NONLINEAR AEROELASTIC SOLUTIONS APPLIED TO ANALYSIS OF A BRIDGE

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ABSTRACT

So far the static as well as dynamic aeroelastic tasks were commonly solved by using linear models of fluid flow (p-k method, Doublet Lattice Method) implemented e.g. in system MSC.Nastran. These are reliable methods that allow fast solution to aeroelastic response of aircraft structural parts of classical conception. Together with development of aeroelasticity discipline and increasing performance of the computational hardware the possibility is coming up to solve aeroelastic phenomena also by CFD-FEM coupling. This method allows specifying description of non-stationary aerodynamic forces more precisely. With this method it is possible to predict interaction of flow and structural response closer to the real conditions and also in those cases when the current methods fail: flow around the thick profiles, non-aeronautical profiles, dynamic response of the structure to the periodic eddy detaching.

The presented article deals with the simulations of 2D fluid-structure interaction especially of wing profiles with their typical aeroelastic effect – flutter and a solution to interaction within whirl resonance behind a cylinder as a verification of the method. Then it is applied to the solution of the response of a bridge profile.

1. INTRODUCTION

As mentioned in the abstract thanks to the increased performance of the computational hardware the solution to aeroelastic response has become possible by coupling CFD and FEM codes. Computational studies of aeroelastic FSI simulations on simple aircraft and non-aircraft structures were conducted with the aim to compare method of coupling with currently used linear aerodynamic models and/or with theoretical or experimental results. Virtual simulations of 2D flutter and 2D whirl resonance were solved to validate the method for application to the bridge-structure analysis.

2. FSI SIMULATIONS

During solution of the dynamic aeroelasticity or Fluid-Structure Interaction (FSI) the solvers of FEM and CFD are interconnected (coupled). In each timestep of the solution are solved aerodynamic pressures in CFD and integrated into the nodes of FEM model. Further the load vector *F(t)* for the structural analysis is created and then the vectors of the structural nodal kinematical parameters – displacement, velocity, acceleration – are solved.

The structural displacement is transformed into the movement of the finite volume grid for the next step of CFD solution. In such a loop the aeroelastic response is solved across the whole time interval required.

Aerodynamic domain is solved by finite volume method using laminar or turbulent model of flow. The structural part is solved by finite element method in formulation for structural dynamics using implicit Newmark's numerical method for calculating the movement in each timestep of the solution.

3. 2-DOF FLUTTER SIMULATION

The simplest case of flutter is 2-DOF flutter of 2D profile having first DOF translation (bending) and second rotational (torsion). Bending and torsion are defined by springs having the stiffness $K_h = 105.109$ N.m^{-1} and $K_\varphi = 3.695\ 582$ N.m.rad^{-1}. Mass characteristics are defined by mass $m = 0.086\ 622$ kg, static moment about elastic axis $S_\varphi = 0.000\ 779\ 673$ kg.m and moment of inertia about elastic axis $I_\varphi = 0.000\ 487\ 291$ kg.m^2. Chord of the profile is $b = 0.30$ m and span $b = 0.079$ m. Position of the elastic axes is 40% of chord (measured from leading edge).

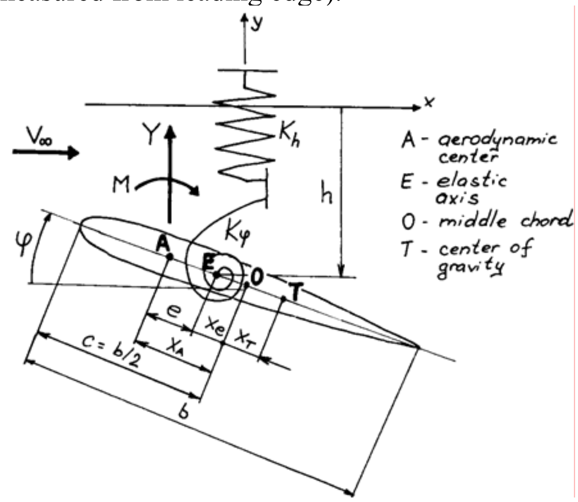

Figure 1: *Scheme of the 2-DOF problem*

Mass and inertial characteristics are defined by reference model that was used for comparison the nonlinear and linear method.

The structure can be described by the system of differential equations of movement solved by Newmark's method:

$$m\ddot{h} + S_\varphi \ddot{\varphi} + K_h h = -Y$$
$$S_\varphi \ddot{h} + I_\varphi \ddot{\varphi} + K_\varphi \varphi = M \quad (1)$$

The load on the right side of equations defines uplift (Y) and aerodynamic moment (M).

3.1 Linear solution

A linear aerodynamic model using Doublet-Lattice Method in computational system MSC.Nastran was employed to find linear solution of flutter. Diagrams at Fig. 2a, 2b describe aero-dynamic damping and frequency of the response. If the damping is negative, the structure is in the appropriate mode-shape damped by the flow if the damping reaches positive values the structure is waked and unstable. The fashion of the instability can be determined by the relationship of frequency on the velocity. In the case that the frequency is nonzero, the instability is unstable oscillation (flutter) if the frequency is zero, the response is one-side continual divergence.

In this case there was found one-side translational continual divergence with critical velocity v_{CR} = 30.0 m/s.

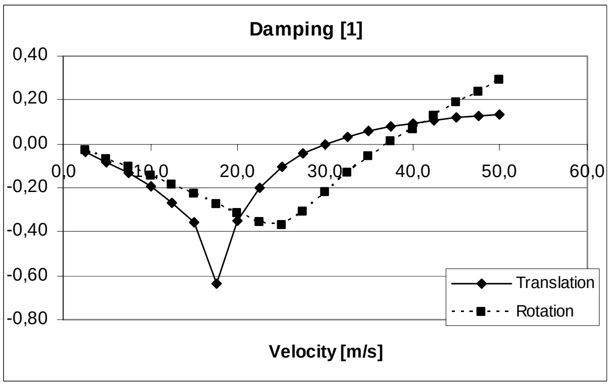

Figure 2a: *Damping – 2-DOF flutter solution*

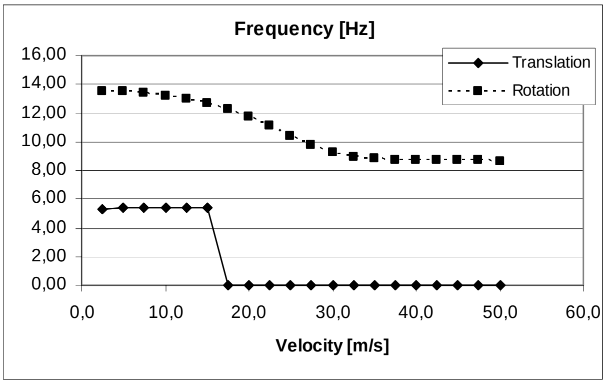

Figure 2b: *Frequency – 2-DOF flutter solution*

3.2 Nonlinear solution

In CFD system STAR-CD there was built 2D computational model of flow with moving grid describing flow around airfoil profile NACA 0012. The moving grid was built in such a form to allow vertical translation and planar rotation of the profile. The movement was controlled by dynamic solution of the structure using Newmark's method which was implemented in the process of the solution. For interconnection of the particular parts of the finite-volume domain there was used Arbitrary Sliding Interface (ASI) condition.

Simulations within various velocities of flow were studied. Initial condition of the wake was the rotation of the profile by φ = 1.5°. Characteristics of the fluid flow were parameters of air by ISA for altitude 200 m with laminar flow.

As show particular graph lines in Fig. 3 it is obvious that in nonlinear solution there is one-side divergency after reaching a flow velocity of 30 m/s. The vibration that proceedes at the start of the solved time period is caused by initial condition of rotation and the sudden increase in the flow velocity. Within continual increase in the velocity and zero initial condition the divergence it would be continuous during whole the period.

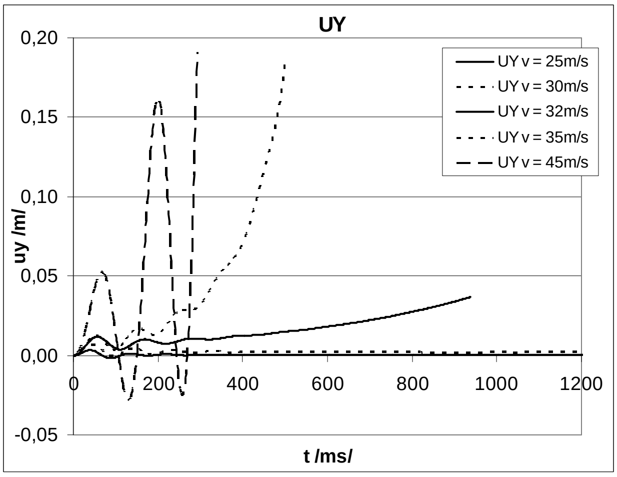

Figure 3: *Structural response – CFD-FEM coupled solution of 2-DOF problem*

4. 3-DOF FLUTTER SIMULATION

This is a similar task as described in the previous section but with one more DOF that represents rotation of aileron on the torsional spring attached to the wing profile.

In this case one has to deal with the lift force Y, torsional aerodynamic moment M_φ, and the hinge moment of the aileron M_δ.

The treated 3-DOF structure has the same global mass and stiffness parameters as the 2-DOF model. Just more aileron parameters were added: mass of aileron m_a = 6.064 e-3 kg, static moment of aileron around hinge S_δ = 0 kg.m, moment of inertia of aileron I_δ = 3.411 e-5 kg.m^2, torsion hinge stiffness K_δ = 0.2 N.m.rad^{-1}, chord of the aileron 60 mm. A system of differential equations describing the 3-DOF model can be written:

$$\begin{aligned} &m\ddot{h} + S\ddot{\varphi} + S_\delta\ddot{\delta} + K_y h = -Y \\ &S\ddot{h} + J\ddot{\varphi} + \left[(\bar{x}_k - \bar{x}_E)cS_\delta + J_\delta\right]\ddot{\delta} + K_\varphi \varphi = M_\varphi \\ &S_\delta \ddot{h} + \left[(\bar{x}_k - \bar{x}_E)cS_\delta + J_\delta\right]\ddot{\varphi} + J_\delta\ddot{\delta} + K_\delta \delta = M_\delta \end{aligned} \quad (2)$$

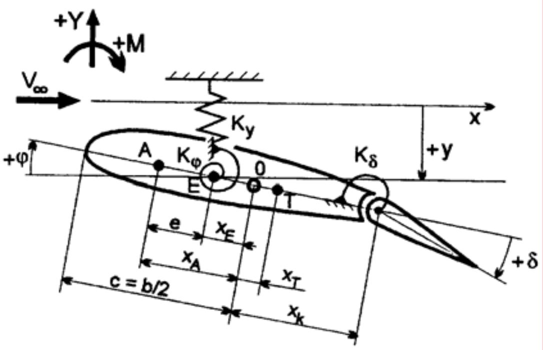

Figure 4: *Scheme of the 3-DOF problem*

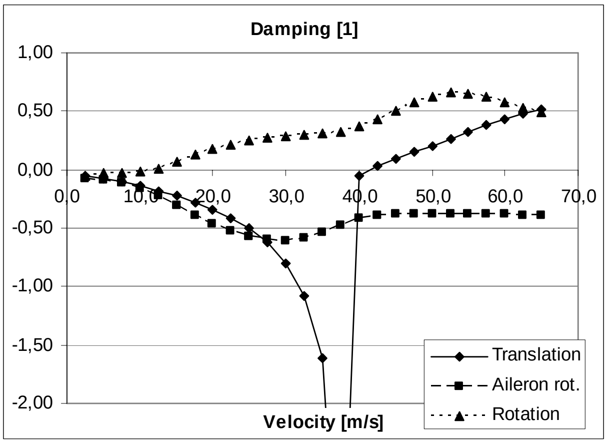

Figure 5a: *Damping – 3-DOF flutter solution*

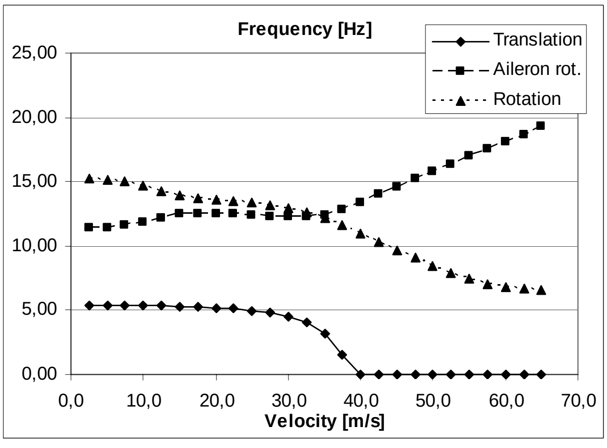

Figure 5b: *Frequency – 3-DOF flutter solution*

4.1 Linear solution

Solution was performed by means of linear aerodynamic theory in system MSC.Nastran in the same way as described in the previous article. The critical velocity of flutter v_{CR} = 11.3 m/s was obtained from the flutter solution. The form of divergence was found as diverging torsion oscillation followed by one-side translational continual divergence at the velocity of 41 m/s as shown at Figure 5a/b.

4.2 Nonlinear solution

By analogy to the article 3 there was analyzed nonlinear aeroelastic simulation using CFD-FEM coupled model of the airfoil profile NACA 0012. In this case with aileron attached to the bearing profile.

There was used FVM model with moving grid representing vertical translation, global rotation and rotation of the aileron around the hinge. (See Fig. 9.) Particular parts of the grid were interconnected with ASI boundary condition.

From the diagram at Fig. 6 it is seen that up to a velocity of 11.3 m/s the vibration is damped. Above the velocity 12 m/s there was found diverging torsion oscillation (Fig. 7). When the velocity was increased up to 45 m/s there appeared the transitional oscillating divergence changed to one-side continual divergence (Fig. 8) with a velocity exceeding 40 m/s.

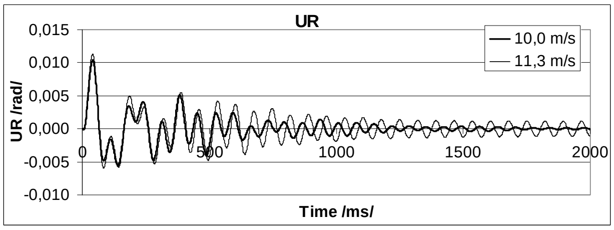

Figure 6: *Structural response – CFD-FEM coupled solution of 3-DOF problem (v = 10,0 – 11,3 m/s)*

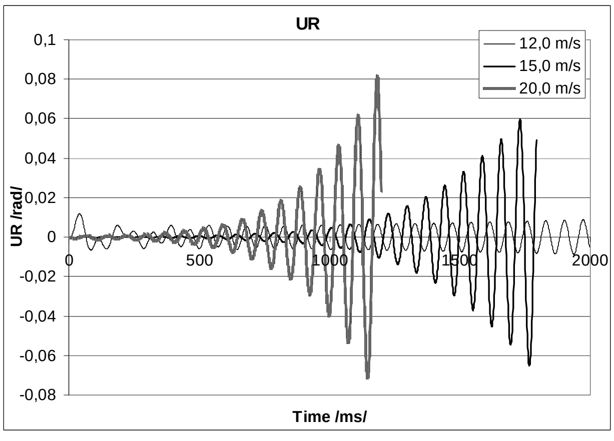

Figure 7: *Structural response – CFD-FEM coupled solution of 3-DOF problem (v = 12,0 – 20,0 m/s)*

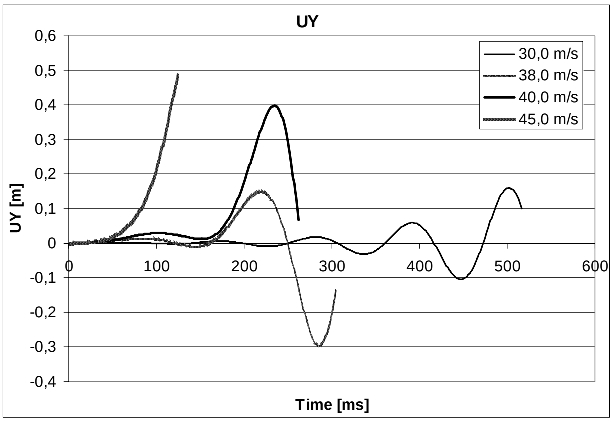

Figure 8: *Structural response – CFD-FEM coupled solution of 3-DOF problem (v = 12,0 – 20,0 m/s)*

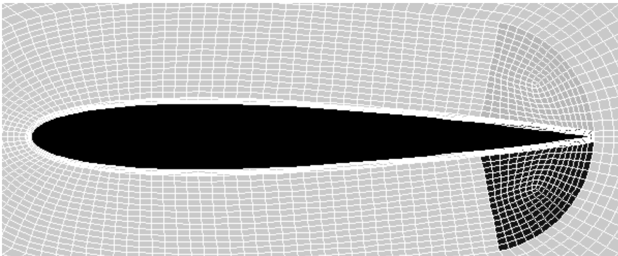

Figure 9: *Detail of the FVM model of the wing profile with rotating aileron*

5. RESPONSE TO THE WHIRL RESONNANCE

A problem of the response of discrete mechanical model to the whirl detaching is discussed. The model describes interaction of a rigid profile of cylinder loaded and interacting with fluid flow with phenomena of detaching of Strouhal (von Karman) vortices that appear in the critical and postcritical region of non-stationary flow that is defined by Reynolds number Re = $(5 \div 350) \cdot 10^3$. Such a problem of interaction is possible to solve only by using CFD solver connected to the FEM dynamical model. Parameters of the system were as followes: horizontal and vertical translational stiffness: $k_{x,y}$ = 4934 N/m, mass: m = 5 kg, natural frequency: $f_{x,y}$ = 5.0 Hz, cylinder height : l = 1.0 m, diameter of the cylinder: b = 0.3 m, velocity of the flow: v_∞ = 8.5 m/s, Strouhal number: $St \approx 0.18$, Reynolds number Re = 210 000.

Figure 10: *Scheme of the 2-DOF whirl resonnance problem*

Whirl resonance frequency:

$$f_{cr} = \frac{St \cdot v_{cr}}{b} = 5.1 \div 5.6 \text{ Hz.} \qquad (3)$$

The problem is described by independent diferential equations

$$\begin{aligned} m\ddot{x} + k_x x &= F_x \\ m\ddot{y} + k_y y &= F_y, \end{aligned} \qquad (4)$$

5.1 Nonlinear solution

In CFD system STAR-CD a 2D computational model was built defining the flow around the cylinder. During CFD solution there was used turbulent model k-Epsilon for low Reynolds numbers with standard near-wall behavior. The thickness of the boundary layer was defined by

$$y = 0.37\, b\, Re^{-0.2} = 0.01 \text{ m.} \qquad (5)$$

It was divided into 16 layers of cells with the first layer thickness of 0.0003 m.

During simulation there occurred lock-in effect and further growth of response amplitude. But the solution collapsed due to the parameter settings of the turbulent flow and also the frequency did not equal to the above mentioned 5.1 Hz but 8.5 Hz that would lead to the Strouhal number of 0.3. The grid was probably too dense.

In further solution there was used laminar model of flow. The run of the aerodynamic forces due to the detaching of whirls was more chaotic than within usage of turbulent model. However, the frequency of whirl resonance 5.0 Hz (see Fig. 11a) agreed to the theoretical/experimental value of $St = 0.18$ for circumfluence of cylinders. The response of the mechanical model (Fig. 11b) matched the wake by aerodynamic forces. The amplitude of the response grows during the time and there is lock of the wake to the response as the amplitude of both increased.

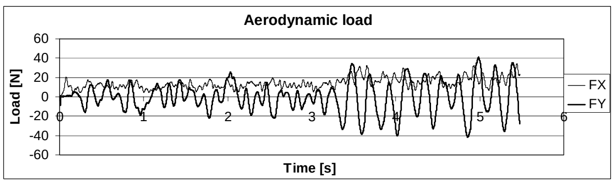

Figure 11a: *Aerodynamic load during simulation of the 2-DOF whirl resonnance problem*

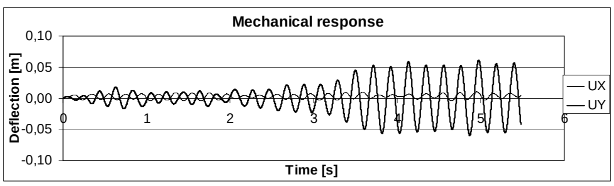

Figure 11a: *Mechanical response of the cylinder during simulation of the 2-DOF whirl resonnance problem)*

6. RESPONSE OF THE BRIDGE TO THE WIND FLOW

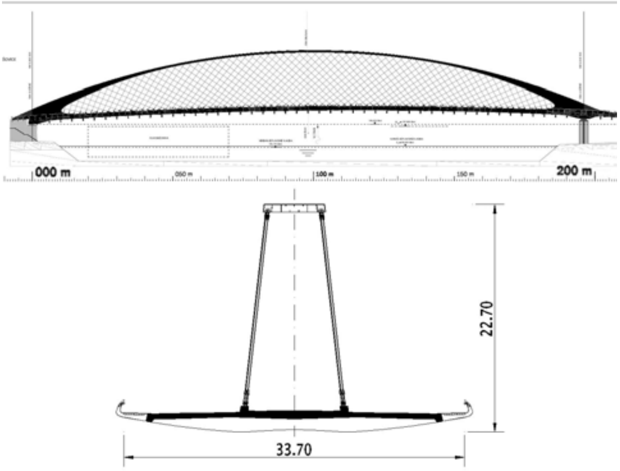

Figure 12: *Overall scheme of the Troja bridge*

There was analyzed response of the planned bridge to the wind. Span of the main field is 198 m, width of the bridge-deck 33.7 m, height of the arch 22.7 m. The bridge-deck is suspended by tendons on the steel arch.

6.1 Mechanical model

The frequency of the trosional mode-shape is closed to the bending frequency as seen in the table of mode shapes. Such a dynamic paramters pose a threat of aerodynamic instability. Furthermore the mode shapes of torsion are combined with horizontal bending so the description of modeshapes is complicated.

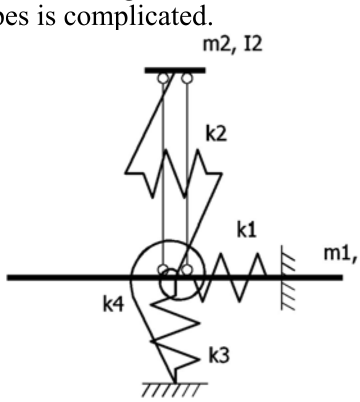

Figure 13: *Scheme of the reduced 2D model of the Troja bridge*

No	f [Hz]	Description
1	0.75	1st horizontal bending
2	0.94	1st vertical bending
3	1.00	1st torsion + 2nd hor. bend.
4	1.30	2nd torsion

Table 1: *Modal analysis results*

Global FEM model of the structure was created by engineers in Mott MacDonald company in Prague.

According to the global modal analysis there was created reduced 2D representative model as seen at Fig. 13. The model has four DOF: horizontal translation of the bridge-deck and of the arch, vertical translation and rotation. The translation and rotation of the bridge-deck and arch are coupled. Each part rotates around its axe. It's mass and inertial parameters were setup to represent 75 meters of bridge span. Then the stiffness was defined to provide demanded mode shape frequencies. There was used damping ratio 3‰ for the nonlinear aeroelastic analysis.

The reduced model could be described by system of differential equations which was solved by Newmark's method:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F(t)\}, \qquad (6)$$

where

$$[M]=\begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_1+m_2 & 0 \\ 0 & 0 & 0 & I_1+I_2 \end{bmatrix},$$

$$[C]=\begin{bmatrix} c_1+c_2 & -c_2 & 0 & 0 \\ -c_2 & c_2 & 0 & 0 \\ 0 & 0 & c_3 & 0 \\ 0 & 0 & 0 & c_4 \end{bmatrix}, [K]=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 \\ -k_2 & k_2 & 0 & 0 \\ 0 & 0 & k_3 & 0 \\ 0 & 0 & 0 & k_4 \end{bmatrix}$$

6.2 Nonlinear analysis

Because of eventual appearance of the aerodynamic instability caused by buffeting or buffeting in combination with flutter there was performed simulation of behavior in the wind flow.

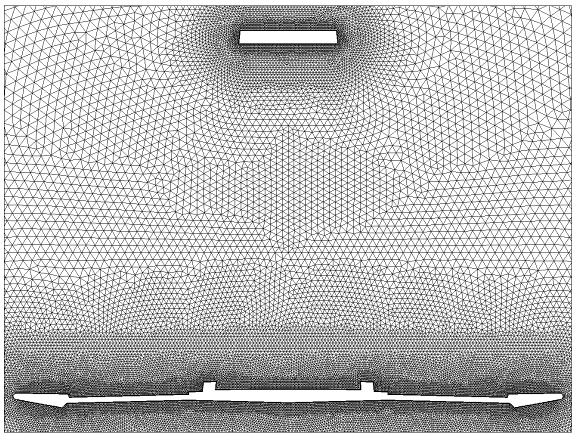

Figure 14: *Detail of the CFD model of bridge section*

6.2.1 CFD model

There was created 2D FVM model representing the cross-section of the bridge-deck with the arch in

CFD system STAR-CD. Boundary layer was defined by four layers of cells with overall thickness 0.05 m. With a purpose to reduce the time of the solution and with the aim to get results on the side of the safety there was used laminar model of flow. Velocity of the flow was set to 35 m/s

6.2.2 Solution of the response

Solution of the response was performed by Newmark's method programmed in the User Subroutines of STAR-CD using FORTRAN language. Every timestep of the CFD solution there was performed one timestep of FEM dynamic transient solution.

Solved movement components were transferred every timestep into the CFD solution. Boundary layer was moved and the rest of the grid was smoothed to obtain optimal cell shape.

Initial conditions of the structure were defined with the aim to obtain some initial oscillation. Amplitude of the oscillation would be damped or intensified by the wake of the flow during the FSI simulation. Hence there was defined initial vertical movement $Uy_0 = U3_0 = -0.42$ m and initial rotation $Ur_0 = U4_0 = 1°$.

6.3 Analysis results

Solved response within flow velocity 35 m/s shows that the initial oscillation is damped during the solution period of 7 seconds. There is just steady horizontal vibration which is probably caused by large initial conditions of the others DOFs. The horizontal response also reaches small values. (See Fig. 16 – 17)

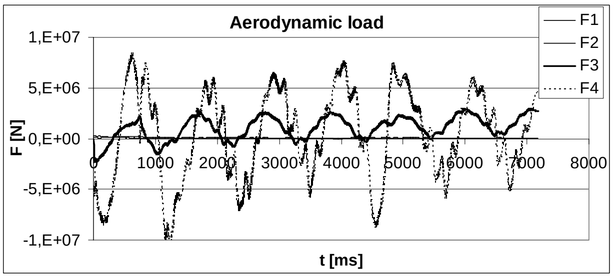

Figure 15: *Aerodynamic load*

The first solution shown that the structure is damped, but there should be performed further analyses. The analyses should be run also for modifications of the 2D reduced model with respect to the modal analysis and duplex mode shapes. Especially the torsion mode-shape frequency should be varied. Furthermore the bridge-deck is stiffened by crosswise diaphragms every 4 meters of its span. So there will be analyzed 3D periodic model with bridge deck diaphragm included.

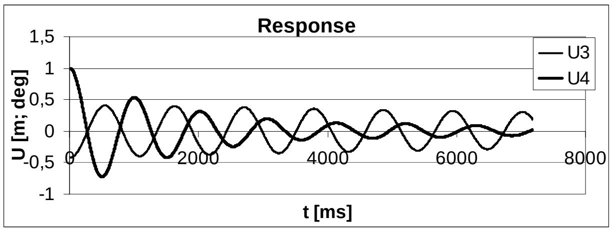

Figure 16: *Mechanical response with the initial conditions*

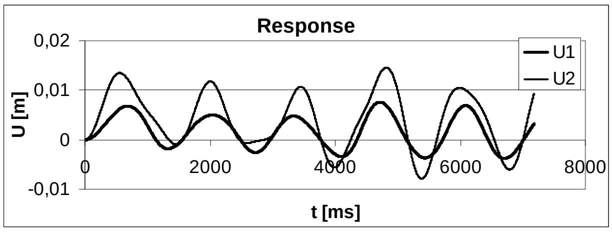

Figure 17: *Horizontal mechanical response*

7. CONCLUSION

Aeroelastic solutions were performed by coupling CFD-FEM solvers with the aim to compare this method with currently used linear methods of flutter solution and with experimental and/or theoretical data. The solution concepts that were performed showed the reliability of the method when the results of nonlinear solutions agreed with reliable methods and/or with theoretical/experimental data. The method was later applied to the analysis of the planned bridge.

The main benefit of this method is possibility to analyze nonlinear aeroelastic effects such as buffeting that could appear especially on the civil engineering structures.

8. REFERENCES

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