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Interaction Dynamic Analysis of Flexible Structures under Wind Load

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Abstract - The analysis of flexible structures under wind load is very difficult and sensitive. The CFD method is an elaborate approach that gives accurate results, but in the same time it needs enough familiarity with this approach in addition to high-speed and large memory computers, workstations at least. In this paper an interaction dynamic analysis, that considers directly the aerodynamic damping due to the deflection of structure under wind load, is proposed. The analysis is examined under several degrees of structure flexibility and two levels of wind turbulence. Moreover, the proposed analysis has been evaluated by comparing its results with the CFD method results, where good agreement has been obtained.

***Keywords*:** Flexible structures-Wind load- Aerodynamic damping - CFD - SRM

1. Introduction

The analysis of flexible structures under wind load is a very hard process due to the fluctuation of the load. Flexible structures are susceptible to the fluctuating of wind load where the structure deflections become significantly operative. Therefore, the response of the structure must be taken into account simultaneously while calculating the wind load with time throughout the analysis.

The computational fluid dynamics CFD is one of the most accurate approaches to analyze the problems of fluid structure interaction although it is a laborious approach and time-consuming analysis.

Another approach to analyze structures under wind load is to calculate the wind velocity through spectral representation method, SRM [6]. Then this generated velocity is used to calculate the wind load which is applied to the structure and dynamic analysis is carried out. This technique has been developed by Shinozuka and Jan [3], where the wind velocity is produced through sample realizations of the process according to the prescribed power spectral density function PSD. A considerable drawback of this approach is that the SRM does not take into account the interaction between the generated wind load and the structure elastic response.

In this research, an interaction dynamic analysis, using generated wind load by the SRM, is proposed, considering the aeroelastic interaction between the wind and the oscillating structure (the aerodynamic damping [5,8]) caused by the structure deflection, especially in case of flexible structures.

2. Computational Fluid Dynamic CFD Method

The CFD problem is to solve the velocity field (u, v, w) and pressure field p inside the control volume [2]. To solve these unknowns, four equations are formulated using the conservation of mass and conservation momentum in the three directions, on a small control volume. These formulated equations called the Navier-Stokes equations. Moreover, the CFD introduces the solution for the fluid structure interaction FSI considering the aerodynamic damping when the fluid forces lead to substantial deformations of the structure and consequently fluid flow pattern variations.

There are two main approaches for the simulation of FSI-problems; the monolithic approach and the partitioned approach. In the present work the partitioned approach was used for better numerical stability, associated with implicit solution scheme for accurate results, despite its time consuming. Moreover, the ALE algorithm (Arbitrary Lagrangian Eulerian which is a combination of the two classical descriptions of motion, the Lagrangian motion and the Eulerian motion) was chosen to describe the kinematics of the fluid continuum to consider the structure deflection.

The analysis by the CFD method has been performed by the commercial software package Comsol fluid dynamics.

3. Wind Load Generation with the SRM

The three-dimensional wind load simulation method SRM is based on a method developed by Shinozuka in the 1950s [3]. G.Deodatis [4] has suggested an algorithm which generates ergodic time histories.

3.1. Stochastic wind field modeling

Stochastic wind speed U (x, y, z, t) is assumed to be a stationary random field, which can be separated into a mean value component $\overline{U}$ (z) and a zero mean value fluctuation component u (x, y, z, t) [1].

$$U_W(x, y, \mathrm{z}, t) = \overline{U}(z) + u(x, y, z, t) \qquad (1)$$

That can be written in brief:

$$U_W(t) = \overline{U} + u(t) \qquad (2)$$

Where: $U_W(t) = U_W(x, y, z, t)$, $\overline{U} = \overline{U}(z)$ and $u(t) = u(x, y, z, t)$

3.2. Coherence functions

The coherence function “ $coh_{i.j}$” is a frequency dependent measure of the amount of correlation between the wind speeds at different points *i and j* in space [1].

3.3. Power Spectrum density of wind velocity Su(z,f)

A convenient formulation of a spectral density function $S_u(z, f)$of wind velocity, suggested by Vonkarman [7], is used.

Where $S_u(z.f)$ is the wind velocity auto spectrum elements at level z. The power spectral density matrix PSD of wind velocity $S_u(f)$ can be expressed as:

$$S_{uiuj}(f) = \sqrt{S_{uiui}(f) S_{ujuj}(f)}\, coh_{i.j}\ (f.\Delta_{i.j}) \qquad (3)$$

Where f is the desired frequency, $S_{uiui}(f)$ (the diagonal elements) are the wind velocity auto spectrum, $coh_{i.j}$ is the coherence function and $\Delta_{i.j}$ is the separation distance between the two points. The indices *i and j* vary from 1 to n (the number of nodes).

3.4. Generation of wind velocity turbulent component ‘u(t)’

Once the wind velocity PSD matrix has been formulated the Cholesky decomposition method is used to decompose the definite-positive matrix of the PSD of wind velocity into a product of a lower triangular matrix $H(f)$ and its conjugate transpose $H^{T*}(f)$, as follows:

$$S_u(f) = H(f) H^{T*}(f) \qquad (4)$$

The generation of the wind velocity turbulent component ‘$u_j(t)$’ can be performed with double indexing technique [4], as indicated in the following equation:

$$u_j(t) = \sqrt{2\cdot\Delta \mathrm{f}}\sum_{m=1}^{n}\sum_{l=1}^{N} H_{jm}(f_{ml})\cdot Cos(2\pi f_{ml}t + \emptyset_{ml}) \tag{5}$$

Where Δf is the frequency step, n is the number of nodes, N is the number of studied frequencies, $\emptyset_{ml}$ is the random phase angle (0-2π), f_{ml} is the studied frequency and j is the node number at which the wind velocity is calculated.
In this research a computer program has been developed, using Matlab, and verified with published results [7].

4. Interaction dynamic analysis

In this research an interaction dynamic analysis that considers directly the effect of the elastic structure response on the wind load throughout the analysis (the aerodynamic damping) has been proposed by the first author. The elastic interaction effect [5] is taken into account through the calculation of the instantaneous wind load by applying the relative velocity between the wind and the structure as indicated in the following equation.

$$F_W(t) = 0.5\; C_D A\rho(U_W(t) - \dot{\delta})^2 \tag{6}$$

where F_W(t) is the instantaneous wind load, $U_W(t)$ is the wind velocity generated by the SRM (Spectral Representation Method), $\dot{\delta}$ is the structure velocity, A is the reference area, C_D is the drag coefficient and ρ is the wind density.

Equation (6) is applied directly in the general dynamic equation as follows:

$$m\ddot{\delta} + C_s\dot{\delta} + K\delta = F_W(t) \tag{7}$$

where *m*, C_S, and *K* are the mass, damping and stiffness of the structure, respectively. δ, $\dot{\delta}$ and $\ddot{\delta}$ are the displacement, velocity and acceleration for the structure.

The problem in the solution of equation (7) is that the simultaneous wind load F_W(t), the right hand side of the equation, is still unknown, where it is dependent on the instantaneous structure velocity $\dot{\delta}$, as indicated in equation (6). In this proposed analysis the structure velocity $\dot{\delta}$ throughout the current time interval Δt is assumed to be equal to the value of the structure velocity obtained at the end of the previous time interval, in the term of F_W(t). To initiate the solution, the structure velocity $\dot{\delta}$ is assumed to be zero, in the term of F_W(t), throughout the first time interval.

This direct interaction dynamic analysis is carried out for each time interval Δt and continued along the total desired time t through a batch file, where a complete dynamic analysis is done for each time interval Δt and the calculated structure velocity $\dot{\delta}$ at the end of the last time interval is assumed to be constant, when calculating the wind load F_W(t) for the new time interval. It is worth noting that to get reliable results using this proposed analysis, an appropriable small time interval Δt should be used.

The present analysis has been examined through analyzing plates of several degrees of flexibility under wind load with different levels of turbulence. The result of each analyzed case by the present analysis has been compared with the result of the CFD analysis to verify the validity of the proposed analysis. Good results have been obtained as will be shown in the following numerical investigations.

This proposed interaction analysis has been performed through the commercial software package Comsol Multiphysics.

5. Numerical investigations

Several numerical investigations were carried out to verify the efficiency of the present proposed analysis through the comparison between the results of the following analyses: the robust CFD analysis, the proposed interaction dynamic analysis (considering the aerodynamic damping) and the typical dynamic analysis (without aerodynamic damping).

These numerical investigations have been done on rectangular steel plates fixed at bottom, with several degrees of flexibility (variable thicknesses), across wind flow with two levels of turbulence ($\overline{U}$=10 m/s and $\overline{U}$=20 m/s at the height of the plate tip), as shown in figure (1) and the tables (1,2,3 and 4).

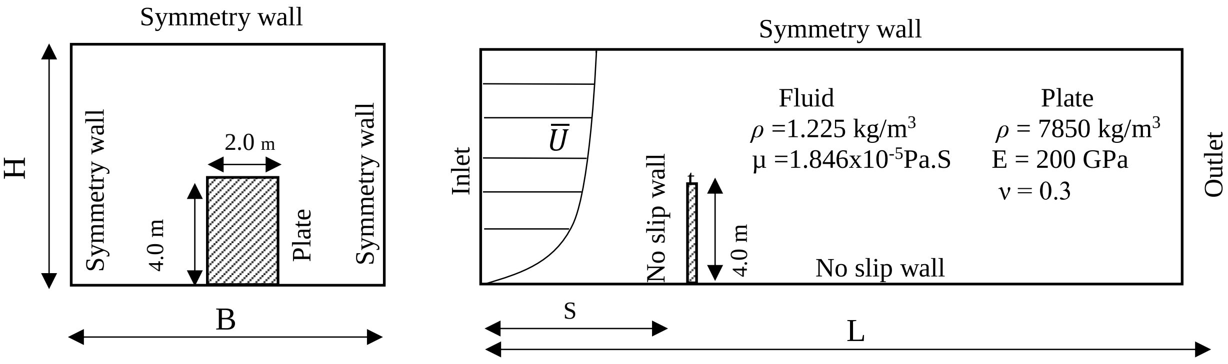

Figure. 1: The CFD domain and properties of the studied fluid and plate (ρ is the density, µ is the dynamic viscosity, E is the modulus of elasticity and ν is the Possion's ratio).

All results of the present numerical investigation are indicated in tables (1, 2, 3 and 4). Moreover, a sample of wind velocity time history at one of the plate nodes (the mid-point of the plate tip) generated by the SRM is shown in figure (2). Samples of the plate deflection computed by the proposed interaction dynamic method (considering the aerodynamic damping) compared with the result of the typical dynamic analysis (without the aerodynamic damping) and then the results of the proposed method compared with the results of CFD method, are shown in figures (3 to 10). These samples are selected for the smallest plate thickness (t = 10 mm) and the largest plate thickness (t = 20 mm), studied under two wind velocities ($\overline{U}$=10 m/s and $\overline{U}$=20 m/s) representing two levels of wind turbulence.

From the shown results (tables 1 to 4 and figures 3 to 10) it is clear that the deflection of the plate, computed by the proposed interaction analysis (where aerodynamic damping is considered) is smaller than the deflection computed with typical dynamic analysis (without aerodynamic damping). The difference ranges from 6.2% to 36.4% under velocity $\overline{U}$=10 m/s and ranges from 20.8% to 54.6 % under velocity $\overline{U}$=20 m/s, depending on the plate thickness. It can be noted that the effect of the aerodynamic damping increases with the increase of the plate flexibility (decreasing the plate thickness). Also, the aerodynamic effect increases with the increase of the wind turbulence (increasing the wind velocity).

To evaluate the proposed analysis, the average of the deflection in the steady state range computed by this analysis is compared with the corresponding deflection computed by the CFD method under the same condition. Good agreement has been achieved, where the maximum difference does not exceed 14.3%.

The computation time with the proposed interaction dynamic analysis including the wind velocity generation was almost 1 hour and half. For the same problem by the CFD method it took about 3 hours and half with normal mesh while with fine mesh the time ranged from 19 hours to 23 hours depending on the plate thickness. The analysis of the proposed method has been executed by a laptop with a processor Core i5 (2.4 GHz) and installed memory 'RAM' 6 GB. The CFD analysis was done using workstation with 2 processors Xeon (R) each 2.0 GHz and installed memory 'RAM' 56 GB. It is worth noting that 3-dimendional analyses were done by both the dynamic method (with and without aerodynamic damping) and the CFD method.

Table.1: Dynamic analysis results under wind velocity $\overline{U}$=10 m/s at the plate tip.

Plate thickness (t)	Max. Peak of deflection* (without aerodynamic damping)	Max. Peak of deflection* (proposed analysis considering aerodynamic damping)	Difference percentage
10 mm	744.74	473.53	36.4 %
12 mm	358.21	264.10	26.3 %
16 mm	162.56	126.23	22.3 %
20 mm	91.695	86.064	6.20 %

*Maximum peak of deflection history (mm) at the mid-point of the plate tip in the steady state zone.

Table.2: Results of the CFD method and the proposed method under wind velocity $\overline{U}$=10 m/s.

Plate thickness (t)	Deflection*(CFD method)	Average deflection* (Proposed method)	Difference percentage
10 mm	115.58	133.0	13.1 %
12 mm	67.452	68.20	1.10 %
16 mm	28.561	28.10	1.60 %
20 mm	14.634	16.00	9.30 %

* Deflection (mm) at the mid-point of the plate tip in the steady state zone.

Table.3: Dynamic analysis results under wind velocity $\overline{U}$=20 m/s at the plate tip.

Plate thickness (t)	Max. Peak of deflection* (without aerodynamic damping)	Max. Peak of deflection* (proposed analysis considering aerodynamic damping)	Difference percentage
10 mm	2384.1	1069.4	54.6 %
12 mm	1351.4	946.3	30.0 %
16 mm	707.64	533.59	24.6 %
20 mm	310.23	245.61	20.8 %

*Maximum peak of deflection history (mm) at the mid-point of the plate tip in the steady state zone.

Table.4: Results of the CFD method and the proposed method under wind velocity $\overline{U}$=20 m/s.

Plate thickness (t)	Deflection*(CFD method)	Average deflection* (Proposed method)	Difference percentage
10 mm	442.68	432.00	2.400 %
12 mm	263.06	276.00	4.900 %
16 mm	113.65	130.00	14.30 %
20 mm	58.511	57.400	1.900 %

* Deflection (mm) at the mid-point of the plate tip in the steady state zone.

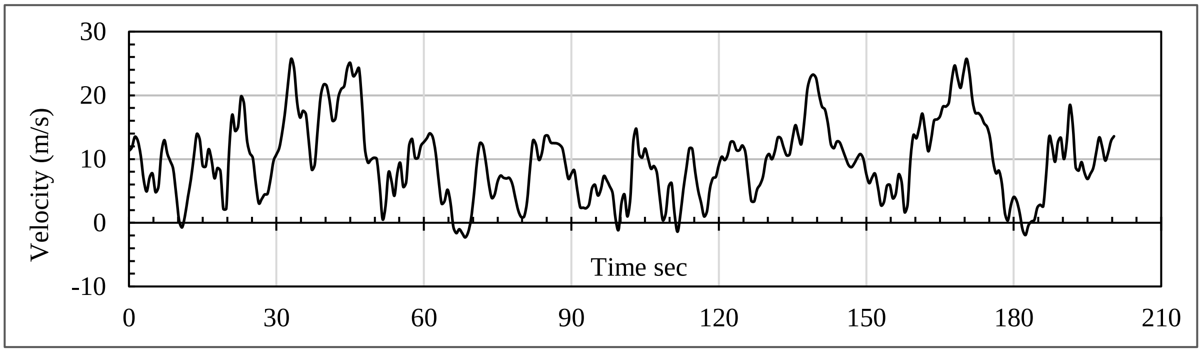

Figure. 2: A sample of wind velocity (at the mid-point of the plate tip) generated by the developed program (SRM) at $\overline{U}$=10 m/s.

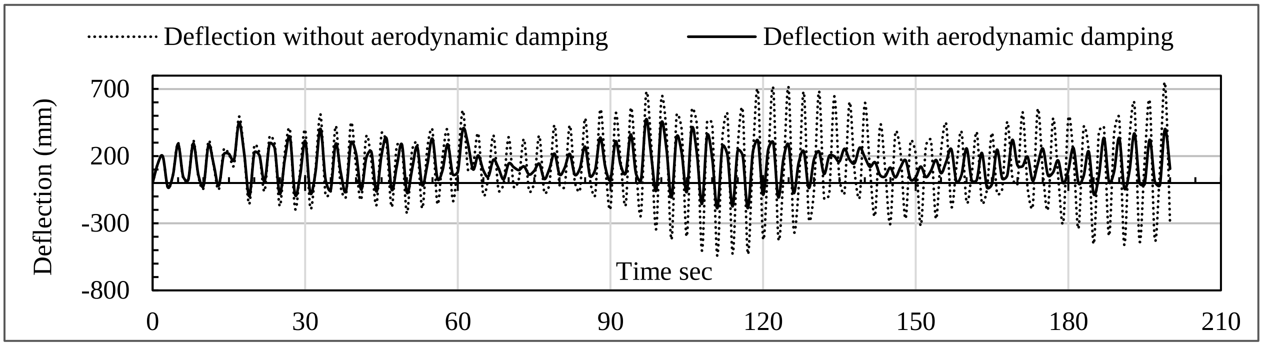

Figure.3: Mid-point deflection of the plate tip with and without aerodynamic damping at $\overline{U}$=10 m/s and t=10mm.

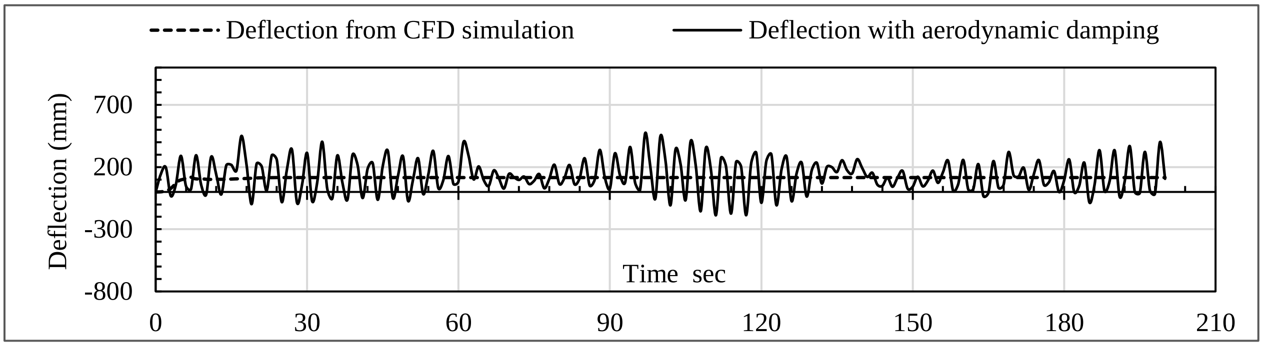

Figure.4: Mid-point deflection of the plate tip with CFD method and proposed method at $\overline{U}$=10 m/s and t=10mm.

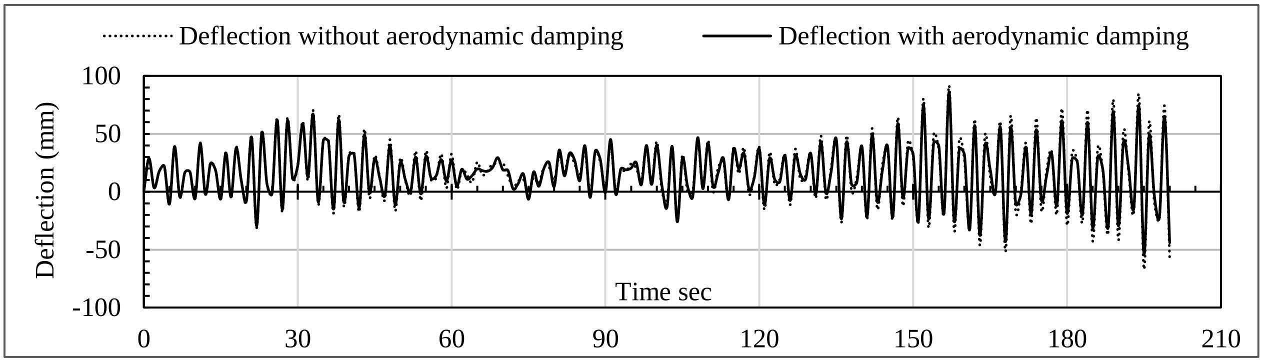

Figure.5: Mid-point deflection of the plate tip with and without aerodynamic damping at $\overline{U}$=10 m/s and t=20mm.

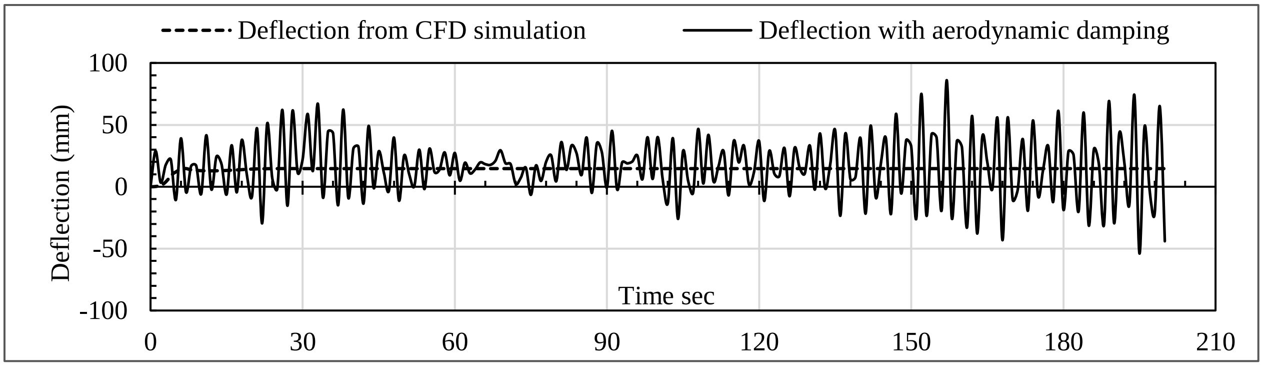

Figure.6: Mid-point deflection of the plate tip with CFD method and proposed method at $\overline{U}$=10 m/s and t=20mm.

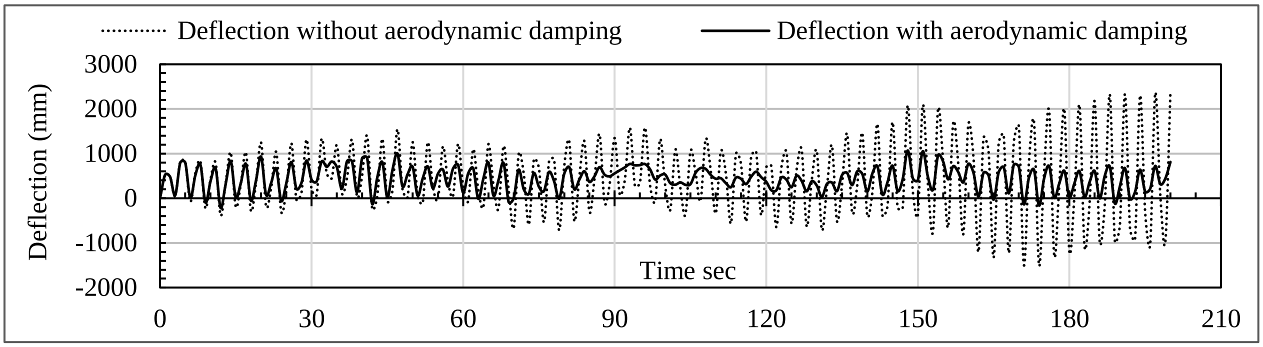

Figure.7: Mid-point deflection of the plate tip with and without aerodynamic damping at $\overline{U}$=20 m/s and t=10mm.

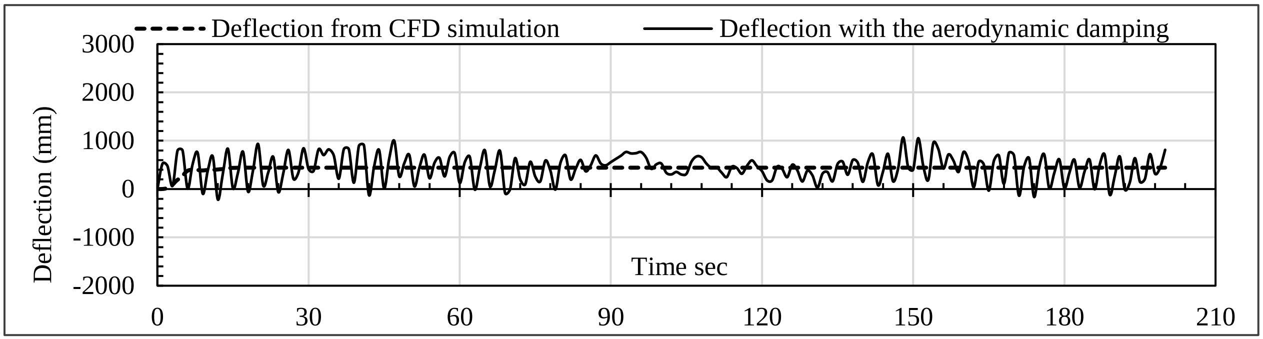

Figure.8: Mid-point deflection of the plate tip with CFD method and proposed method at $\overline{U}$=20 m/s and t=10mm.

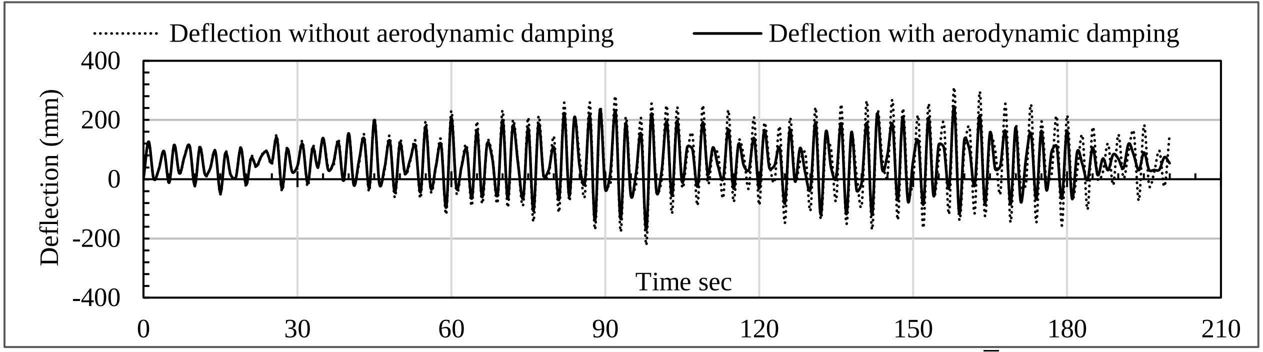

Figure.9: Mid-point deflection of the plate tip with and without aerodynamic damping at $\overline{U}$=20 m/s and t=20mm.

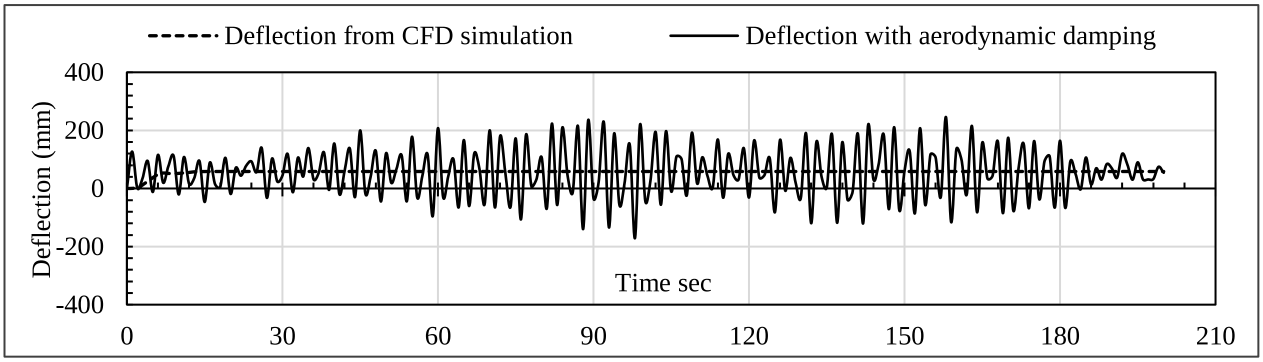

Figure.10: Mid-point deflection of the plate tip with CFD method and proposed method at $\overline{U}$=20 m/s and t=20mm.

6. Conclusion

1. An interaction dynamic analysis, considering the aerodynamic damping, has been proposed and proved to be reliable through comparing its results with CFD method results. This analysis can be used with a correction factor that can be determined through more extensive parametric studies to get results close to the CFD method.
2. The present analysis takes much less computation time, including the wind velocity generation, compared with the elaborate CFD method.
3. It is clear from the present study that the aerodynamic damping effect increases with the increase of structure flexibility and wind turbulence.

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