Studies of Vortex Induced Vibration on the NACA0015

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Abstract— In this paper, numerical and experimental schemes have been developed for the response of Vortex Induced Vibration (VIV) on the thin symmetric airfoil. VIV occurs where a bluff body interacts with a fluid flow. This phenomenon can be seen in many practical or industrial applications such as heat exchanger tube bundles, marine structures, power transmission lines and airfoils. Due to VIV, the structures could be subjected to very large transverse vibrations which may lead to fatigue failure. Both of methods that used in this research have been applied on the NACA0015 with various models, such as different stiffness, flow velocity and angle of attack. A numerical method, that using finite element based software ANSYS, modal and harmonic (3D) finite element analysis have been developed, is presented to study the VIV. Also experimental method is based on the image processing and direct measurement. The results show that, in VIV the response amplitude depends upon the initial condition. Also there is a frequency with large amplitude which is smaller than the shedding frequency. Therefore in transverse VIV, resonance of the frequency occurs with the 4 th sub harmonic of vortex shedding. This is an important issue in studying resonance.

Keywords**—**Vortex Induced Vibration; Vortex Shedding; NACA0015; Resonance;

I. INTRODUCTION

Induced vibration is a special kind of vibration which is corresponding to structure in contact and intraction with fluids.

When a bluff body is subjected to a fluid flow at sufficiently large Reynolds numbers, the flow separates from a wider section of the body giving rise to periodic vortex shedding from either sides of the body.

This alternate vortex shedding characterized by definite periodicity would cause fluctuating pressure forces on the surfaces of the body due to which the body undergoes vibrations, if it is flexibly mounted. Vortex shedding depends on flow state, geometric properties of the body and even roughness or smoothness of the body surface.

The position, place and intensity of created vortices determine the amount of induced lift and drag forces from fluid to the body as for example increasing attack angle to more than 15 degrees in a blade which develops the vortices forward, causes the flow to separate from the upper surface and lift lift force reduces considerably [1]. Then, Vortex-Induced Vibration (VIV) is a possible phenomenon in situations where a bluff body interacts with a fluid flow.

Vortex shedding behind bluff bodies arises in many fields of engineering, such as heat exchanger tubes, marine cables, flexible risers in petroleum production and other marine applications, bridges, and chimneys stacks.

Roshko declared that vortex shedding from a straight circular cylinder in a subsonic steady flow is a function of Reynolds number and lift and drag forces varies in different stages of developing and shedding of eddies in wake zone[2].

The reviews of vortex induced forces and vortex-induced vibration are Gabbai and Benaroya (2005), Williamson and Govardhan (2004), Norberg (2003), Sarpkaya (1979, 2004), Khalak and Williamson (1999), Griffin and Hall (1991), Blevins (1990), Bearman (1984), King (1977), and Leinhard (1966). Recent experimental papers include Nowinski, Ott and Boles (2000), Jeon and Gharib (2004), Flemming and Williamson (2005), Dahl, Hover, and Triantafyllou (2006), Laneville (2006), Klamo (2006), Dipankar, Sengupta and Talla, (2007), Carberry and Sheridan (2007), Prasanth and Mittal (2008)[3].

Numerical and experimental methods that used in this research have been applied on the NACA0015 with various models, such as different stiffness, flow velocity and angle of attack.

The numerical method is based on finite element and using ANSYS software. Also experimental method is based on the image processing and direct measurement. The results show that, there is is a frequency with large amplitude which is smaller than the shedding frequency. Therefore in transverse VIV, resonance of the thin symmetric airfoils frequency occurs with sub harmonic of vortex shedding. This is an important issue in studying resonance.

II. VORTEX SHEDDING AND “LOCK IN”

Flow-Induced Vibration (FIV) is a phenomenon arising out of fluid-structure interaction. Not all structures are subjected to flow induced vibrations. Generally, ‘bluff’ structures from which flow separates from a wider section of the body tend to experience such vibrations when they are exposed to a fluid flow. Most of the practically used structures are bluff in nature such as bridges, buildings, heat exchangers tubes, cooling towers, aircraft control surfaces and etc [4].

Four classes of FIV are commonly identified galloping, flutter, buffeting and vortex induced vibrations [1].

Galloping is a fluid-elastic self-excited phenomenon characterized by low frequency, large amplitude vibrations. This kind of structural instability occurs mainly in the direction normal to the flow direction with a continuous increase of amplitude with flow velocity. This phenomenon was first noted in ice-coated power transmission lines subjected to strong winds. Even though very similar to galloping, flutter exhibits coupled modes of vibration and hence, not essentially one-dimensional (unlike galloping). Flutter of aircraft wings and turbo-machinery blades could be cited as examples to the occurrence of this phenomenon. It may be noted that all non-circular sections are prone to galloping and flutter instabilities. Buffeting is basically a kind of excitation induced by turbulence contained in the fluid flow. To cite some examples, this phenomenon could be observed in the wind-induced vibration of buildings and bridges. It may be pointed out that, all these excitation mechanisms are important from practical point of view. However, in this review, the scope of discussion is restricted to the phenomenon of VIV which is seen to be the most common type of flow-induced vibration.

Vortex shedding behind bluff bodies arises in many fields of engineering, such as heat exchanger tubes, flexible risers in petroleum production and airfoils. These examples are only a few of a large number of problems where VIV is important. The practical significance of vortex-induced vibrations has led to a large number of fundamental studies such as Sarpkaya (1979); Griffin and Ramberg (1982); Bearman (1984); Parkinson (1989); Blevins (1977) [5]. The case of an elastically mounted cylinder vibrating as a result of fluid forcing is one of the most basic and revealing cases in the general subject of vortex-induced bluff–body fluid–structure interactions. Consequently, determination of the unsteady forces on the cylinder is of central importance to the dynamics of such interactions. Despite the extensive force measurements for a cylinder undergoing transverse forced vibration, there have appeared no direct lift-force measurements in the literature for an elastically mounted arrangement. Sarpkaya recently presented a set of drag measurements for a cylinder which can oscillate both inline and transverse to the flow [6]. Khalak and Williamson have presented new force measurements of lift and drag for a hydroelastic cylinder of very low mass and damping [7]. Consequently, for numeric, comparisons of forces with experimental data are difficult. Vortex-induced vibration is generally associated with the so-called ''lock-in'' phenomenon where the motion of the structure is believed to dominate the shedding process, thus synchronizing the shedding frequency.

Lock-in is characterized by a shifting of the vortex shedding frequency to the system natural frequency $(f_s \approx f_n)$. Lock-in can also refer to the coalescence of the shedding, the cylinder oscillation and natural frequency $(f_s \approx f \approx f_n)$ [8]. Numerous studies in vortex-induced vibration literature support the existence of lock-in such as Griffin et al., (1973); Anagnostopoulos and Bearman (1992); Goswami et al., (1993); Brika and Laneville (1993); Blackburn and Henderson (1996); Fujarra et al., (1998). However, Gharib (1999) has noted the absence of lock-in behavior from almost all experimental studies for small mass ratios [5].

In almost all the literature, the problem of vortex-induced vibration of a cylinder with a large mass ratio has been well studied. However, there remain some rather basic questions concerning vibration phenomena under the conditions of very low mass and damping, for which there are few laboratory investigations.

III. Governing Equations

Equations are presented throughout in nondimensional form. The velocity scale is the reference velocity, U_∞ the length scale is cylinder diameter or projection of body section, D and time is nondimensionalized by the aerodynamic scale D/U_∞.

The unsteady incompressible Reynolds-averaged Navier–Stokes equations can be written in the following strong-conservation form, in the inertial system, i.e., the frame connected to the laboratory [9]:

$$\frac{\partial U}{\partial t} + \nabla . F = 0 \tag{1}$$

With the Cartesian components, F_{kj}, given by:

$$F_{kj} = (U_j - \hat{U}_j)U_k + \delta_{jk} P - \frac{1}{\mathrm{Re}}\frac{\partial U_k}{\partial x_i} + \overline{u}_j \overline{u}_k \tag{2}$$

They involve the Cartesian velocity components U_k, the mesh velocity $\hat{U}_j$, the pressure P, the Reynolds stress tensor components $\overline{u}_j \overline{u}_k$, the Reynolds number $\mathrm{Re} = U_\infty D/\nu$, where ν is the kinematic viscosity of fluid, and the Kronecker symbol δ_{jk}.

The resulting turbulent closure problem is solved by means of a Newtonian model as follows [5]:

$$\overline{u}_j \overline{u}_k = -\nu_t \left(\frac{\partial U_j}{\partial x_k} + \frac{\partial U_k}{\partial x_j} \right) + \frac{2}{3} K \delta_{jk} \tag{3}$$

The eddy viscosity, ν_t is given by the turbulence model, while the contribution of the turbulent kinetic energy K is simply neglected if the model does not use this variable. In this study, just the shear-stress transport (SST) K−ω model of Menter used [5]. This model solves one equation for the turbulent kinetic energy K and a second equation for the specific turbulent dissipation rate ω. This model is a low-Reynolds number model. Consequently, we do not use wall functions.

As mentioned before, structures under contact of fluid flows are exposed to lift and drag forces. Lift and drag factors which are generally functions of flow parameters, the geometry and position of body, are used in order to calculate lift and drag forces. Studying an ideal fluid flow, net force on the body along an x axis is:

$$F_x = \int Pnds \qquad (4)$$

P is static pressure and the unit normal vector outward to the surface is n, s is the surface of the body. According to the Bernoulli equation:

$$P = -\rho \frac{\partial \phi}{\partial t} - \frac{1}{2}\rho u^2 + F(t) \qquad (5)$$

ρ is fluid density, function ϕ called a velocity potential and the $F(t)$ is a function of time but it is independent of location in the reservoir, commonly it is included in ϕ. Thus:

$$F_x = \rho \int (\frac{\partial \phi}{\partial t} + \frac{1}{2}u^2)nds \qquad (6)$$

Finally a force is obtained for each model. For example in a cylinder with radius a, that is horizontally connected to a spring and is placed in a tank of a static ideal fluid [10]:

$$F = -\rho \pi a^2 \frac{du}{dt} \qquad (7)$$

This equation shows that this force is in fact product of a part of the mass of fluid (that is dragged by the body) in fluid acceleration. This mass is called added mass, acts along fluid acceleration which appears in the motion equation of the cylinder as [1]:

$$m\frac{d^2x}{dt^2} + kx = -\rho \pi a^2 \frac{du}{dt} \qquad (8)$$

m is mass of cylinder per unit depth and k is the spring constant per unit depth, finally:

$$(m + \rho \pi a^2)\frac{d^2x}{dt^2} + kx = 0 \qquad (9)$$

Added mass increases the effect of structure mass in dynamic analysis which is experimentally evaluated and presented by Blevins (1984) and Pettigrew (1988) for various sections. Blevins also proposed added mass as 20% of airfoil mass in the airfoils that move in air and have less thickness relative to chord [1], [3]. Therefore in this research for aerodynamic airfoil model NACA0015, added mass is assumed on the base of Blevins' paper.

Lift and drag factors vary in different stages of eddy creating and shedding in wake zone. This variation which is due to eddy shedding develops induced vibration. To evaluate the frequency of eddy shedding, non-dimensional Strouhal number is used which is the ratio of eddy shedding frequency to the velocity of free flow:

$$f_s = \frac{SU}{D} \qquad (10)$$

Where f_s, U and D are eddy shedding frequency, velocity of free flow and diameter or projection of body section respectively [11]:

Roshko indicated that in subsonic flow, non-dimension Strouhal number is a function of Reynolds number and slightly depends on surface roughness. Generally non-dimensional Strouhal number is approximately assumed 0.2 in the range $2 \times 10^5 < Re < 2 \times 10^6$ to simplify the evaluation [1], [2].

In this research for aerodynamic airfoil model the results of Reference [1] is used to calculate non-dimensional Strouhal number relative to flow states.

Various models can be considered for dynamic analysis of induced vibration due to eddy shedding. One of the models is simple harmonic linear model. Considering fluid approaches eddy in the angle of α (angle of attack) or vice versa, mentioning the definition of lift and drag forces, following equation can be used to calculate applied force along y direction:

$$F_y = -F_L \cos\alpha - F_D \sin\alpha \qquad (11)$$

Where F_L, F_D and F_y are lift force, drag force and resultant force in y direction respectively. Negative mark is because of considering the positive direction downward in y axis. Considering body motion with one degree of freedom in y direction, when fluid flow approaches to body with the velocity of U:

$$U_{rel}^2 = \dot{y}^2 + U^2 \qquad (12)$$

In the other hand, because of the similarity of F_y to F_L and F_D:

$$F_y = \frac{1}{2}\rho U^2 DC_y \qquad (13)$$

$$C_y = -\frac{U_{rel}^2}{U^2}(C_L Cos\alpha + C_D \sin\alpha) \qquad (14)$$

These parameters are used in dynamic analysis in y direction to calculate forces of fluid. Thus in simple harmonic linear model of induced vibration due to eddy shedding, effective force is considered as:

$$F_y = \frac{1}{2}\rho U^2 DC_y Sin(\omega_s t) \qquad (15)$$

Where $\omega_s = 2\pi f_s$ and the equation of vibration's motion takes the form:

$$m\ddot{y} + ky = \frac{1}{2}\rho U^2 DC_y Sin(\omega_s t) \qquad (16)$$

In this equation m is including added mass. It should be mentioned that for aerodynamic bodies in small attack angles about 8 degrees, lift force is much larger than drag force [1]. Therefore, in above equation power of applied force is y direction can be assumed approximately equal to lift force. This fact is used in this research and coefficients of obtained equation in flow state and airfoil position are calculated.

IV. Numerical Method

The commercial finite element code ANSYS has been used to carry out the modal and harmonic analysis.

The analytical algorithm used in this study to calculate the frequency and amplitude due to the working is presented in Fig.1.

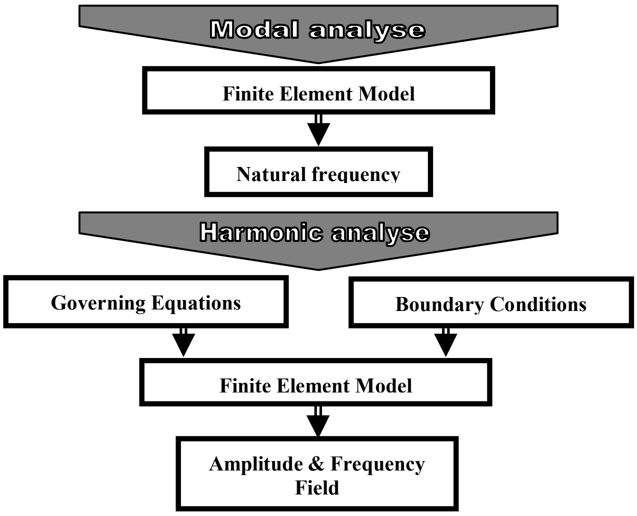

Figure 1. Flowchart of analysis

The geometry of the model considered in this study is shown in Fig.2.

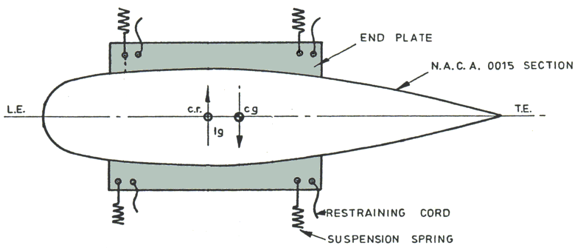

Figure 2. Schamatic of the Susppond airfoil (2D)

In this model a NACA0015 airfoil with 100 mm length suspended by 4 springs in both of the plate that is parallel and used to change the angle of attack. Fig.3 shows the FE mesh of the airfoil.

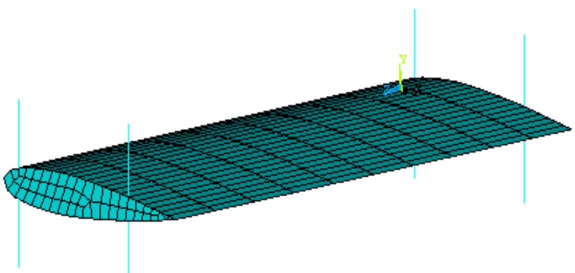

Figure 3. The FE mesh of the NACA0015

V. Experimental Method

Experimental studies are often performed on the models of structure which are used by designer as guide. In these types of studies, there most be a dynamic similarity between the model and prototype and its necessity is kinematical similarity. In this research after providing experimental set, frequencies and induced vibration amplitudes are measured. According to Fig.4 experimental set consists of subsonic wind tunnel, model of suspended airfoil NACA0015, velocimeter set and frequency meter set.

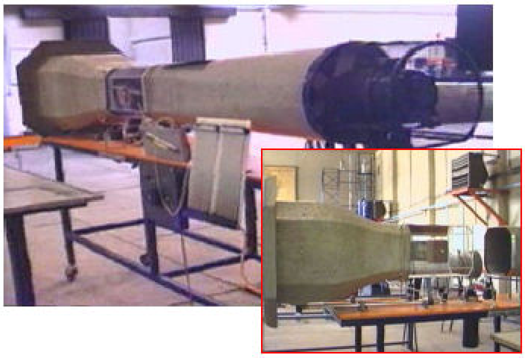

Figure 4. Experimental set: wind tunnel and test section

This wind tunnel is able to create a flow with velocity up to 25 m/s. the model of airfoil is wooden with approximate mass of 185 gr, approximate density of 656.8 kg/m3, module of elasticity 980 MPa and consists of eight similar spring with same stiffness and two supports. After installing airfoil model NACA0015 in test section on wind tunnel by supports (Fig.5), in a particular position of the airfoil increase flow velocity gradually.

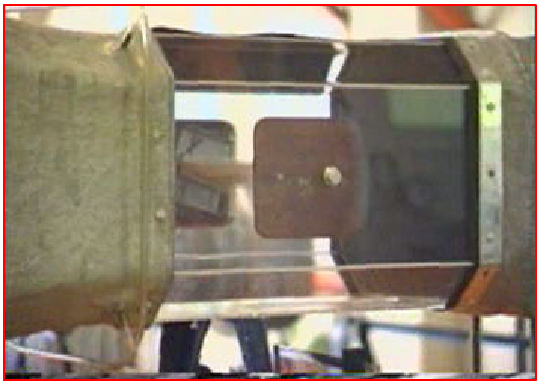

Figure 5. Set of NACA0015

In a particular velocity of flow, the suspended airfoil by the springs which is in balance begins to vibrate. In this situation induced vibrations are recorded by the method of image processing of vibration amplitudes. A film is produced by using a camera capable to record 10000 frames in a second. It is separated to different frames to obtain maximum and minimum amplitudes [11].

VI. ESULT AND CONCLUSION

In this research numerical and experimental investigations on various models regarding to spring stiffness and different flow velocities and contact (attack) angles of airfoil NACA0015 are performed but results of airfoil model with spring stiffness of 363N/m which is accord with the results of other models, are presented.

- Fig.6 and Fig.7 show the amplitude of vibration in different flow velocities and contact (attack) angles. Presented results show, our simulations in numerical method are in good agreement with experiment for study of induced vibration. Also these figures show that the maximum value of the amplitude of vibration of the airfoil is obtained with the increasing velocity condition. Thus, the response amplitude depends upon the initial condition.

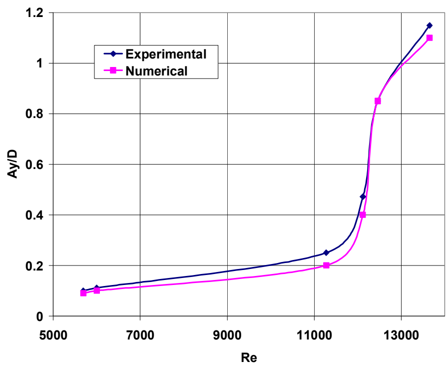

Figure 6. Relative vibration amplitude with different conditions (α =8)

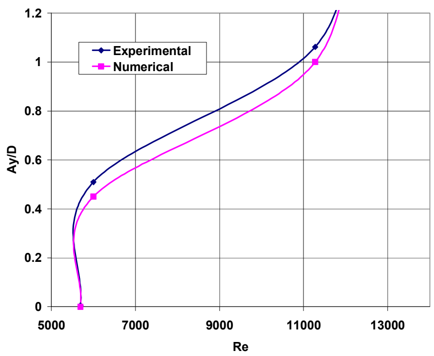

Figure 7. Relative vibration amplitude with different conditions (α =12)

- Experimental and numerical studies in natural frequency and frequency of maximum amplitude of NACA0015 in VIV show that there is a frequency with large amplitude which is smaller than the shedding frequency (frequency of induced vibration) than corresponding natural frequency of set Therefore in transverse VIV, resonance of the thin symmetric airfoils frequency occurs with the 4 th sub harmonic of vortex shedding. This is an important issue in studying resonance.
- Also, the results indicate that by increasing the attack angle to more than 8 degrees –even in mentioned velocities- the response of system-because of different behavior of lift factors in these situations- shows different behavior relative to induced vibration, as by increasing attack angle, frequency of forth sub harmonic will not appear.
- Results of experimental and also numerical studies indicate that by increasing contact (attack) angle in a particular velocity of fluid flow, amplitudes of induced vibration increase. Also in particular attack angle, by increasing the velocity, the increase of amplitudes is obvious in both studies.

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