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Derivation of non-dimensional across-wind force spectrum of tall buildings using ANSYS software

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Abstract

In this paper, the across responses of tall rectangular buildings under wind loads by ANSYS, which is a numerical simulation software, is investigated. A rectangular building with 12:6:1 dimension ratio and 300 m high is considered in this research. The considered building is placed in two states; 1) the short after body orientation is perpendicular with wind direction, 2) the short after body orientation is in the same direction with wind. Wind tunnel and the building is modeled in 2D format by ANSYS. The non-dimensional across-wind force spectrum is derived by time history displacement of ANSYS outputs. It is accomplished that the behavior of the buildings (such as separate stream at building surroundings) is properly simulated by ANSYS.

Key words: Wind, Tall Building, Across-wind Force Spectrum, ANSYS software

INTRODUCTION

Aeroelasticity science is applicable for fluid-structure interaction, and focuses on aerodynamic forces and structural motions as well as their affection on together, considerably. In the last decades, application of numerical methods in modeling of the aeroelastic behavior of the various structures, aerodynamic assessment of bluff bodies and development of computational computers have significantly drawn researchers attention; and are currently the innovative issues in the wind engineering domain. Experimental and analytical (which are dependable to experimental methods) approaches require numerous examinations, which are exorbitant and time consuming. Accordingly, ability of the current softwares in simulation of the fluid behavior, structure behavior and fluid-structure interaction increased in wind engineering field. Not only these analyses can properly create the simulation issues, but also benefit information can be derived from complex steps of the fluid-structure interaction by researchers (Salehi Aali 2006). The forces produced by dynamic pressure of the wind cause vibrations in the structures, which these motions may be in the wind direction, in perpendicular with the wind orientation (across wind) or in torsion state. In the tall buildings, across wind responses are dominant compared to those of wind orientation. Solari (1985) pointed out that across dynamic wind load in tall buildings is created in three mechanisms: 1) wind orientation turbulence, 2) across wind turbulence and 3) self excitation mechanisms; that the third one is crucial. In this paper, it is supposed to evaluate the behavior of the structures under wind load utilizing an ideal model of tall buildings by ANSYS software. Then, the across-wind force spectrum is derived. The models are simulated in 2D format by ANSYS (the finite element software). Fluid and structure coupling equations are solved using sequentially coupled analysis (Motlagh et al. 2008) and the fluid-structure interaction is

(FSI) modeled by application of Multiphysics lateral software. Implementation of the compatibility and equilibrium on the structure in contact with fluid is done by ALE (Arbitrary Lagrangian–Eulerian).

DESCRIPTION OF MODELING

The buildings with rectangular plan, 300 m high, 50 m length, 25 m width, 182 kg/m^3 density, 5.8 s period in the length of plan, 6.9 s period in the plan width, 1.5% damping in wind orientation and 2% damping in perpendicular with wind orientation are considered in this study. The aforementioned building is modeled in two states: (a) and (b) subjected to wind tunnel (Aghaalizadeh 2013).

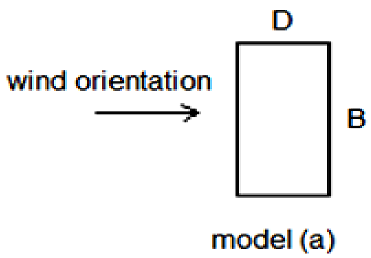

Fig. 1. length of plan is perpendicular with wind orientation (model a)

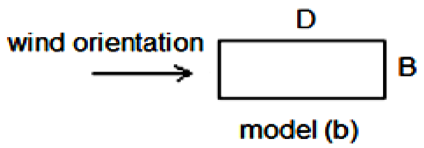

Fig. 2. width of plan is perpendicular with wind orientation (model b)

Natural vibration periods of the models after performing modal analyses are obtained and presented in figures (3)-(4).

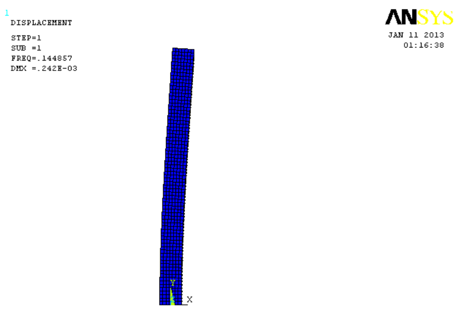

Fig. 3. base mode shape in width of plan

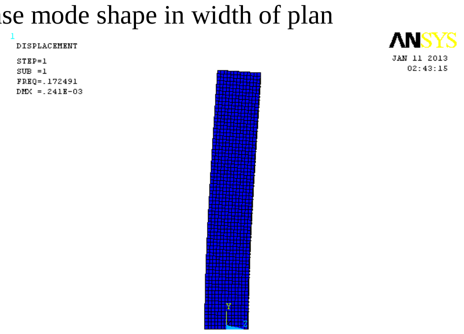

Fig. 4. Base mode shape in length of plan

Wind tunnel is simulated in 2D format. The properties of the building are modeled by mass, spring and damper subjects in ANSYS software. The stream behavior is assumed to be laminar, isothermal and viscous. Fluid density (air) is constant and equals to 1.23 kg/m^3 with 1.5*10^{-5} m^2/s kinematic viscous for 20^{o}c temperature. The structure is modeled in 2D format and considered as a rigid area with planar strain (Hay 1992) behavior and connected to mass-damper systems (elastic dampers) in the fluid vicinity. The wind tunnel and building simulation by ANSYS software are presented in figure (5). The separation of the stream lines around the structure are illustrated in figure (6).

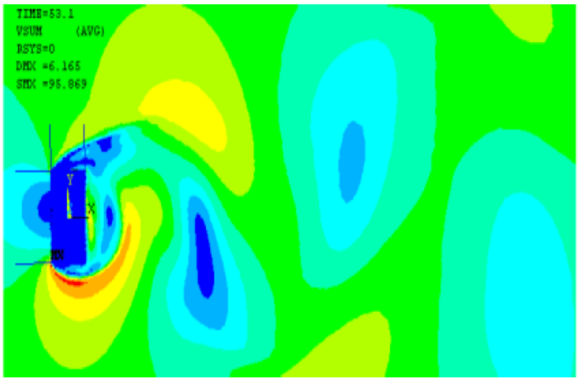

Fig. 5. 2D simulation of the building in the wind tunnel (stream separation around the building and vortex in the back of building can be observed)

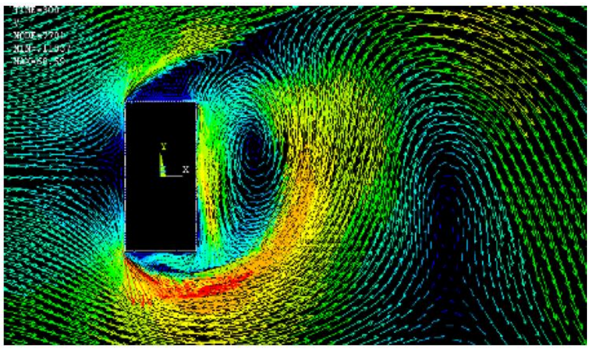

Fig. 6. stream lines around the structure

EQUATIONS AND CONSIDERED METHODS FOR ANALYSIS OF FLUID AND STRUCTURE

Fluid and structure analyses are performed by Navier Stokes equations and structural dynamic equations, respectively. In order to evaluate the fluid-structure interaction (FSI) in numerical simulation of various aeroelastic phenomena, it is essential to solve such equations simultaneously in a unique system which makes complex problems due to different coordinates. As a matter of fact, Navier Stokes equations are presented in Eulerian coordinates while structural dynamic equations described in Lagrangian coordinates. Consequently, accommodation of the two aforementioned discretizations (or meshing two kinds of region) to solve the equations would be complicated practice; Due to grid type applied in fluid region different from structure region, which it is constant in fluid region because of Eulerian system and movable in structure region because of Lagrangian system.

Accordingly, it is obvious that application of a movable grid in fluid region, which can follow the structure motion in each step of analysis, would be essential (Donea et al. 2004). Arbitrary Lagrangian–Eulerian (ALE) relations recommended by Nomura and Hughes (1992) is one of the current methods in this field. Essentiality of the fluid grid following from structure motions caused coupled fluid-structure equations to be solved in this way, which Navier Stoks equations in fluid region are solved and then the velocity and pressure distributions due to fluid movement in fluid region are presented. The distributed pressure in the vicinity of the bluff body acts as an external plane load around the body. The external force ($P_{(t)}$) opposed to the structure is obtained from the integration of pressure distribution caused by fluid stream. The structural dynamic equations governing the displacements U of a building subjected to external forces ($P_{(t)}$) are presented below (Chopra 2007):

$$M\ddot{U}+C\dot{U}+KU=P_{(t)} \tag{1}$$

Where M, C and K are a diagonal mass matrix, the damping matrix and the stiffness matrix, respectively. Then, the fluid region grid is modified according to the new shape of structure region. Those aforementioned steps would be repeated for new grid. Accordingly, it is essential to apply nonlinear geometric analysis (NGA) approach in this process.

ASSESSMENT OF PERFORMED ANALYSES IN ANSYS

Two considered models (a and b) are subjected to several wind loads with reduced velocity (equation 2) by ANSYS software, and time history displacement (THD) for each velocity are recorded by the software (Simiu and Scanlan 1996).

$$R_V=\frac{U}{n_o \times b} \tag{2}$$

Where R_v, U, n_o and b are non-dimensional reduced velocity, mean velocity of the wind at the peak point of building, natural frequency of structure and dimension of plan which is perpendicular with wind orientation, respectively. The considered wind velocity values are presented in table (1).

Table 1: Wind velocity values

Model	Velocity (m/s)						
(a)	17.2	23.9	28.7	29	29.5	30.17	31
	32.1	34.48	39.1	43.1	44.2	51.72	60
(b)	21.7	32	39.1	44.2	46.8	48.3	56

Time history responses (THD) are buildings across displacements which illustrated in figures (7)-(15) for model (a) and figures (16)-(21) for model (b).

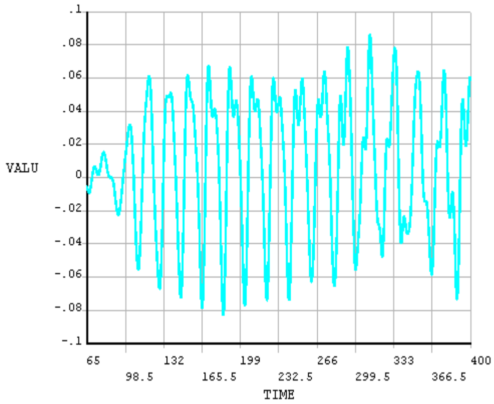

Fig . 7. THD for model (a) with 17.24 m/s velocity

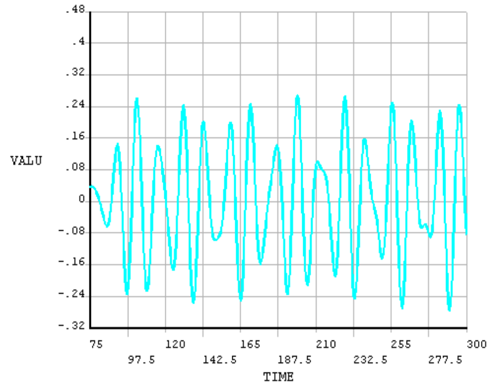

Fig. 8. THD for model (a) with 23.94 m/s velocity

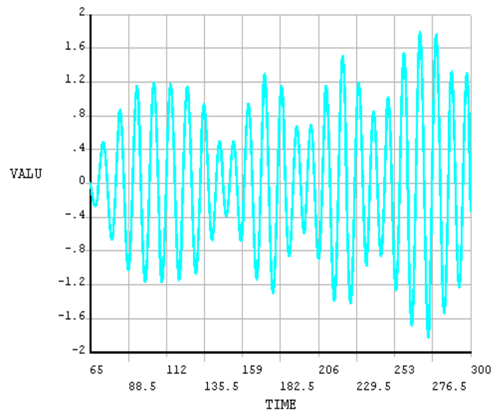

Fig. 9. THD for model (a) with 29 m/s velocity

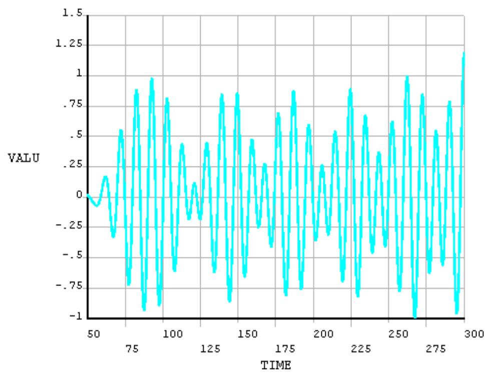

Fig. 10. THD for model (a) with 28.73 m/s velocity

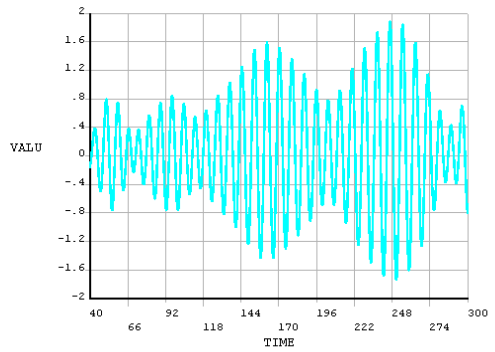

Fig. 11. THD for model (a) with 43.1 m/s velocity

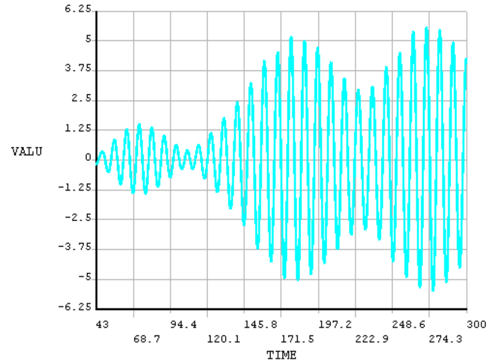

Fig. 12. THD for model (a) with 39.18 m/s velocity

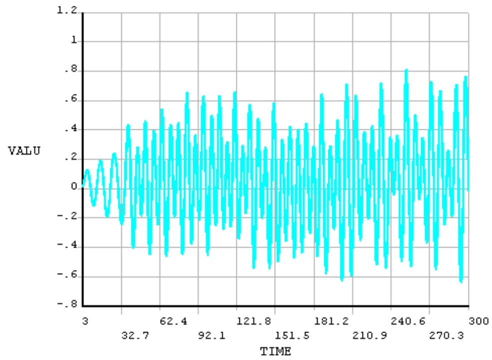

Fig. 13. THD for model (a) with 51.72 m/s velocity

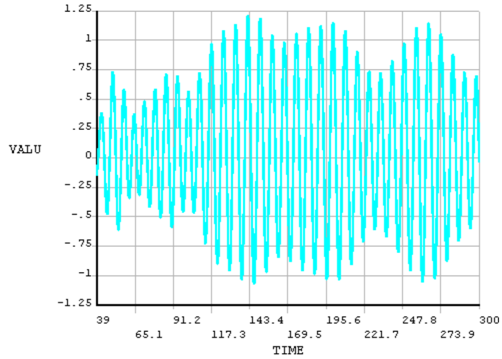

Fig. 14. THD for model (a) with 44.2 m/s velocity

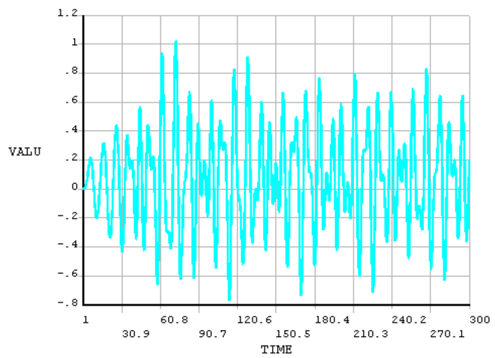

Fig. 15. THD for model (a) with 60.34 m/s velocity

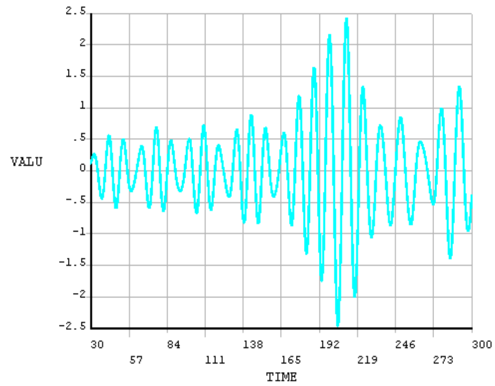

Fig. 16. THD for model (b) with 39.18 m/s velocity

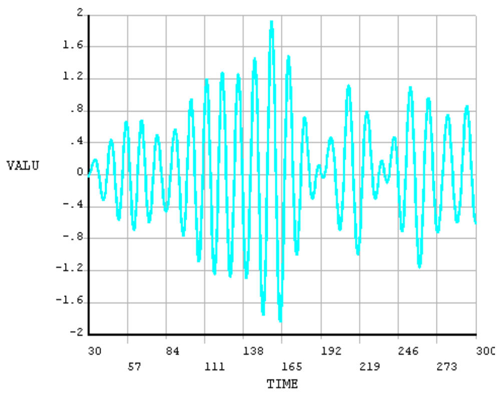

Fig. 17. THD for model (b) with 32 m/s velocity

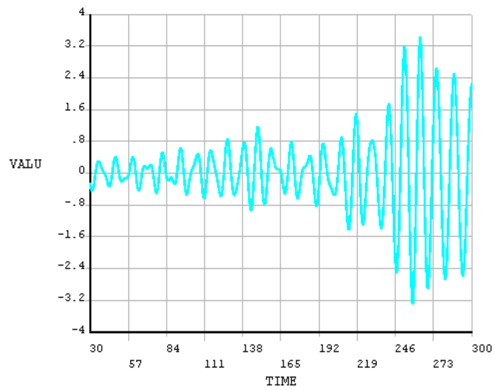

Fig. 18. THD for model (b) with 46.8 m/s velocity

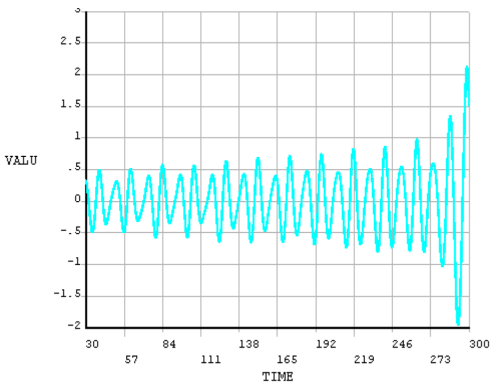

Fig. 19. THD for model (b) with 44.2 m/s velocity

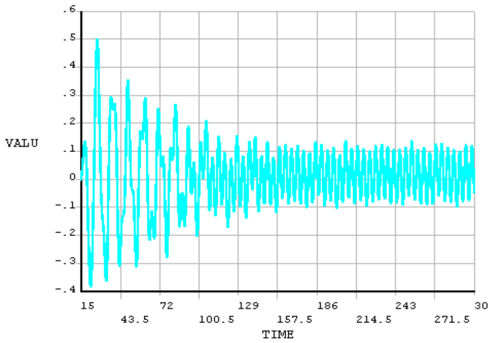

Fig. 20. THD for model (b) with 56.3 m/s velocity

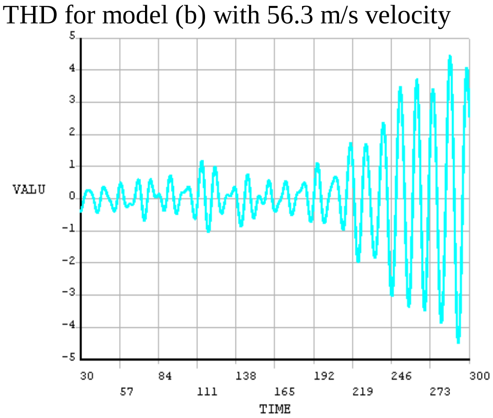

Fig. 21. THD for model (b) with 48.3 m/s velocity

The time history displacement of all velocities are combined together utilizing current quadratic combination rule, square roots of sum of squares (SRSS), and are presented in figures (22)-(23) for models (a) and (b). The responses are normalized by 100000/H scale value (H: building height).

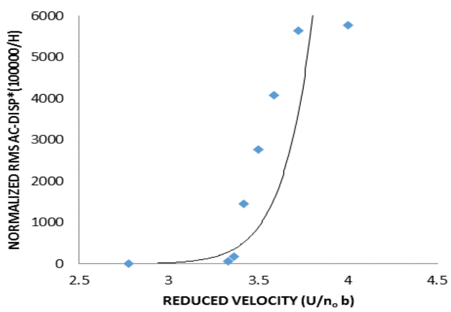

Fig. 22. Across response for model (a)

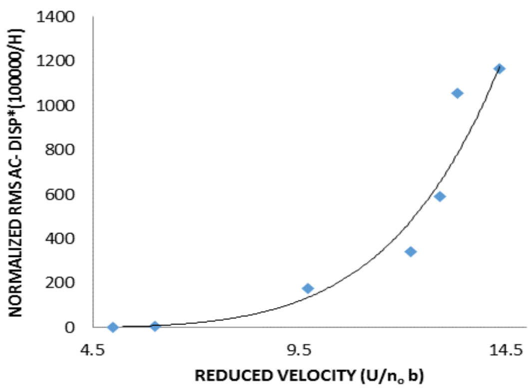

Fig. 23. Across response for model (b)

The equation related to each curve illustrated in above figures can be derived by relation suggested by Majukava (1992) in order to get across responses of buildings (Eimani 2000). The related equation presented below:

$$\sigma_y = C \times (R_V)^n \tag{3}$$

Where σ_y and R_V are across displacement RMS (root mean square), reduced velocity, respectively. C and n are constant values obtained from examinations. Across response of buildings can be computed easily by applying such relation.

DERIVATION OF NON-DIMENSIONAL ACROSS-WIND FORCE SPECTRUM

Across-wind force spectrum can be obtained by application of following equation (Saunders 1974). Actually, this equation makes a relation between across displacement and force spectrum.

$$S_F(n) = \frac{K_o^2 \times S_y(n)}{H^2(n)} \tag{4}$$

Where $S_F(n)$ and $S_y(n)$ are aerodynamic across-wind force spectrum density and across displacement spectrum density at the top of building, respectively.

$H^2(n)$ is mechanical admittance, which computed using following equation:

$$H^2(n) = \frac{1}{[1-(\frac{n}{n_o})^2]^2 + 4\xi^2(\frac{n}{n_o})^2} \tag{5}$$

Where ξ, n and n_o are damping ratio of system, vibration frequency and natural frequency, respectively. K_o is generalized stiffness in base mode of building, which computed using following equation:

$$K_o = (2\pi n)^2 \times M_o \tag{6}$$

Where M_o is generalized mass of building in base mode with linear mode shape assumption, and equals to one third of building total mass. Eventually, across-wind force spectrum can be normalized non-dimensionally using an equation as follows (Eimani 2000):

$$\frac{n \times S_F(n)}{(0.5 \times \rho \times U^2 \times b \times h)^2} \qquad (7)$$

Where ρ, U, b and h are air density, mean velocity of the wind at the peak point of building, dimension of plan which is perpendicular with wind orientation and building height, respectively. The non-dimensional across-wind force spectrum graphs for models (a) and (b) are illustrated in figures (24)-(25).

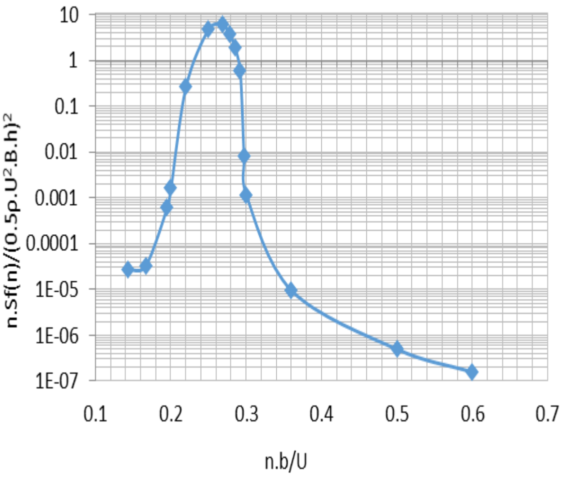

Fig. 24. The non-dimensional across-wind force spectrum when the length of plan is perpendicular with wind orientation (model a)

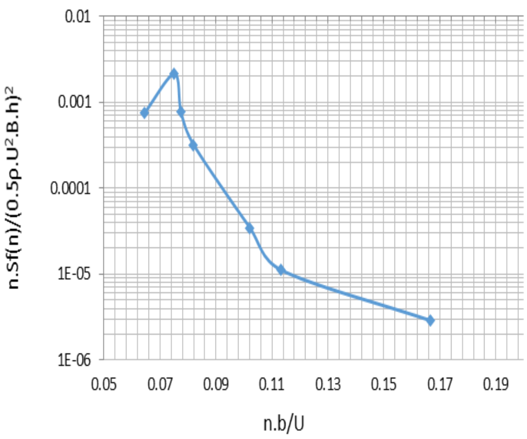

Fig. 25. The non-dimensional across-wind force spectrum when the width of plan is perpendicular with wind orientation (model b)

In order to estimate the variance of building responses, an equation is recommended as follows (Kareem 1984):

$$\sigma_y^2(r) = \sum \frac{\pi . n . S_F(n) . (2\pi . n)^{2r}}{4(2\pi . n)^4 . \xi_n . m_n^2} \qquad (8)$$

Where $S_F(n)$, m_n and ξ_n are across-wind force spectrum in *n*-th mode, mass in *n*-th mode and damping ration in *n*-th mode, respectively. The derived response is shown by r value, which equals to 0 for displacement, 1 for velocity, 2 for acceleration and 3 for acceleration variations. Aforementioned equation is essential for probabilistic description of peak response of buildings subjected to wind random vibrations. Peak responses of buildings can be computed experimentally using following relation (Eimani):

$$Y_{max}(r) = g_y(r) . \sigma_y(r) \qquad (9)$$

Where g_y is peak factor, usually equals to 4.

CONCLUSION

The across responses of tall rectangular buildings under wind vibrations by ANSYS software, is investigated in this research. Wind loads carry different velocities. A rectangular building with 12:6:1 dimension ratio and 300m height is considered. The considered building is modeled in two formats; first, the length of plan is perpendicular with wind orientation (model a) and the second, width of plan is perpendicular with wind orientation (model b). The non-dimensional across-wind force spectrum graphs for models (a) and (b) are extracted based on across displacement of buildings utilizing some equations. The main results of this study are summarized in the following:

1. The behavior of the structures such as stream separation in the vicinity of buildings and vortex shading in the back of buildings can be appropriately simulated by ANSYS software.
2. As the considered time steps and meshing parts carry small measures, the buildings responses subjected to wind loads would be more precise.
3. As the wind velocity increases, the vortex frequency in the back of building as well increases; this increment goes on until the vortex frequency equals to structure frequency, the lock-in phenomenon occurs at this time. Subsequently, as the vortex frequency increases, structure responses decrease.
4. It is concluded that when the structure frequency equals to frequency of vortex shedding, the across-force value in that frequency equals Strouhaly number.
5. The placement of the building in front of the wind, effects on the across response of the building. As a result, across response of the buildings with rectangular plan is more when the length of plan is perpendicular with wind orientation than the state which width of plan is perpendicular with wind orientation.

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