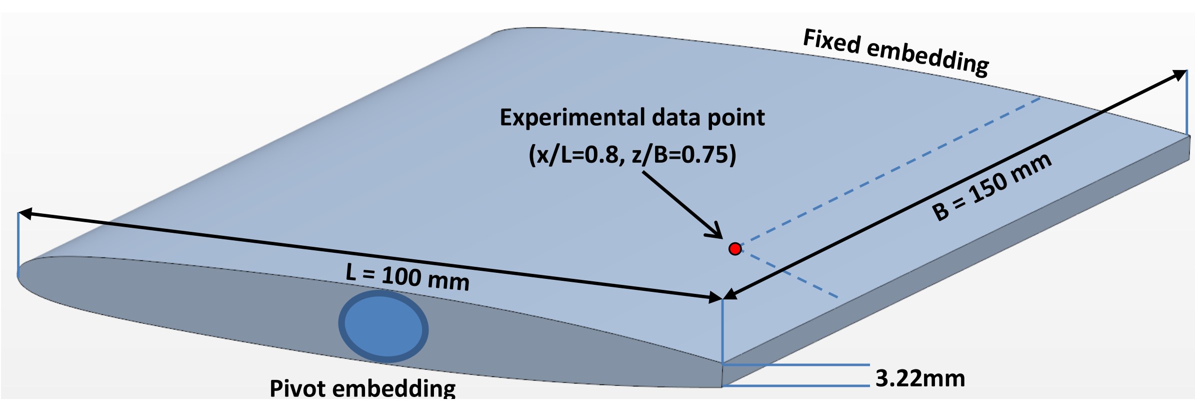
CFD simulation requirements:
- **Time accurate (high Hz, small time steps)**
- **Predict the correct shedding frequency of the fluid flow**
- **Accurately calculate fluid forces on structure**

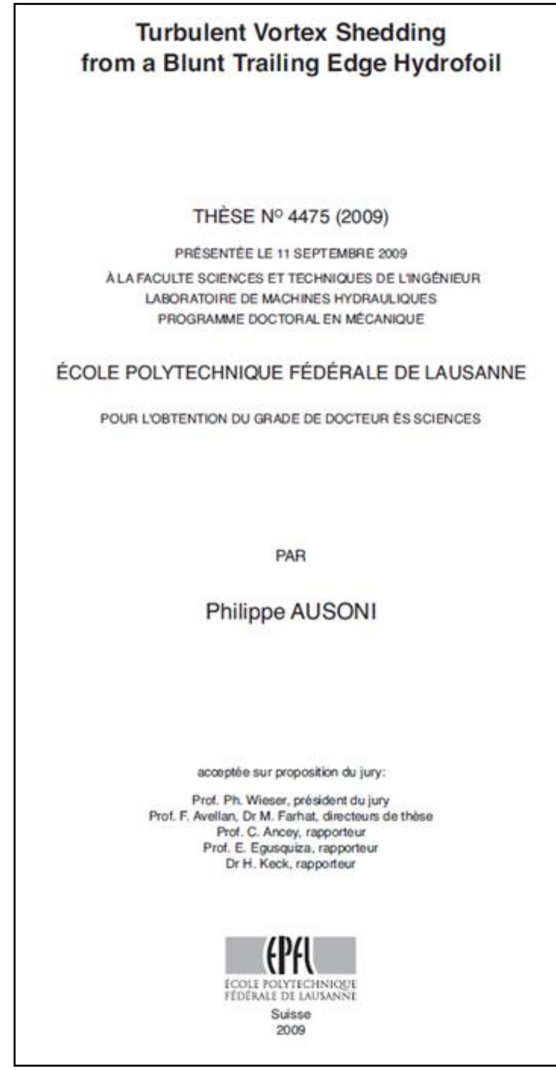
Fluid-Structure Interaction (FSI) Simulation

The model problem: NACA009 hydrofoil

The model problem: NACA009 hydrofoil

- This test case available in the open literature.
- Provides experimental data for a blunt trailing edge NACA009 hydrofoil in a water tunnel (fixed at one end, pivots at the other) for a range of free stream velocities.
- Critically, results from these experiments included the detection of the lock-in condition. This observed lock-in phenomenon has many similarities occurrence of blade singing, and a clear two-way fluid-structural coupling is observed.
- Due to the hydrofoil’s geometric simplicity yet complex physics, it has proved to be a valuable test case for validating CFD codes ability to accurately predict blade singing.





Turbulent Vortex Shedding
from a Blunt Trailing Edge Hydrofoil

THÈSE Nº 4475 (2009)

PRÉSENTÉE LE 11 SEPTEMBRE 2009
À LA FACULTE SCIENCES ET TECHNIQUES DE L'INGÉNIEUR
LABORATOIRE DE MACHINES HYDRAULIQUES
PROGRAMME DOCTORAL EN MÉCANIQUE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

PAR

Philippe AUSONI

acceptée sur proposition du jury:

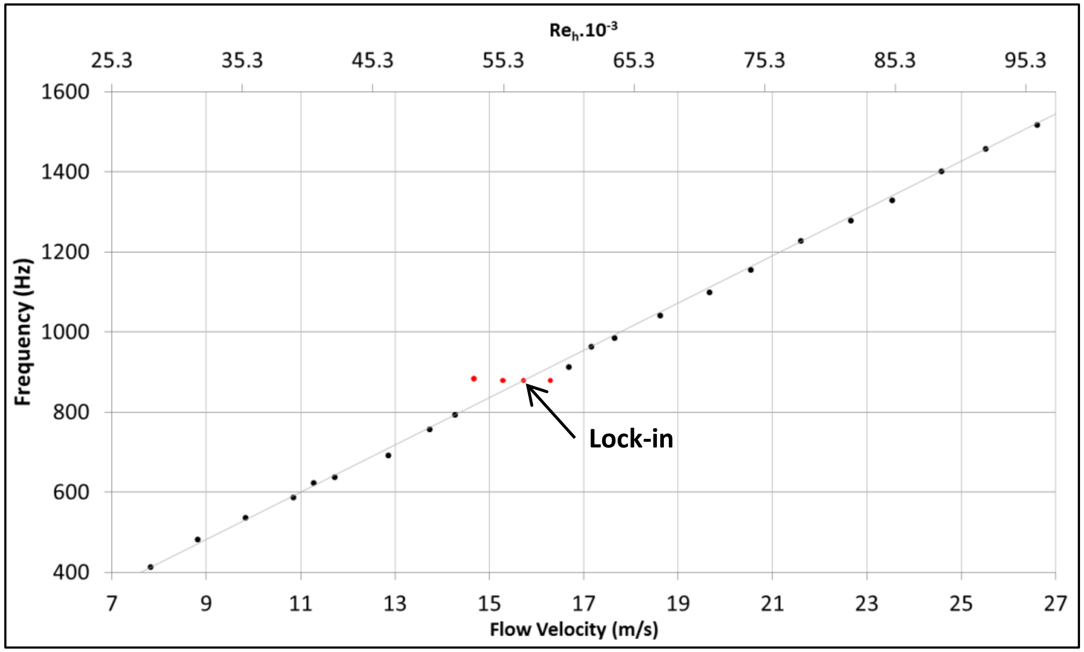
Prof. Ph. Wieser, président du jury
Prof. F. Avellan, Dr M. Farhat, directeurs de thèse
Prof. C. Ancey, rapporteur
Prof. E. Egusquiza, rapporteur
Dr H. Keck, rapporteur

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Suisse
2009

The model problem: experimental results

- As the water flows over the hydrofoil von-Karman vortices are shed from the blunt trailing edge. For the range of experimental Reynolds numbers, as the flow velocity in the tunnel was increased one would expect the trailing edge shedding frequency to increase in a linear fashion as determined by the Strouhal number.



Vortex shedding frequency for varying free stream velocities showing the lock-in frequency (reproduced from Ausoni data)

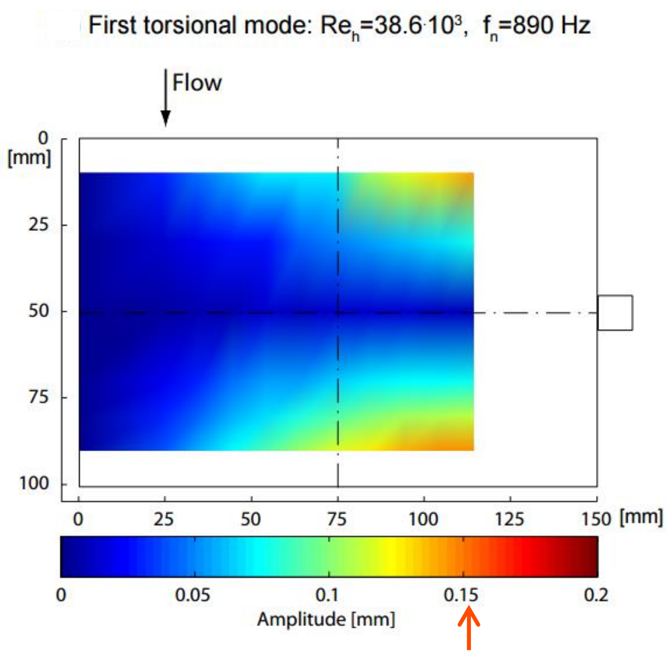
- However, the vortices cause the hydrofoil to vibrate and when the frequency of the vortices approach a natural frequency of the hydrofoil a lock-in condition is created.

(In this case the 1st torsional mode: 890 Hz)

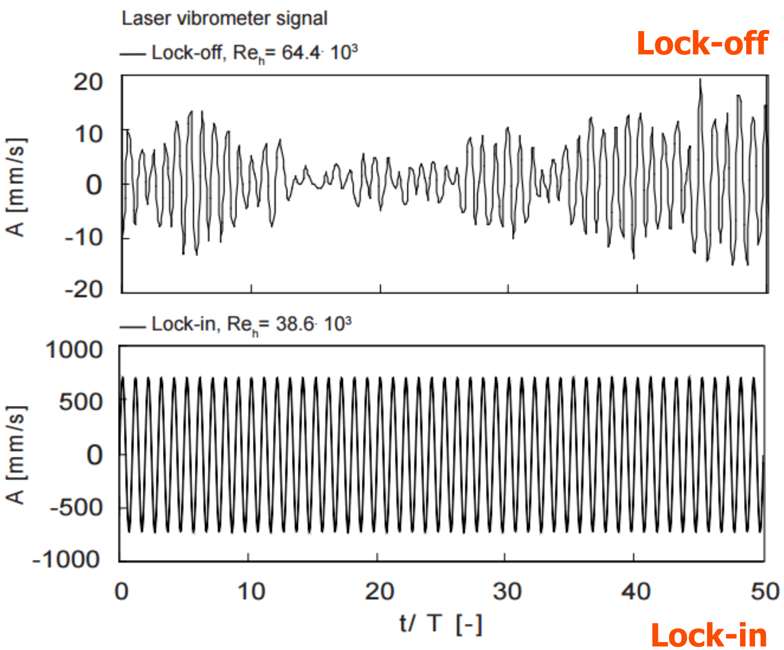
The model problem: experimental results

- Over this range of velocities the hydrofoil became excited and the vibration levels were significantly enhanced. Despite further increases in flow velocity, the large amplitude vibration remained locked-in to the torsional vibration mode frequency.
- Increased coherence in the wake profile was also observed during lock-in.

<u>Laser vibrometer results (Ausoni data)</u>



Lock-in displacement of 0.15 mm at the experimental point



Velocities at the experimental point

Simulation of the NACA009 hydrofoil test case using a fully-coupled FSI methodology in Star CCM+

Step 1: Modal analysis of NACA009 hydrofoil

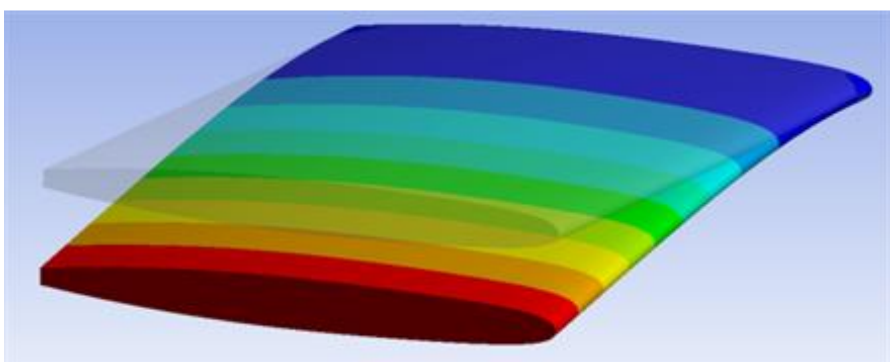
The modal analysis of the blunt hydrofoil was performed using ANSYS v18 Mechanical.

To correctly predict the natural frequencies of the submerged hydrofoil structure, the added mass effect of the surrounding water had to be taken into account.

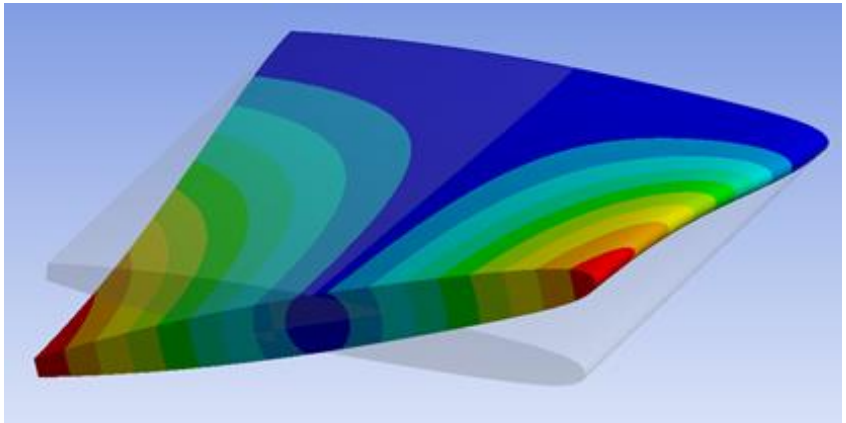
The frequency of the first torsional mode is seen to drop from 1133Hz to 921Hz due to the added mass effect of the surrounding water.

Mode	Vacuum (Hz)	Submerged (Hz)
1	319.57	240.65
2	1132.7	660.33
3	1929.8	920.96
4	2660.3	1504.3
5	3630.3	2231.3

(Experimental lock-in frequency: 890 Hz)



First bending mode



First torsional mode

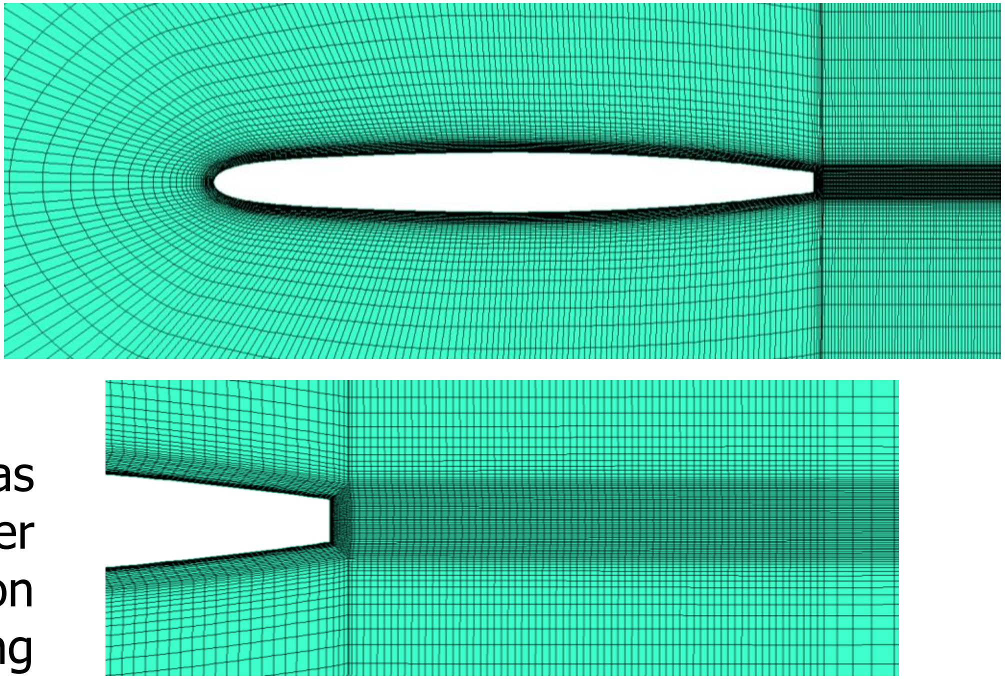
Step 2: Stand-alone URANS CFD simulation

Stand-alone CFD simulations using the URANS formulation were undertaken to determine the ability of the CFD codes to accurately predict the shedding frequency of the trailing edge vortices (without the added complication of the FSI).

CFD codes: ANSYS CFX & FLUENT, Siemens Star-CCM+

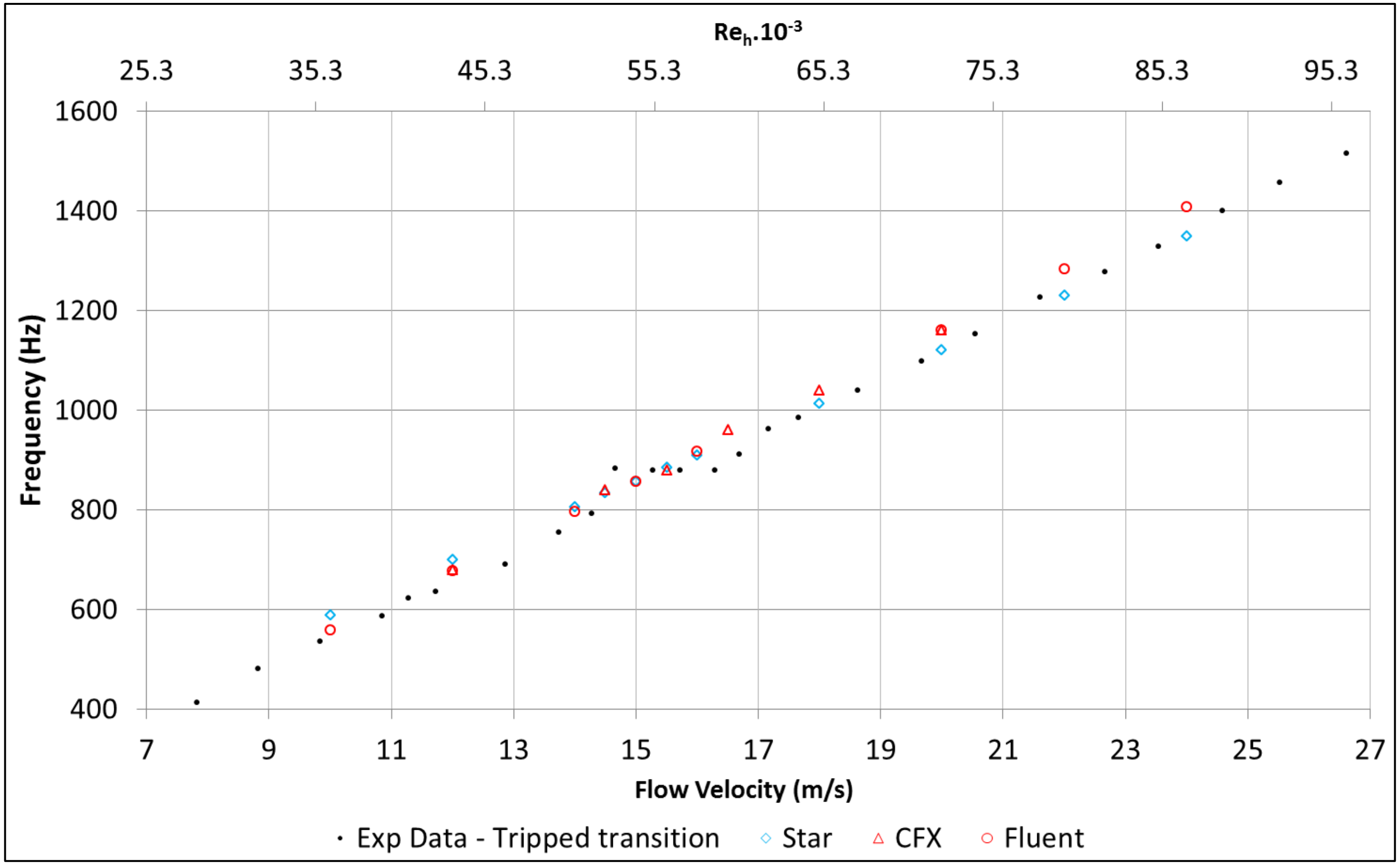
- Segregated solver,
- SST k-w turbulence model,
- Hybrid wall treatment,
- Constant density,
- 2nd order in time and space,
- Time step: 1×10^{-5} s,
- 30 inner iterations.

The lift force on the hydrofoil was monitored every time step. A Fast Fourier Transform (FFT) was then performed on this force to obtain the corresponding frequency of the shedding.



Mesh used for URANS simulations (~2.4 million elements)

Step 2: Stand-alone URANS CFD simulation



URANS simulation results for the blunt hydrofoil (experimental data showing lock-in at 890 Hz).

The predictions generated by all the solvers were found to be in good agreement with the experimental results.

Step 3: Star-CCM+ fully-coupled FSI simulation

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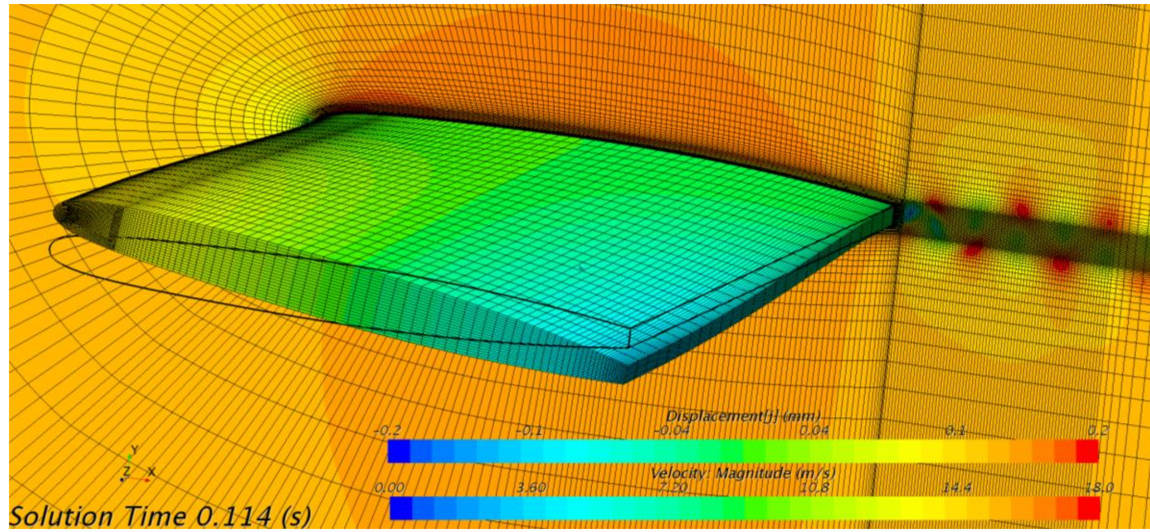
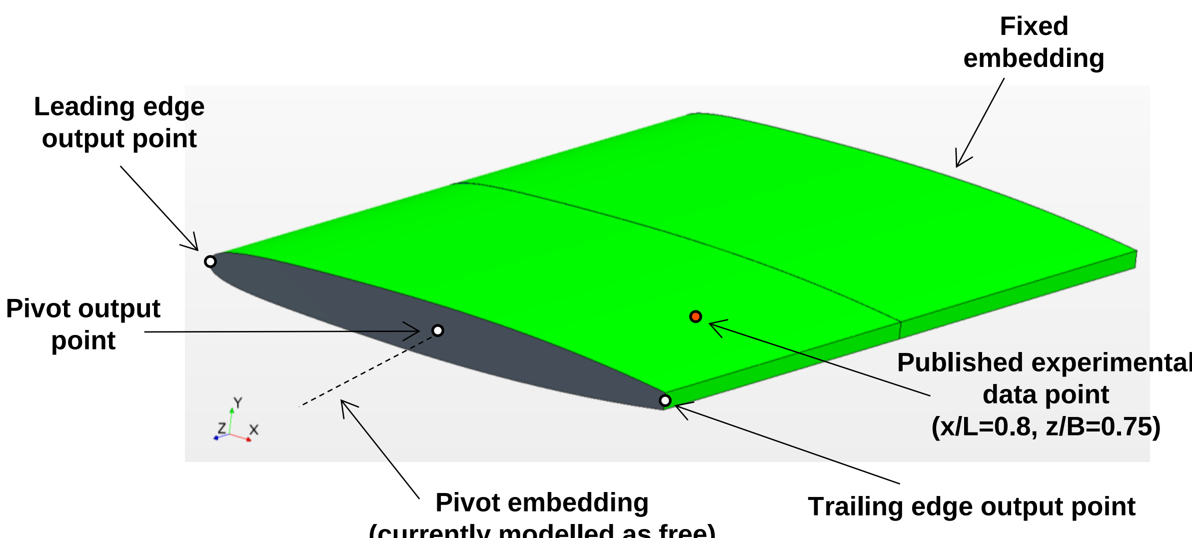
The Star-CCM+ FSI simulation uses a single monolithic solver for both fluid and structural domain.

(fully-explicit two-way coupling)

Simulations were run over the range of velocities lock-in was observed.





- Solid mesh: 77,500 elements
- Fluid mesh: 2,433,600 elements

Steel properties:

- Density: 7900 kgm^{-3}
- Young's modulus: 2x10^{5} MPa

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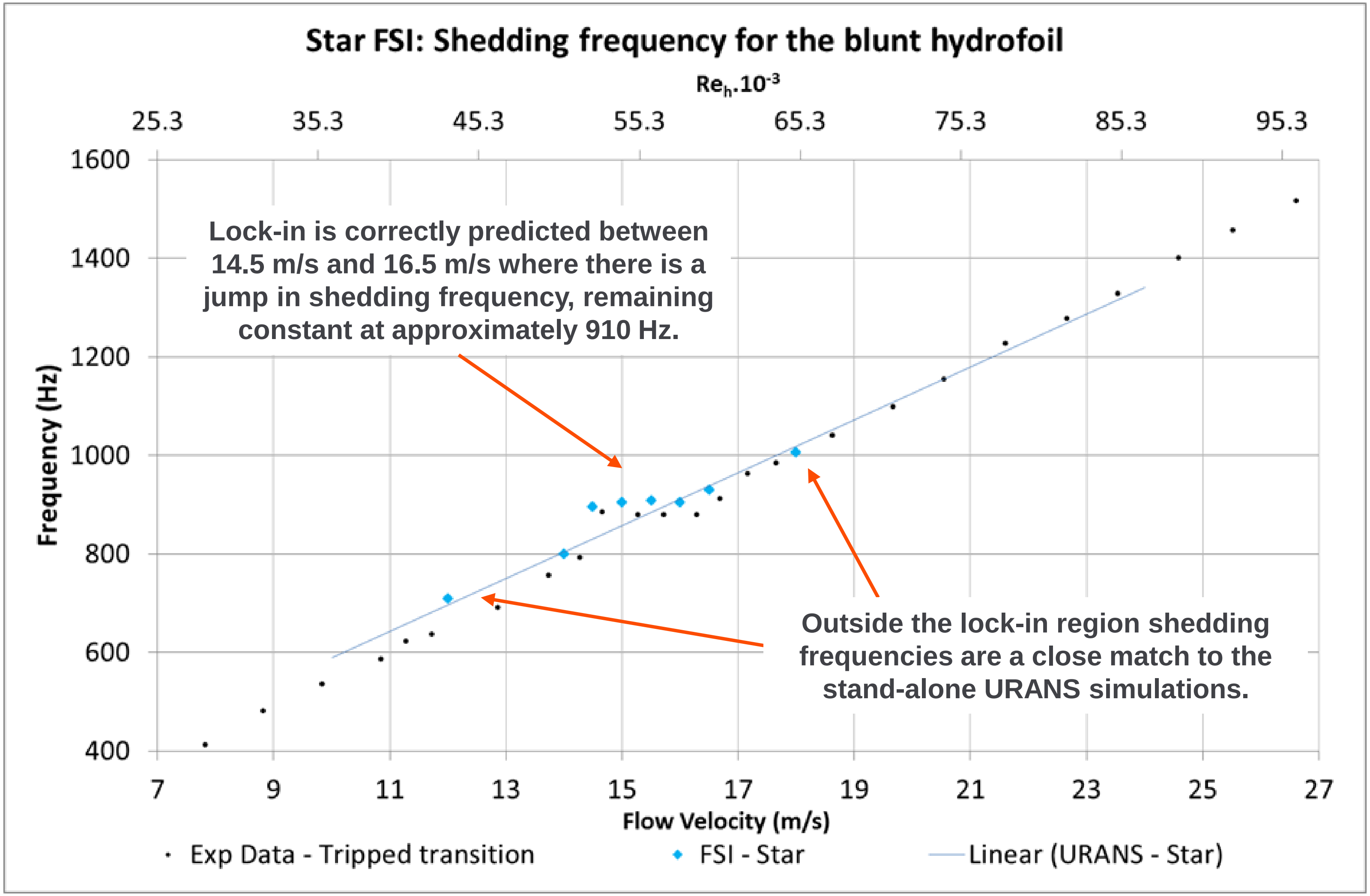
Step 3: Star-CCM+ fully-coupled FSI simulation



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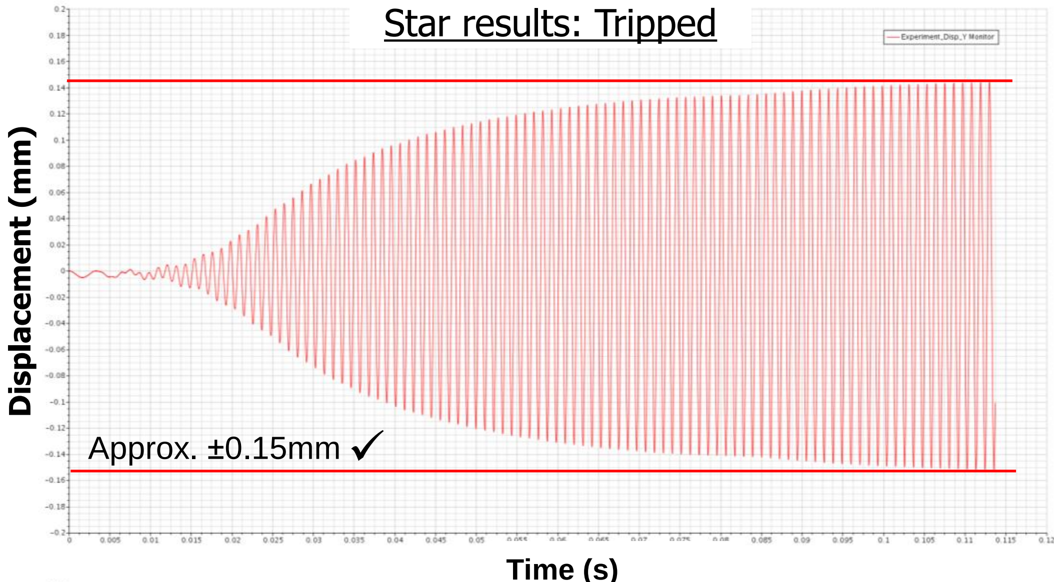
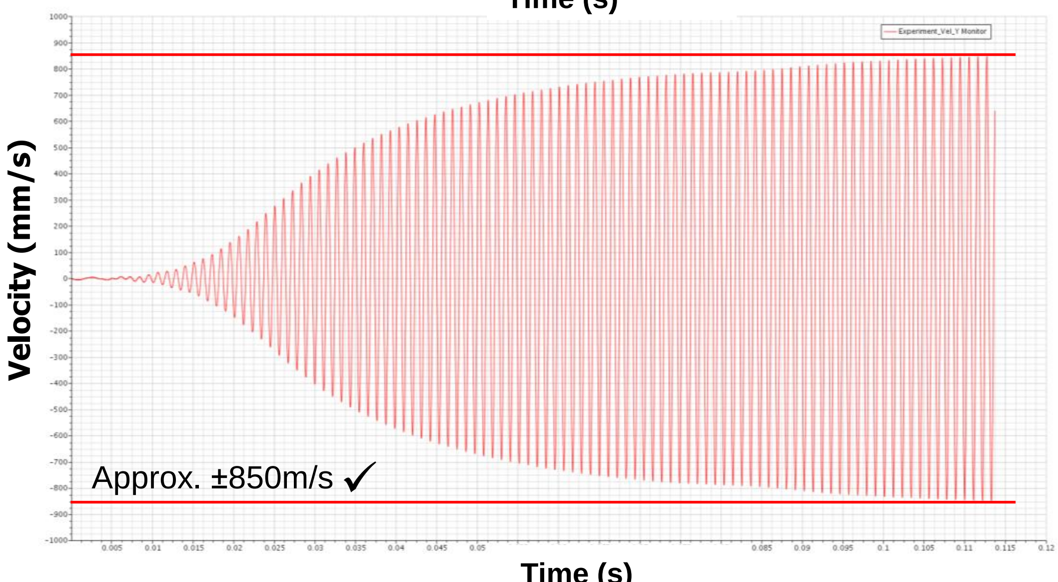
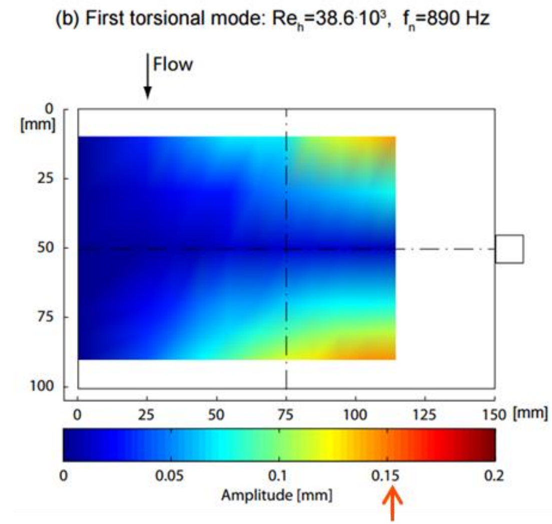
Step 3: Star-CCM+ fully-coupled FSI simulation

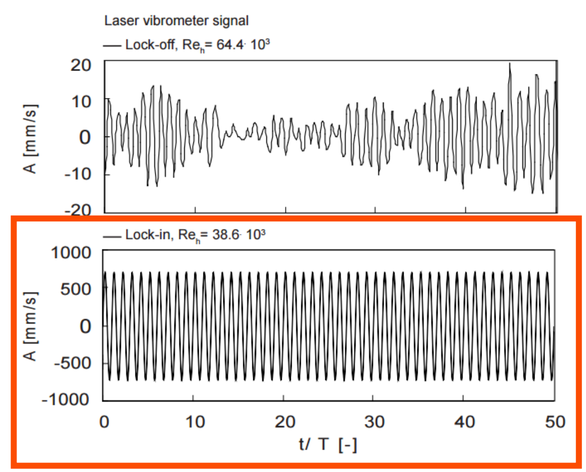
Star results: Tripped





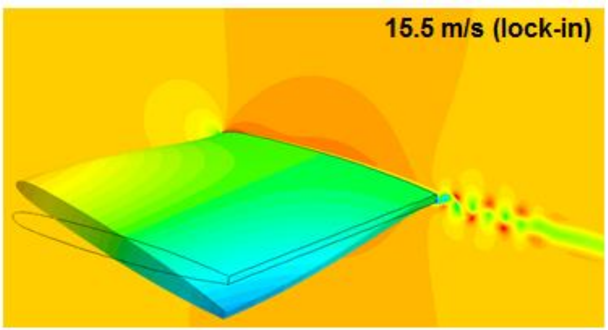
Experimental results: Natural transition (Phd thesis: Ausoni, P)

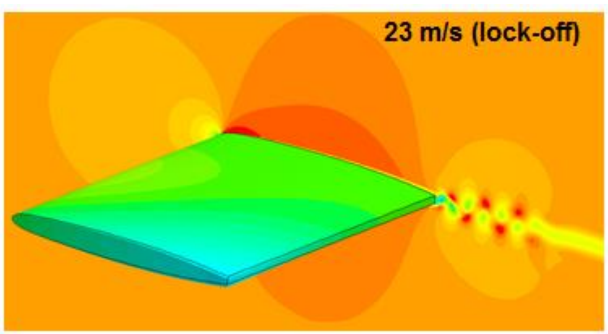


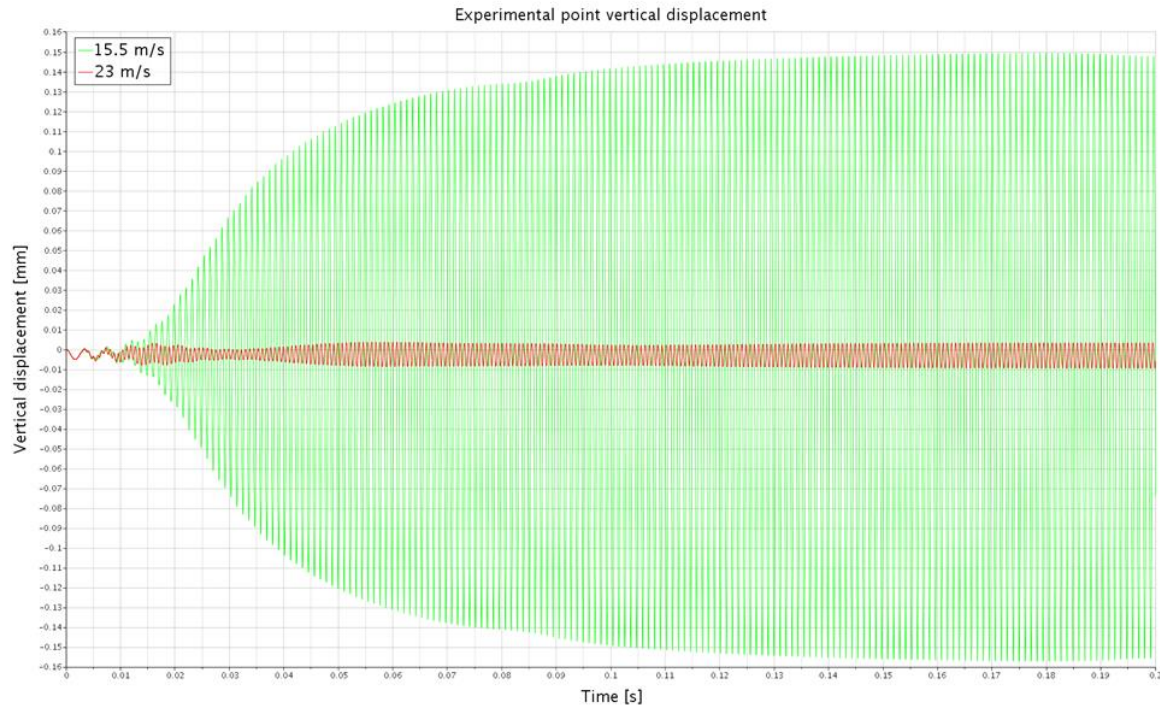


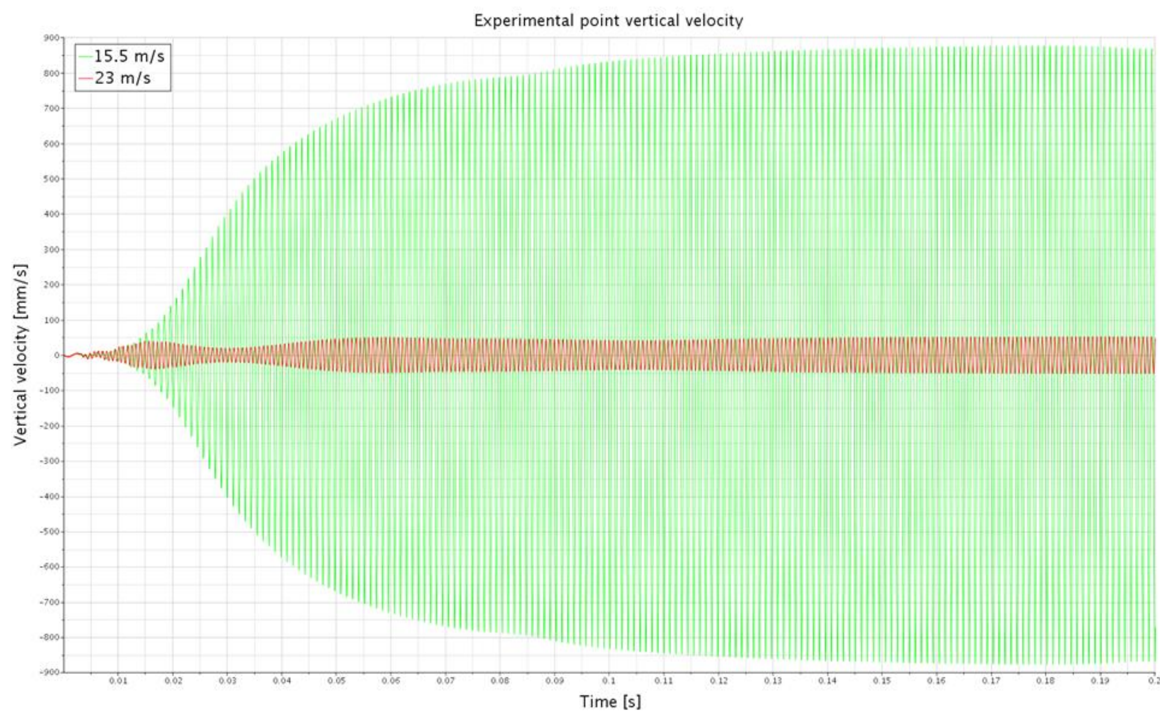
Star CCM+ results

The lock-in hydrofoil displacements and velocities are over an order of magnitude greater than those observed under lock-off conditions.



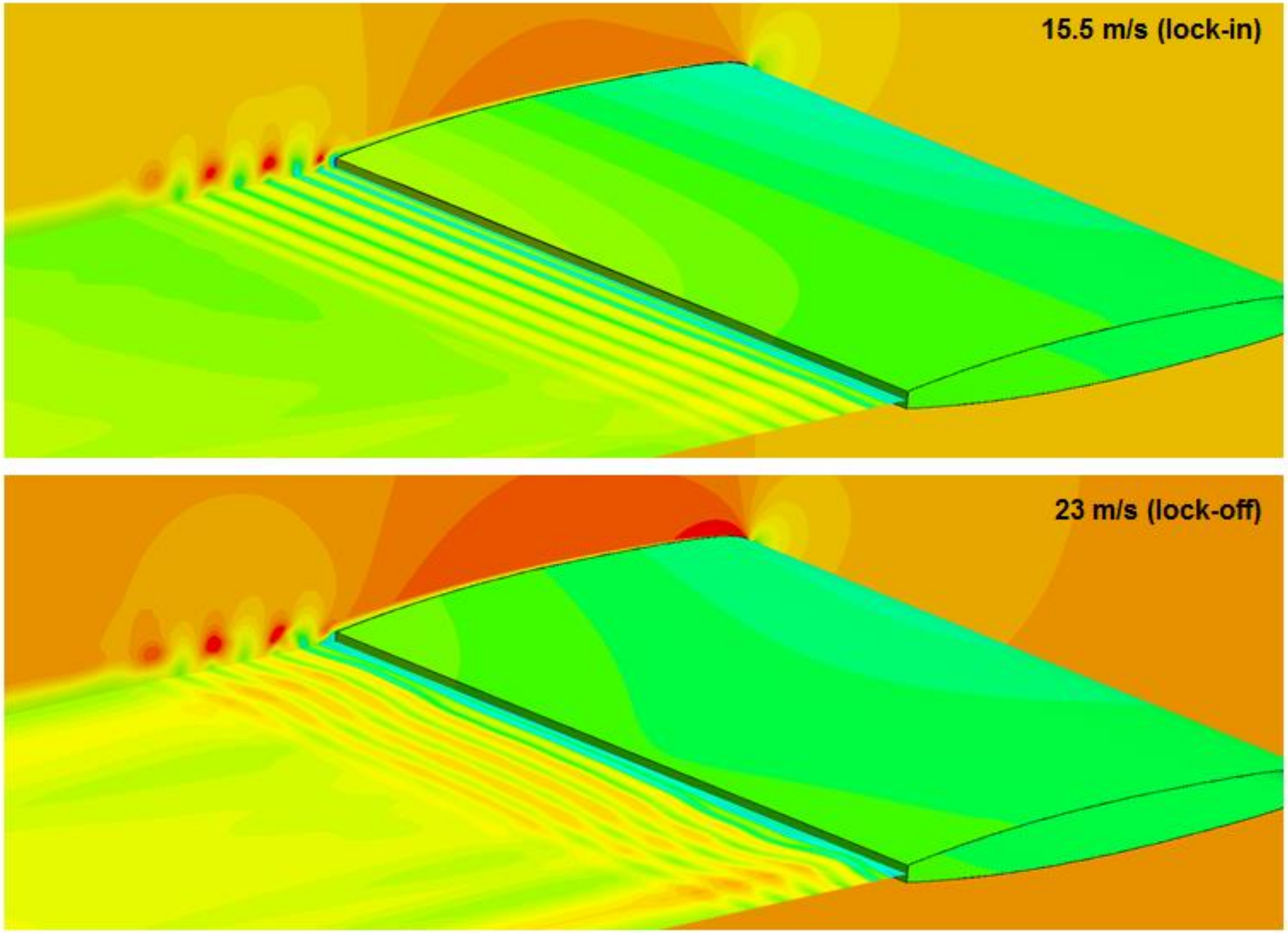






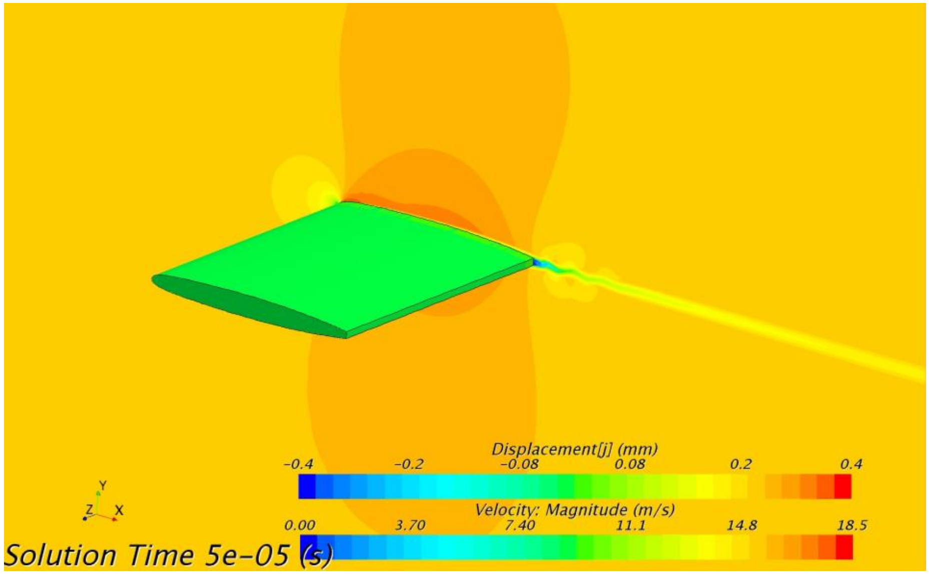
Step 3: Star-CCM+ fully-coupled FSI simulation

Under lock-in conditions there is increased coherence and lower average velocities in the wake region.

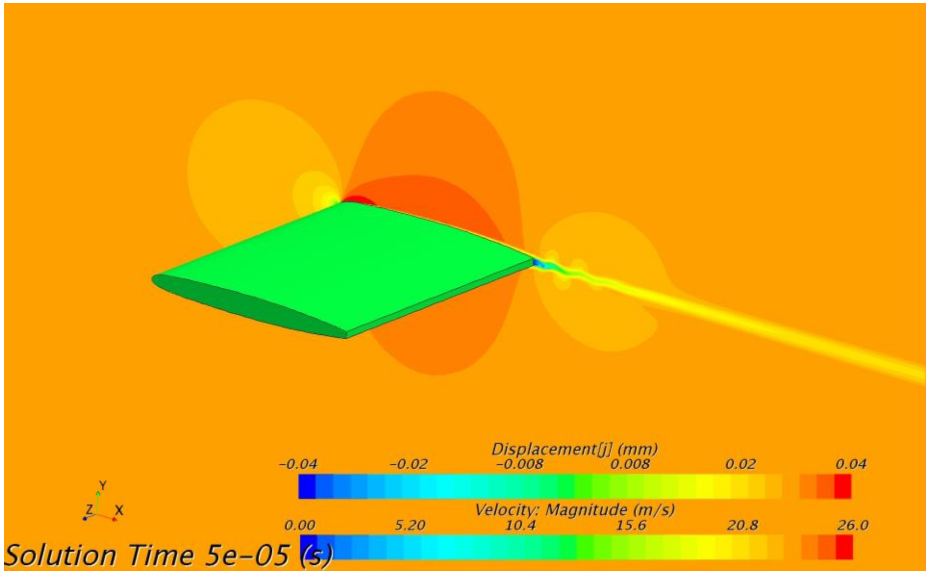


Step 3: Star-CCM+ fully-coupled FSI simulation

Lock-in (15.5 m/s)



Lock-off (23 m/s)



Hydrofoil displacements (scaled x50)

Simulations were computationally expensive running on ~150+ cores with run times in the order of ~3 – 5 days for 0.1 s simulation time.

Due to the need for a large number of very small time steps and tight convergence requirements per iteration.

Simulation difficulties and an alternative simulation approach

Simulation difficulties and an alternative simulation approach

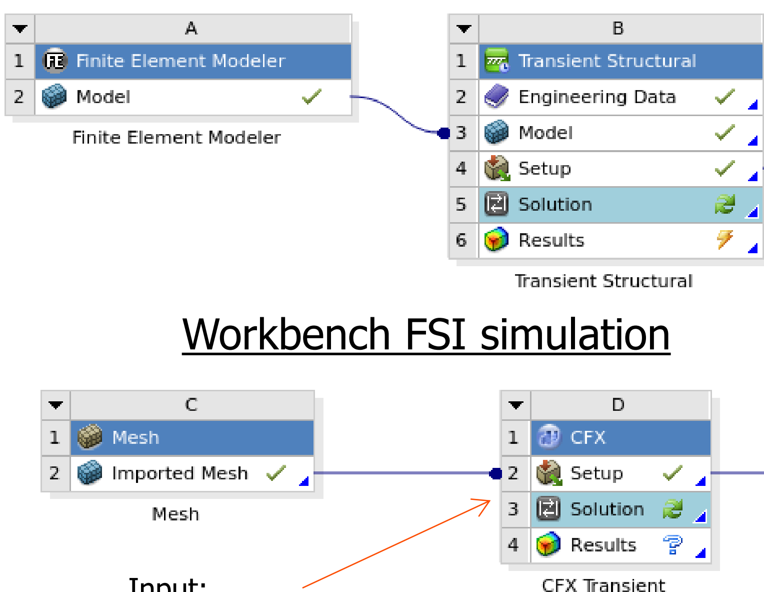
Briefly discuss some of the issues which were identified in the course of the research and an alternative modelling approach.

- <u>Implicit two-way coupling using ANSYS Workbench with CFX and Mechanical</u>

Adopting ANSYS Mechanical FE solver would allow for more complex structures, boundary conditions and material properties (e.g. composite models).

ANSYS Mechanical

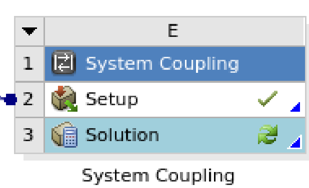
- Numerical damping parameter



<u>Workbench FSI simulation</u>

<u>Input:</u>
Steady RANS solution

<u>Standard simulation variables:</u>
- Time step
- Inner iterations
- Mesh



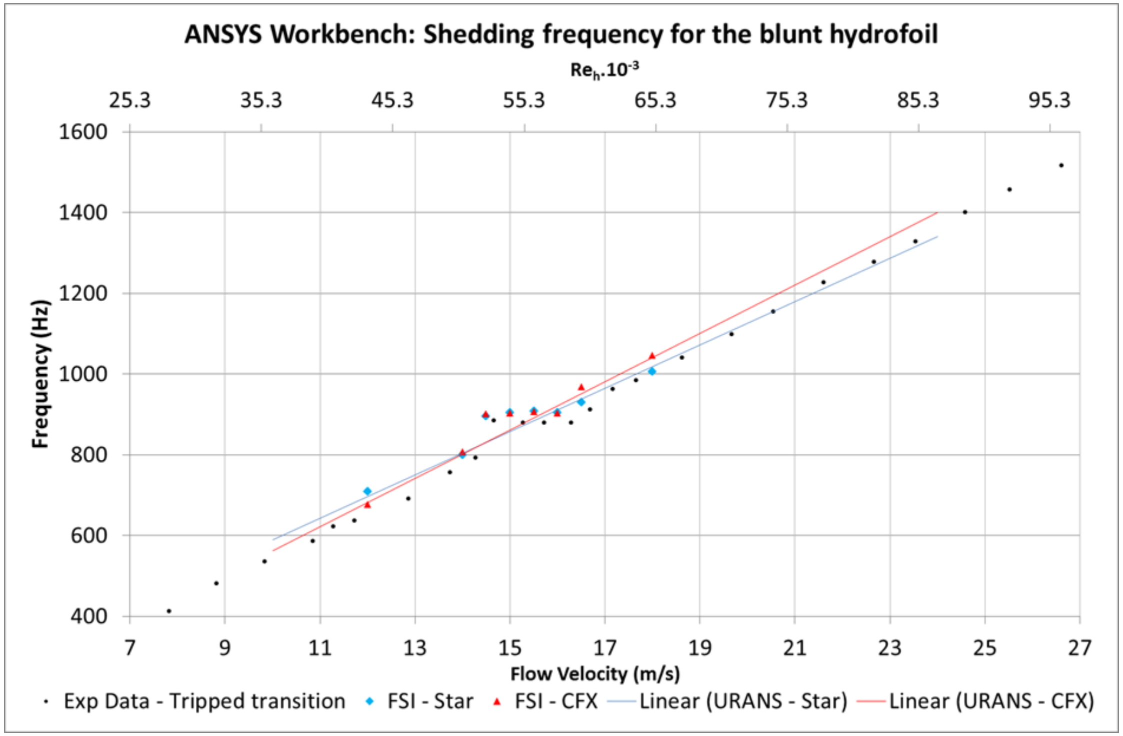
<u>Additional SC parameters:</u>
- Max number coupling iterations
- RMS coupling tolerance

Implicit coupling – additional coupling iterations

Simulation difficulties and an alternative simulation approach

A number of issues were encountered:

- Instability in mesh morphing (using Fluent) necessitated the use of CFX – being fixed.
- Local system instabilities while using Workbench.



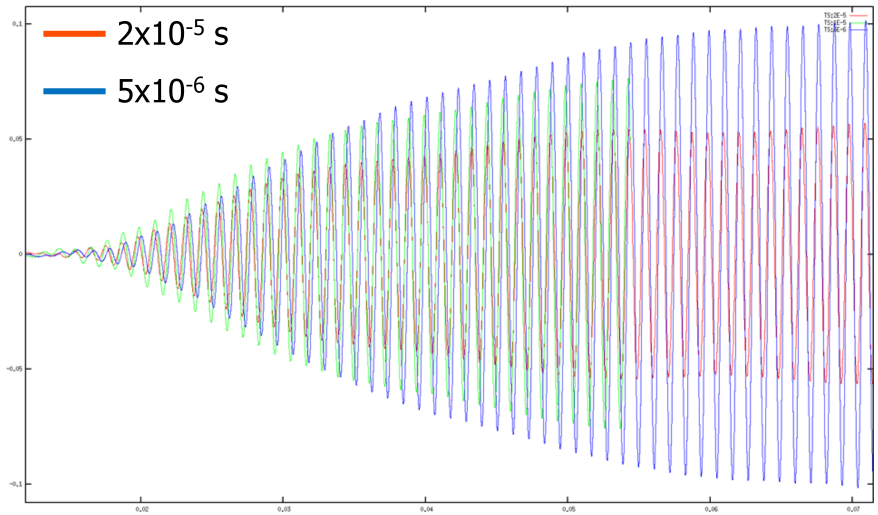
Coupled FSI simulation results for Star CCM+ and ANSYS Workbench (experimental data showing lock-in at 890 Hz).

Unfortunately, the hydrofoil displacement predictions using ANSYS Workbench were not so good.

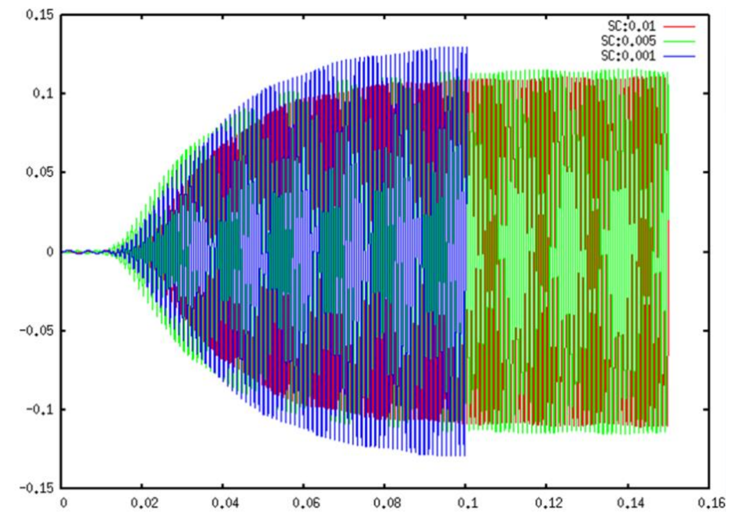
Simulation difficulties and an alternative simulation approach

The hydrofoil response was found to be very sensitive to the values chosen for the time step and the system coupling tolerance.

- A sensitivity study was undertaken for a single flow velocity of 15 m/s.
- As before, for each simulation the vertical displacement of the experimental point is plotted to assess the influence of the Workbench parameter on the response of the hydrofoil.



ANSYS Workbench sensitivity to simulation time step.



ANSYS Workbench sensitivity to coupling tolerance parameter.

To obtain comparable displacement predictions using ANSYS Workbench, the parameters were such that the simulations were significantly slower than Star-CCM+.

Discussion on-going with ANSYS

Simulation difficulties and an alternative simulation approach

At this point in time the main limitations of the fully-coupled approaches are the long run times and computational requirements.

- Modal decomposition methods:

Simulations can be significantly sped up if the response of the structure is calculated by solving the structural dynamic equation in modal form.

With this approach a full finite element model is not required to be solved every time step. This potentially yields much faster run times compared to fully coupled CFD-FE simulations.

Limitation:

Such approaches assume nonlinearities due to material or large displacements or contacts are not present and limited to structures with linear elastic, homogeneous and isotropic material properties.

- Siemens is developing a capability for Star-CCM+
- ANSYS plug-in RBF Morph for Fluent
- BAE Systems, in-house capability

Initial results using RBF Morph have been encouraging. Simulations typically ~12 hours and correctly predict lock-in frequency for the hydrofoil test case.

Work is on-going

Conclusions

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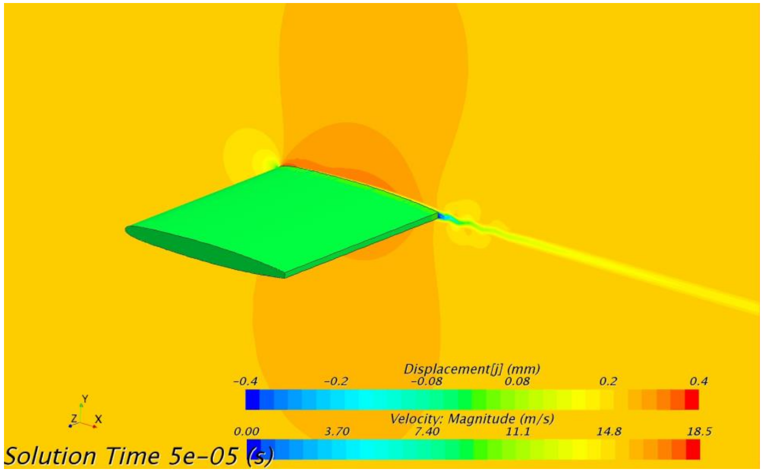
Conclusions

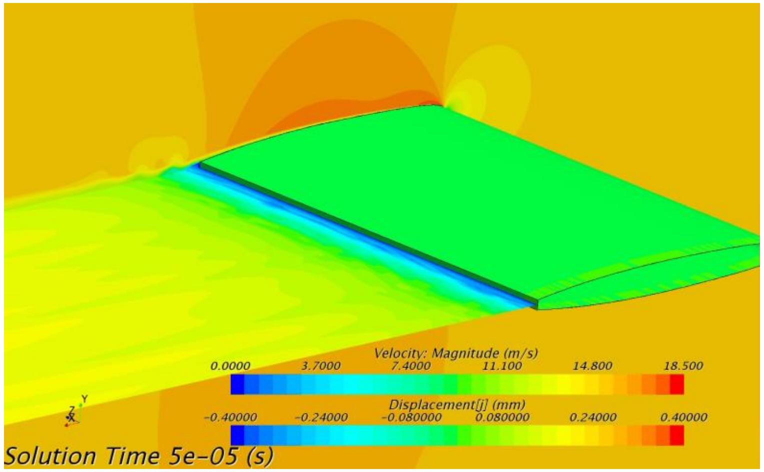
The capability for simulation to be used to model blade singing phenomenon has been demonstrated.

The problem remains challenging:

- Computationally intensive,
- Difficult to accurately predict the structural deformation.

Work within the Computation Engineering Department is on-going with further validation studies and application to more complex blade structures.





Thank you for your attention.

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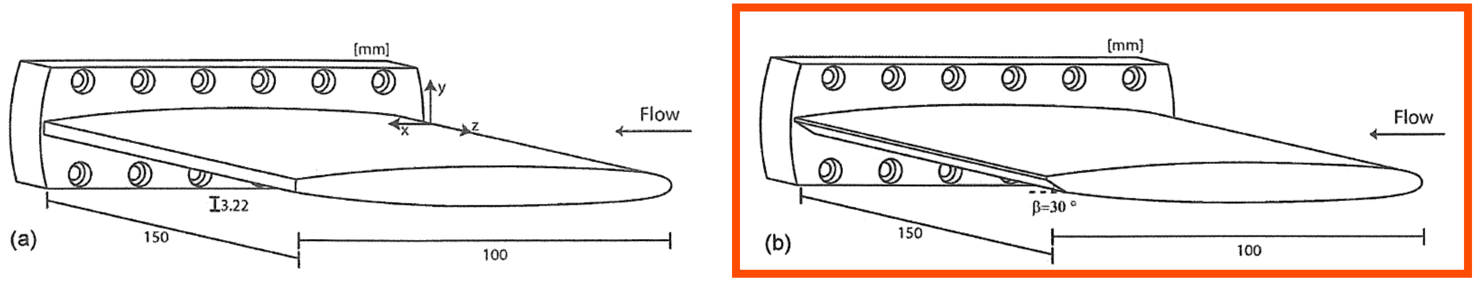
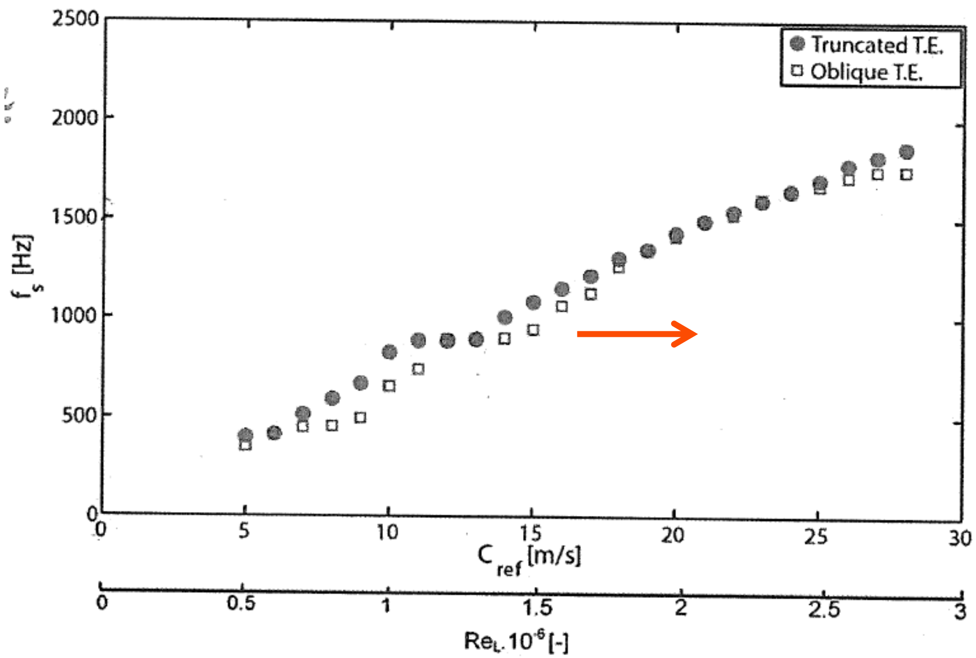
Oblique hydrofoil test case

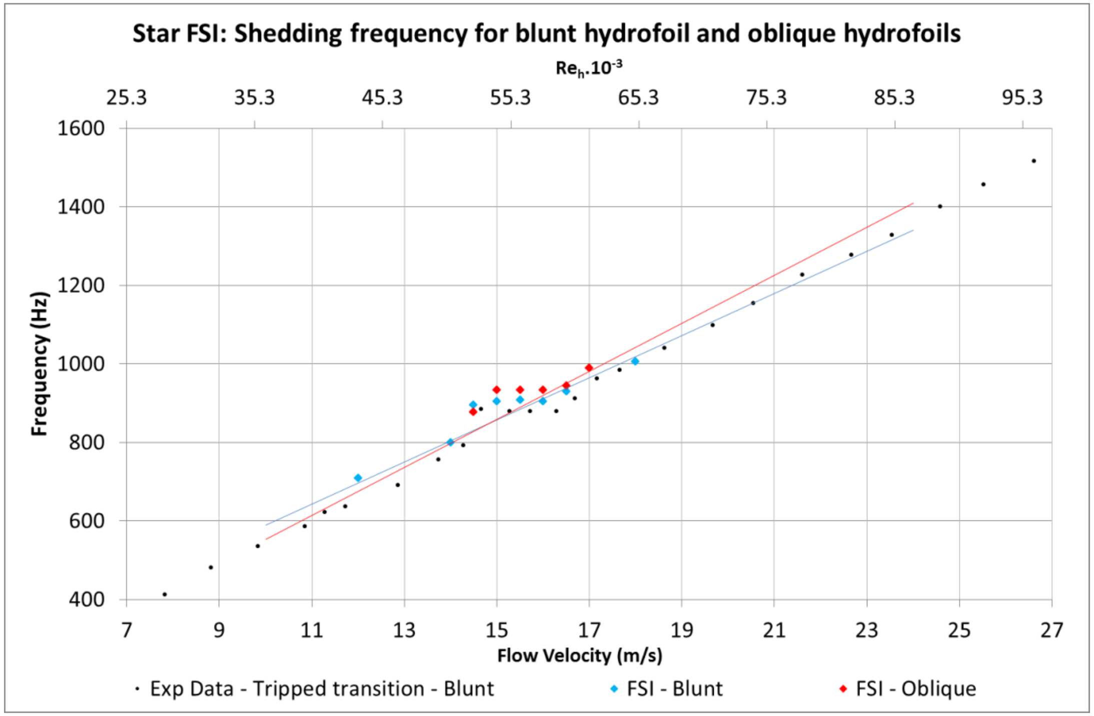


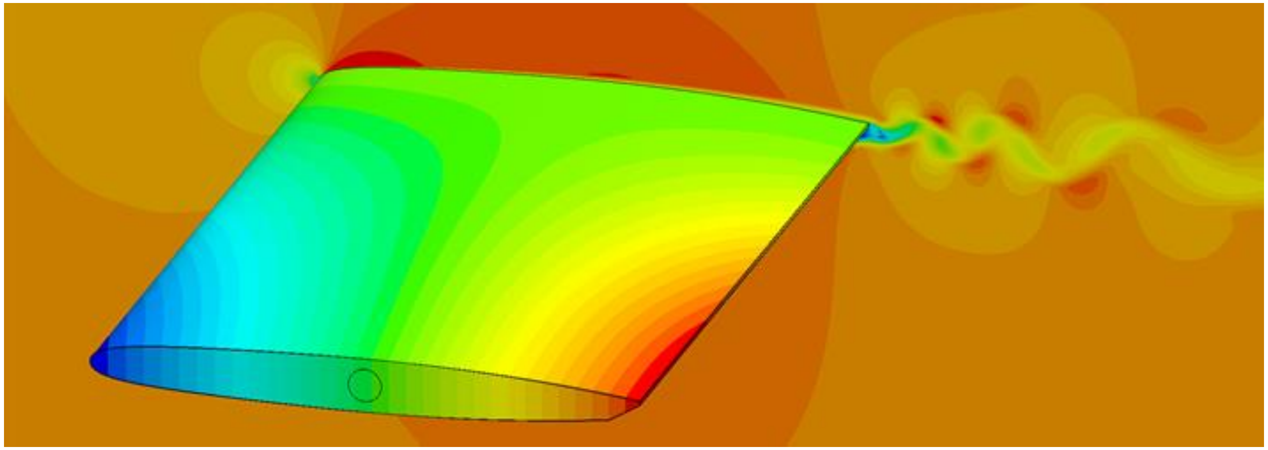


The oblique hydrofoil was seen to shift the lock-in region by ~1m/s.

The magnitude of the blunt hydrofoil was ~50% greater than the oblique hydrofoil.

Oblique hydrofoil test case





Star-CCM+ simulation correctly predicts the shift of the lock-in region and the reduced vibration.