11th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2021-166**
8-10 September 2021 - METU, Ankara TURKEY

DESIGN AND EXPERIMENTAL INVESTIGATION OF A WIND TUNNEL GUST GENERATOR

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ABSTRACT

This work aims at developing a two-vane gust generator for a small size open-loop wind tunnel to study the unsteady aerodynamic response of lift producing test models. The focus of the study is two-fold: (1) the design of a gust generator which produces the desired gust profiles by varying the parameters such as flow speed, pitching frequency of the vanes, maximum angle of deflection of the vanes and spacing between the vanes and (2) the experimental investigation of the gust velocity profiles via particle image velocimetry (PIV). Preliminary results of the numerical simulations reveal that a sinusoidally pitching vane design with NACA0015 profile is capable of generating a gust ratio of 0.15. The outcomes of this study will serve as a starting point for the design of a gust generator which will be placed in the Large Scale Wind Tunnel of METU Center for Wind Energy Research (RÜZGEM).

INTRODUCTION

Artificial gust generating systems are essential for the studies in which the unsteady response of lift-producing surfaces is of interest. Their practical use in a wide variety of wind tunnels have made them popular among the researchers who are interested in gust response of wind turbines, helicopters, micro-air vehicles and fixed-wing aircrafts [Wei et al., 2019] and have caused institutions to design their own gust generating systems that can be employed in conventional wind tunnels.

Gust generators are devices which are located upstream of wind tunnel test sections and capable of generating gusts with different profiles and magnitudes. They are composed of oscillating vanes number of which varies depending on the size of the wind tunnel. As the vanes oscillate, the flow direction in the test section alters as a result of the synthesis of two flows, i.e., the main flow of the wind tunnel and the flow induced by the oscillating vanes in the transversal direction.

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Different gust profiles can be obtained by varying the maximum deflection angle of the vanes and the frequency at which the vanes oscillate [Buell, 1969].

There are many studies in the literature discussing design and development of gust generation systems. Wood et al (2017) performed a combined experimental and numerical study to find out the design parameters that affect the gust generator performance and accordingly built a gust generation system for the large low-speed wind tunnel located in the University of Bristol. Their work stresses the effectiveness of two design parameters, i.e the chord length of the vanes and the distance between the vanes, on the gust amplitudes. Increasing the chord length and decreasing the distance between the vanes increases the gust amplitude, yet a decrease in the vane spacing results in a decrease in the useful area at which the experiments can be conducted. This study also reveals that the gust profiles obtained in the test section of the wind tunnel have a square shape rather than a sinusoidal shape for frequencies higher than 8 Hz.[Wood et al., 2017]

Another gust generator system has been designed for the Delft University of Technology Open Jet Facility which has a 2.8 m5$\times$2.85 m test section and a maximum flow velocity of 35 m/s [Lancelot et al., 2015]. The preliminary work done for the design of the gust generator revealed that in addition to the design parameters mentioned above, the reduced frequency, which is the ratio of chord length to the wavelength of the vortex shed from the flapping wing, and the maximum deflection angle are of importance in the design of gust generators.

Dynamic response of an elastic wing model to a gust induced by a single NACA0010 shape vane gust generator is investigated in a transonic wind tunnel at DLR [Neumann et al. (2013)]. The experimental results are then compared with numerical solutions. It is stated that the quality of aerodynamic mesh in the wake region of the gust generator is important to match the gust velocity calculated from CFD with the gust velocity measured via PIV. On the other hand, gust uniformity is essential for the repeatability of the experiment and eases the computation of the gust response of the wing. However, it is shown that because of the use of a single gust vane, shear flow region is created in the wake behind the gust generator and this shear flow region due to the airfoil boundary layer reduces the uniformity of the gust in space. Consequently, Lancelot et.al. (2015) suggest to add a second gust vane to increase the gust uniformity.

A computerized gust generator has been developed and tested for the Virginia Tech Stability Wind Tunnel [Grissom et al. (2004)]. The system consists of 10 gust vanes placed from the bottom to the top of the contraction of the wind tunnel. With the vanes being driven independently by stepper motors, the system demonstrates a capability of producing both continuous and impulsive disturbances. With an increase in the motion amplitude, gust weakening is accelerated and shape of the disturbance becomes more rounded. This is explained by enhanced wall dampening at the largest amplitudes.

One other example of a gust generator that is designed for an open jet, closed return wind tunnel consists of six mechanically interconnected oscillating vanes mounted in a frame and fixed to the wind tunnel nozzle [Saddington et al., 2014]. NACA0015 vanes have a limited pitch range up to 12° in order to prevent stalling. Vane oscillation frequency varies between 0.5 Hz and 2.0 Hz. Experimental results demonstrate a good approximation to a sinusoid directly behind the vanes. Further away from the vanes, peaks and troughs of the sinusoidal variations in transverse velocity component, v, become flattened due to the influence of the vane wake. In the Experimental Aerodynamics Laboratory at University of Colorado Boulder, on the other hand, ten NACA0015 vanes placed at the wind tunnel inlet managed to produce continuous sinusoidal oscillations of the freestream velocity magnitude, discrete impulses and linear rumps [Batemend D., 2017]. Periodic gust profiles could be achieved after steady and unsteady response of the gust generator has been investigated. To define the motor sizing, maximum inertial torque was calculated by calculating angular acceleration at the most extreme case.

In this respect, the specific aim of this study is to design and manufacture a two-vane gust generator that will be integrated to a small-size open-loop wind tunnel with the purpose of generating desired gust profiles in the closed test-section. Effects of freestream flow speed, pitching frequency and amplitude and spacing between the vanes on the generated gust profiles will be investigated by means of PIV measurements. This study will constitute a basis for a large-scale gust generator to be implemented in the Large Scale Wind Tunnel in the METU Center for Wind Energy Research (RÜZGEM).

METHOD

Design of the Gust Generator

In the current study, design parameters of the gust vanes have been determined based on literature review and the geometry of the C1 wind tunnel that is located at RÜZGEM. The tunnel is a small scale suction type wind tunnel with a square cross section of 0.34 m×0.34 m with a maximum speed of 25 m/s. A nominal NACA0015 is chosen as the initial vane profile. Although a linear relation between the chord length and the gust amplitude is known to exist, the vane size is constrained by the tunnel geometry and the blockage ratio. In order to conduct the wind tunnel experiments without any serious loss of accuracy, the blockage ratio should be limited by 10%. [Choi C.K. and Kwon D.K., 1998] Hence, the ratio of the maximum projected area of the gust vanes to the test section area should not exceed 10%. This ratio attains a maximum at maximum deflection angle, which is limited to 12° in this study in order to avoid stalling of the vanes. As a result, a chord length of 8 cm has been chosen, yielding in a sufficiently conservative blockage ratio of about 9.5%. Span of the vanes is limited by the area of the test section. To prevent any contact with the test section walls, the vane span is chosen to be 33 cm, leaving an offset of 0.5 cm at both the upper and the lower wall.

Motor sizing is done based on the required torque of the system. This may be investigated in two parts, one of which is the aerodynamic torque and the other is the inertial torque. Inertial torque is described by,

$$T = \sum I\ddot{\theta} \tag{1}$$

where I is the moment of inertia of the system and θ is the angular position and $\ddot{\theta}$ is the angular acceleration. As the vanes will undergo a sinusoidal motion, the angular position, θ, is governed by,

$$\theta = A\sin(\omega t) \tag{2}$$

where A is the amplitude and ω is the frequency of the motion. The angular acceleration can then be calculated as,

$$\ddot{\theta} = -A\omega^2 \sin(\omega t) \tag{3}$$

Inertia values can be calculated based on CAD drawing of the system. Aerodynamic torque, on the other hand, is not the dominant term in the total torque of the system. It can be calculated using the unsteady potential theory. For a sinusoidal pitching motion about the mid-chord, the quasi-unsteady moment coefficient equals to [Gülçat Ü., 2010],

$$\bar{c}_m = \pi C(k)(1 - \mathrm{i}ka)\bar{\alpha} - \mathrm{i}k\pi \left[\frac{1}{2} - \frac{1}{2}C(k) + \frac{1}{8}\mathrm{i}k\right]\bar{\alpha} \tag{4}$$

where k is the reduced frequency, C is the Theodorsen function, a is the non-dimensional rotation point and $\bar{\alpha}$ is the amplitude of the pitching motion. As the pitching motion is with respect to the quarter chord, a equals to 1/2. Based on this formulation, aerodynamic torque can also be calculated. Consequently, required torque of the system can be found to size the motor.

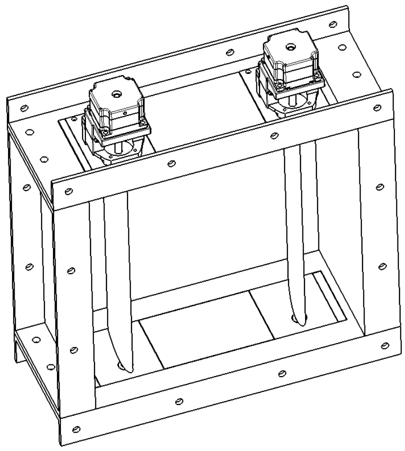

Figure 1: Gust generator, isometric view

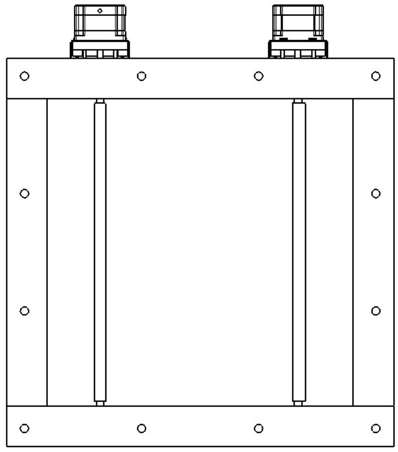

Figure 2: Gust generator, front view

Vanes are mounted at the inlet of the test section, in a metal frame with a length of 15 cm, as shown in figures 1 and 2. Motors are connected to the vanes from the top via a shaft centered at the quarter chord point of the vanes. Shafts have a length of 41 cm and extend through full span of the vanes as well as the test section. Distance between the vanes can be varied to study its effect on the gust profiles. The vanes with NACA0015 profiles are 3D printed using PLA+ filaments and installed on the gust generator system. They are driven by two NEMA 23 stepper motors with a holding torque of 1.4 Nm. The motion profiles are generated by an Arduino MEGA 2560 microcontroller.

Numerical Setup

Two-dimensional numerical simulations are performed in the commercial CFD solver Ansys Fluent. The setup is configured such that two sinusoidally pitching airfoils with a chord length of 8 cm that are placed in a domain with a length of 1.5 meters are analyzed. Airfoils are positioned 50 cm away from the inlet, with a vertical separation of 16 cm corresponding to two chord lengths.

Sinusoidal motion is imposed to the circular regions surrounding the airfoils while a constant velocity boundary condition is utilized at the inlet. Computational grid consists of triangular elements, with increased refinement around the airfoils, in the dynamic mesh regions, and in the wake region. Wall boundary condition is applied on the top and bottom sides of the domain, as they shall represent the tunnel walls. A pressure outlet boundary condition is applied at the outlet of the domain with a turbulence intensity value of 0.35%, which indeed is a property of C1 wind tunnel in RUZGEM.

Dynamic mesh region is created as a circle around each airfoil, with a radius approximately equal to the chord length. Selected mesh methods are diffusion based smoothing with a diffusion parameter of 1.5 and remeshing. The two circular regions are then defined as dynamic mesh regions governed by simple harmonic motion with their center of gravity positioned at the quarter chord of each airfoil.

A baseline case is determined based on the performance and capacity of the wind tunnel and the stepper motors driving the wings. Hence, a freestream velocity of 10 m/s and a frequency of 10 Hz is selected. For the baseline case, grid, time step and turbulence model convergence studies have been done. Three computational grids have been designed and based on the mesh scale information, CFL number is controlled through time step,

$$CFL = \frac{U\Delta t}{\Delta x} \tag{5}$$

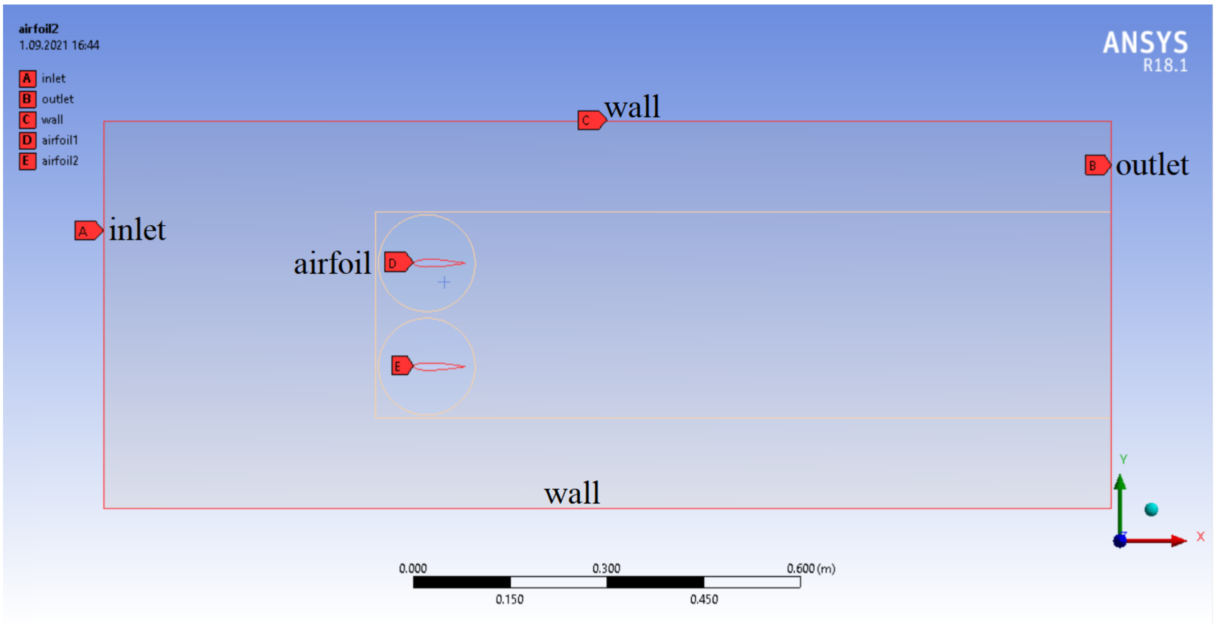

Figure 3: Boundary conditions and geometry

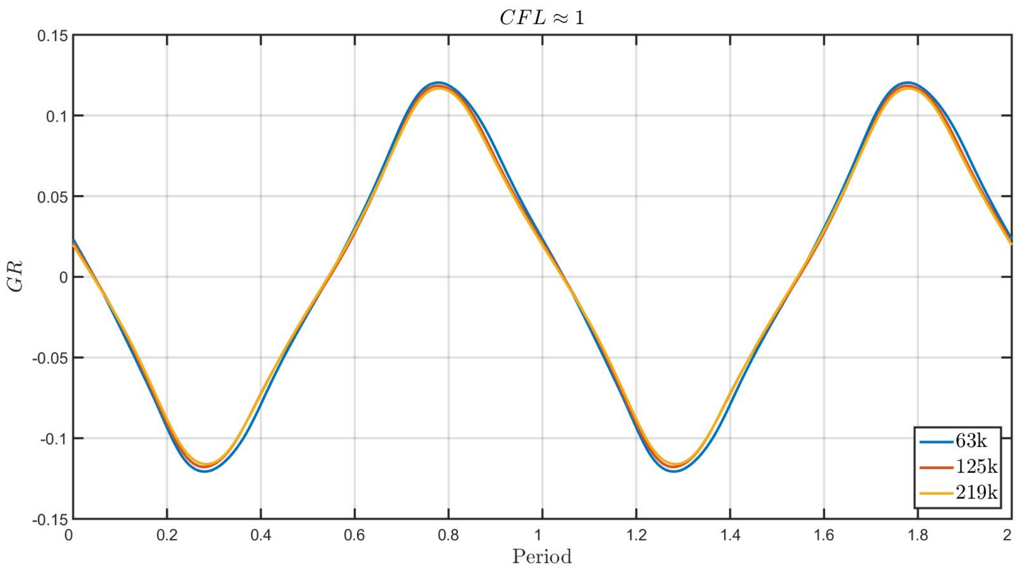

Figure 4: Grid convergence study

As there is a minor difference between the finest and intermediate grids, the one with 125k elements has been determined to be used in further studies.

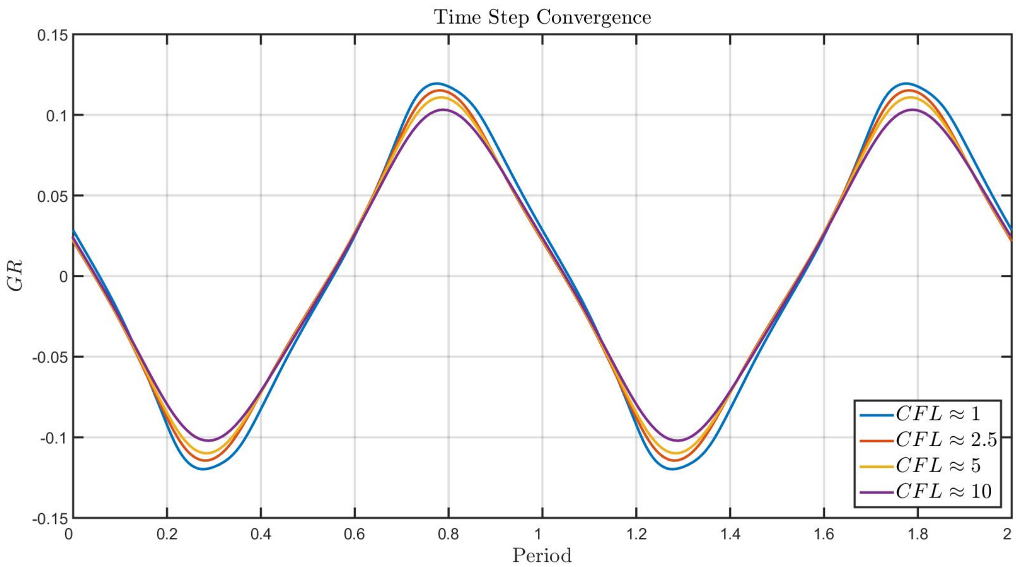

Figure 5: Time step convergence study

As a result of the time step convergence study that is shown in figure 5, the time step value which yields CFL numbers close to 1 has been chosen for further simulations.

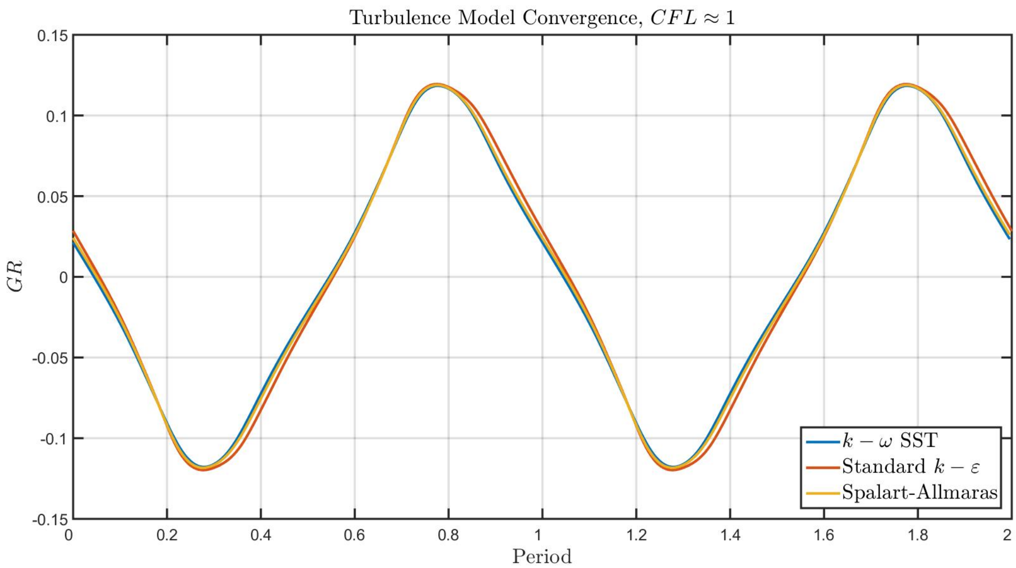

Figure 6: Turbulence model convergence study

As depicted in figure 6, two equation models $k-\omega$ SST and standard $k-\varepsilon$ and one equation model Spalart Almaras yield in close results, and they are all compatible with the physics of the problem. For the rest of the studies, $k-\omega$ SST model has been utilized.

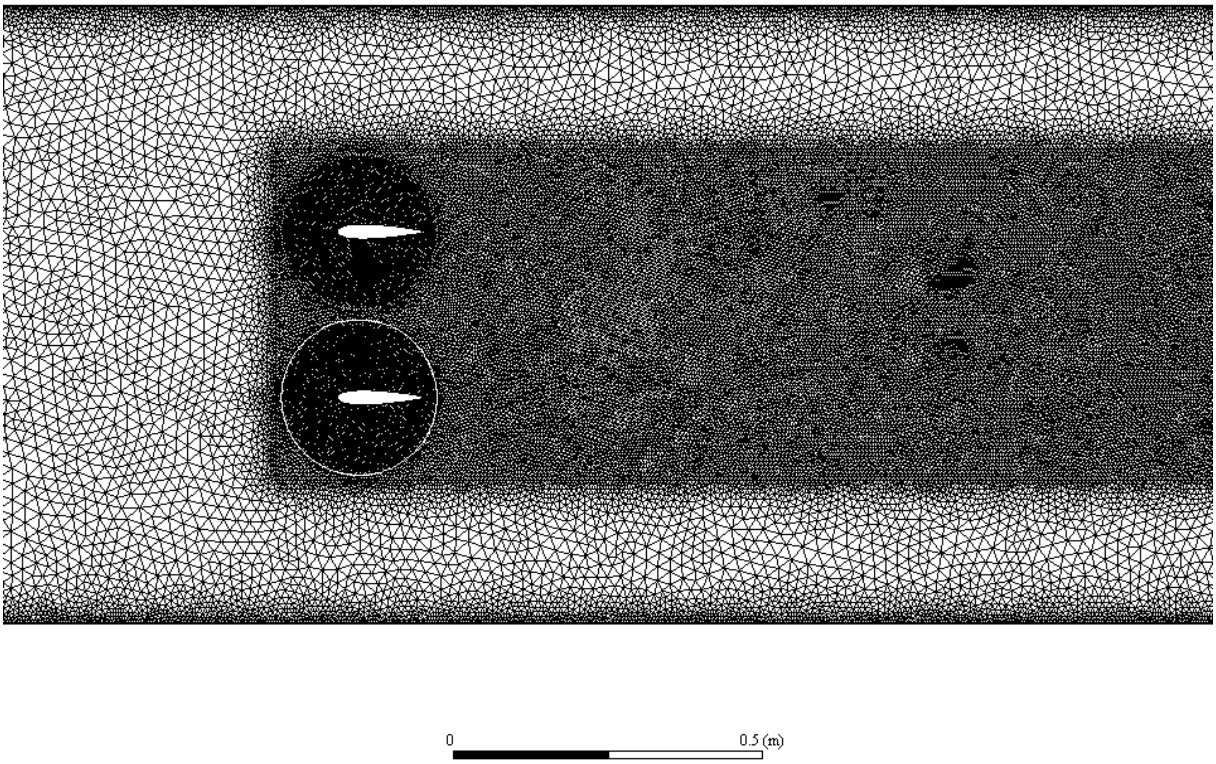

Figure 7: Computational grid

Computational grid shown in figure 7 has 125k triangular elements with the following mesh scale information:

Minimum length scale [m]	$9.43\mathrm{e}^{-5}$
Maximum length scale [m]	0.017882
Maximum cell skewness	0.8694

In the solution, $k-\omega$ SST model is used for turbulence closure. Initialization is done with a steady state solution of 200 iterations while a simple scheme is utilized for pressure-velocity coupling. Then, transient solution is obtained with a coupled scheme for pressure-velocity coupling and transient formulation is first order implicit.

Validation Study

In order to validate the numerical solver, the numerical analysis performed for the artificial gust generator in Delft University of Technology has been replicated using the present numerical setup [Lancelot et al., 2015]. There are two gust vanes of NACA0014 profile with a chord length of 0.3 m and a horizontal separation of 0.7 m, for which motion profile is sinusoidal with a frequency of 5 Hz and a maximum deflection angle of 10°. Freestream velocity is 25 m/s. In the simulations, time step size is 0.002 seconds and Spalart-Allmaras model is used for turbulence closure.

Results obtained with the current numerical setup are in a good agreement with those of Lancelot, et.al (2015). A difference of 8% in the maximum value of the gust angle is obtained as a result of the validation study, which may be considered acceptable for further simulations.

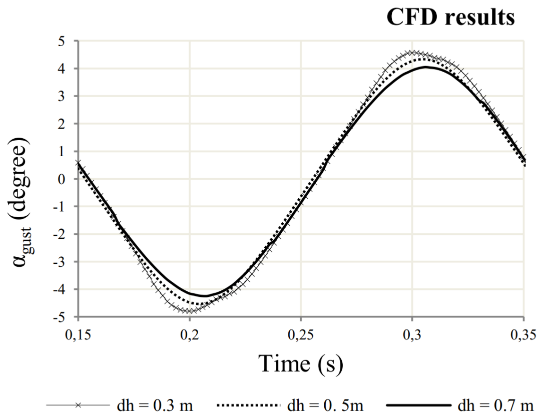

Figure 8: CFD results by Lancelot et. al (2015)

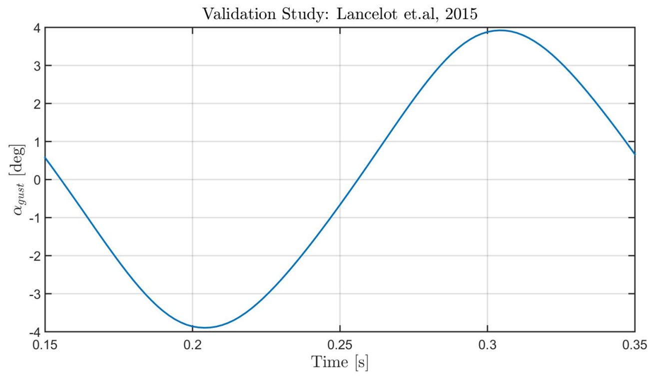

Figure 9: CFD results obtained by the designed computational grid, dh= 0.7m

RESULTS AND DISCUSSION

Contours of velocity magnitude for the baseline case (ω=10 Hz, U_∞=10 m/s and the maximum deflection angle of 12°) for four instants during the period of pitching motion, at the point corresponding to the center of the test section are shown.

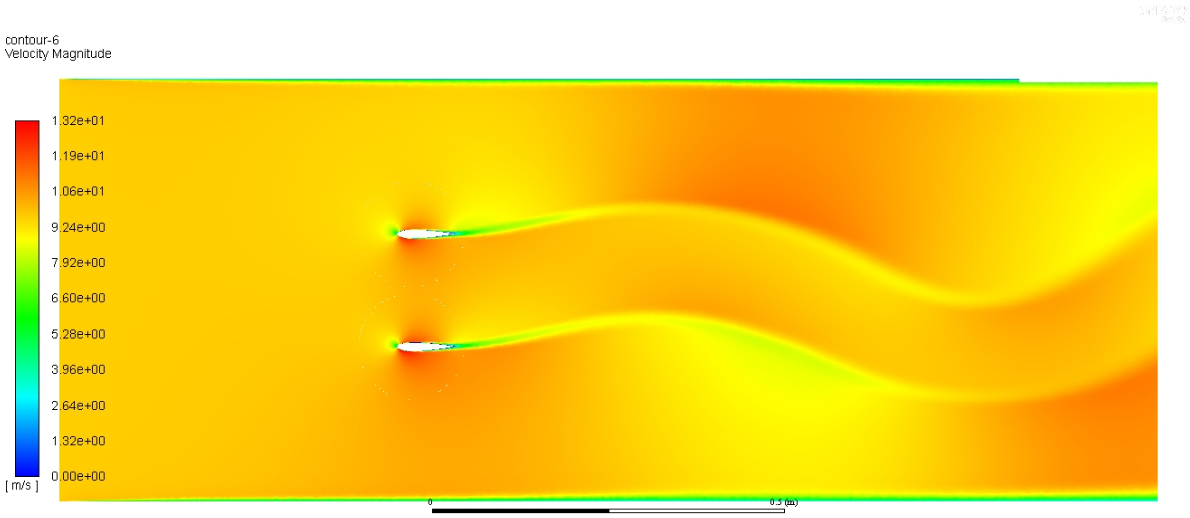

Figure 10: Velocity contour at $t = t_0$

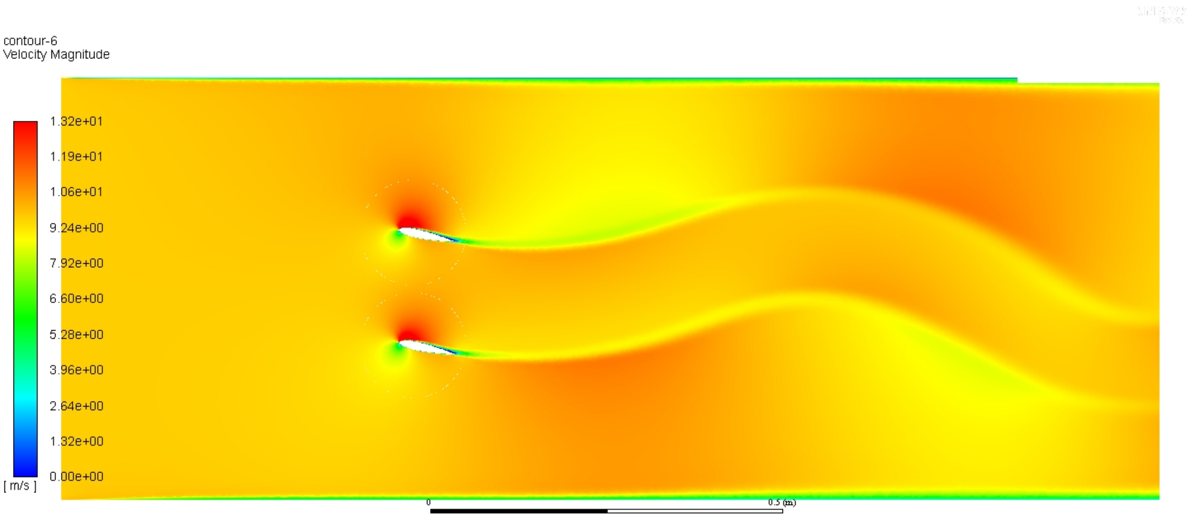

Figure 11: Velocity contour at $t = t_0 + 0.25T$

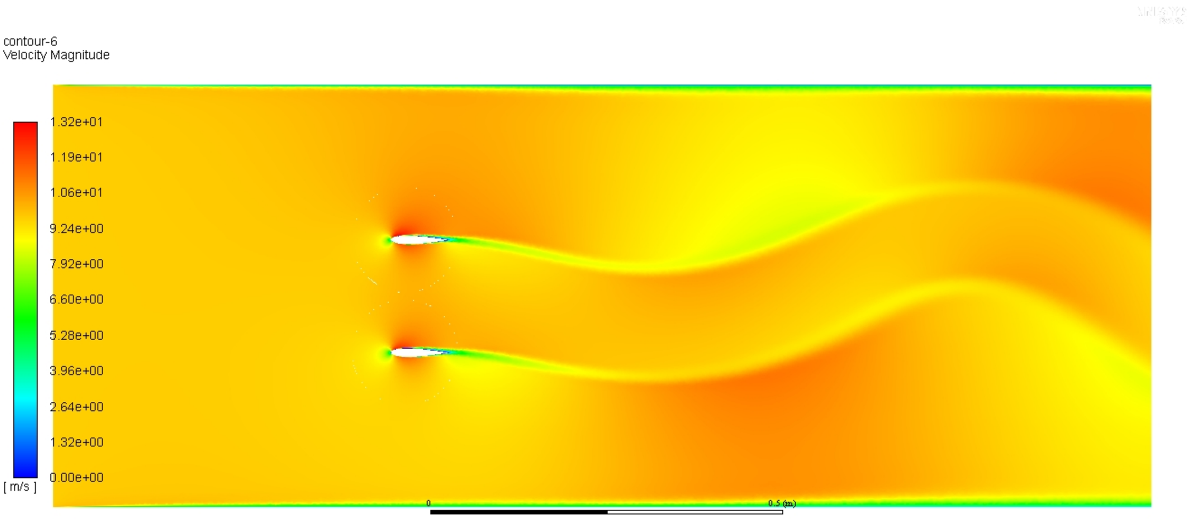

Figure 12: Velocity contour at $t = t_0 + 0.5T$

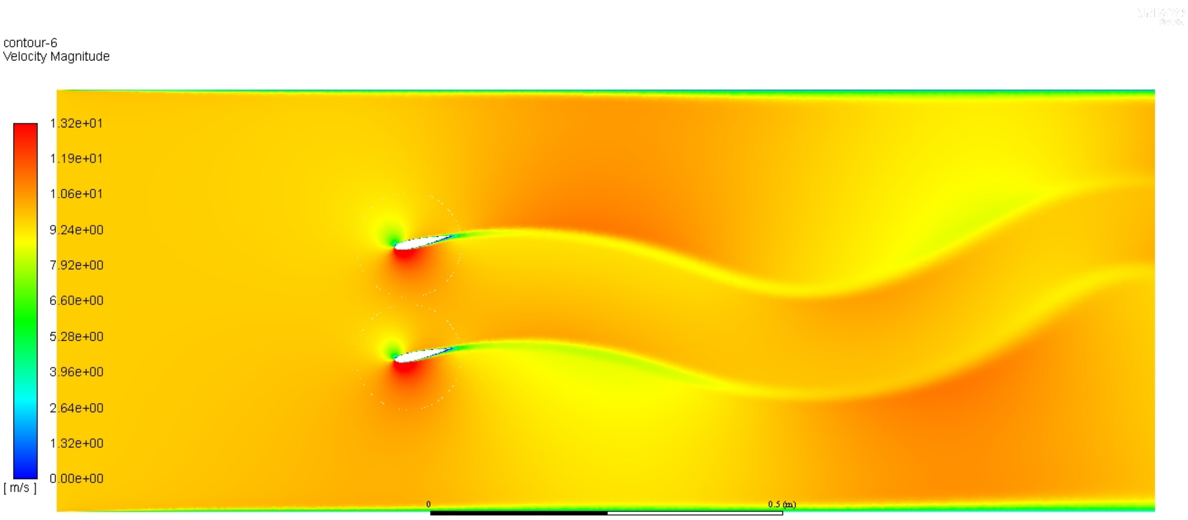

Figure 13: Velocity contour at $t = t_0 + 0.75T$

Clearly, a periodically varying velocity trend is observed downstream of the gust vanes, which indeed is the gust flow generated as a result of synthesis of the main freestream flow and flow induced by the oscillation of the vanes.

Numerical simulations have been performed for various pitching frequencies and freestream velocities in order to investigate the influence of the reduced frequency ($k = \pi f c / U_\infty$) on the gust ratio (GR), which is defined as:

$$GR = \left(\frac{v_{\text{gust}}}{v_{\text{ref}}} \right) \tag{6}$$

where v_{ref} is the freestream velocity. ($U_\infty = 10$m/s)

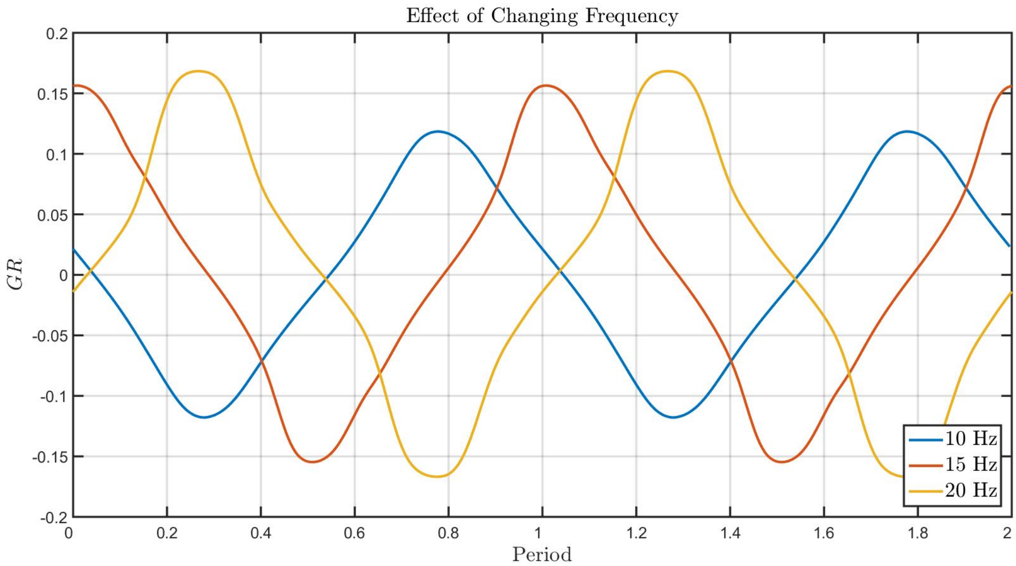

Figure 14: Effect of frequency on gust ratio

Changing the pitching frequency for the free-stream velocity of 10 m/s results in variations in both the amplitude and phase of the gust ratio. Higher pitching frequency yields larger amplitude but it also introduces a phase lag in the temporal variation of the transverse velocity, thus in the gust ratio. It should be noted that at the beginning of the period ($t = 0$), the gust vanes are at zero angle of attack.

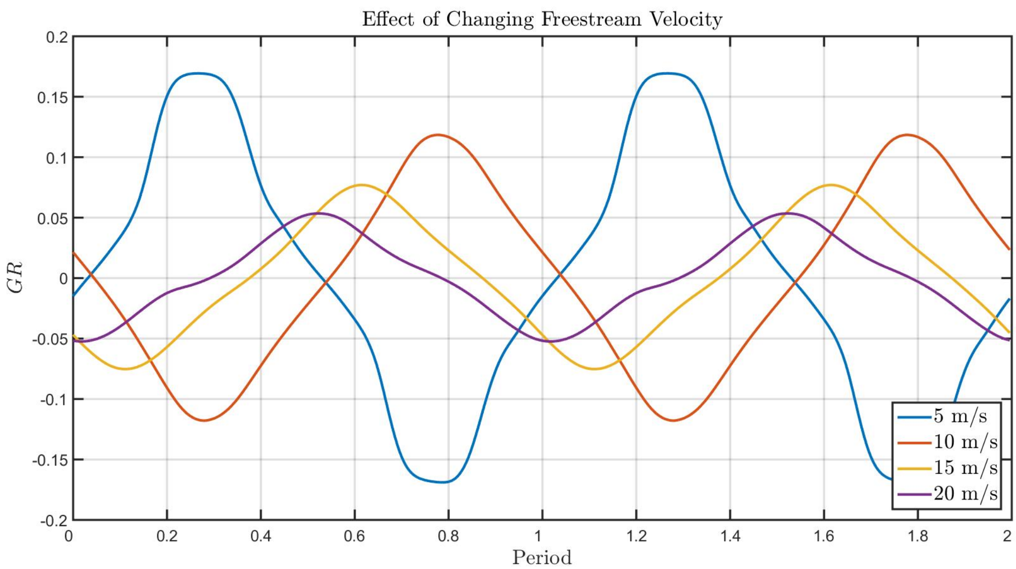

Figure 15: Effect of freestream velocity on gust ratio

Reduced frequency is also varied by changing the free-stream velocity for the fixed pitching frequency of 10 Hz (Figure 15). A similar trend is observed in this case such that decrease of freestream velocity results in greater gust amplitudes.

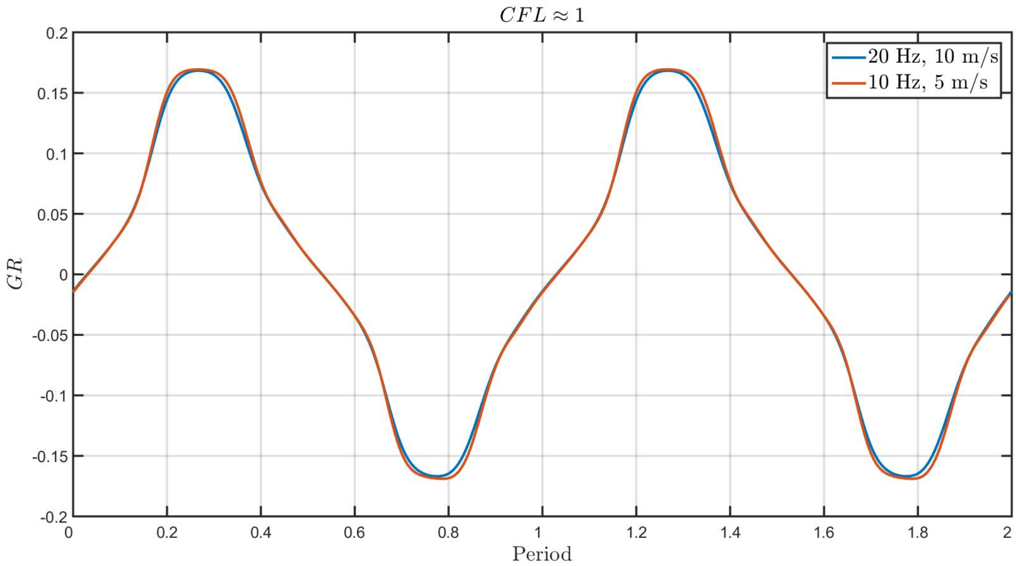

Figure 16: Reduced frequency variation through freestream velocity and pitching frequency

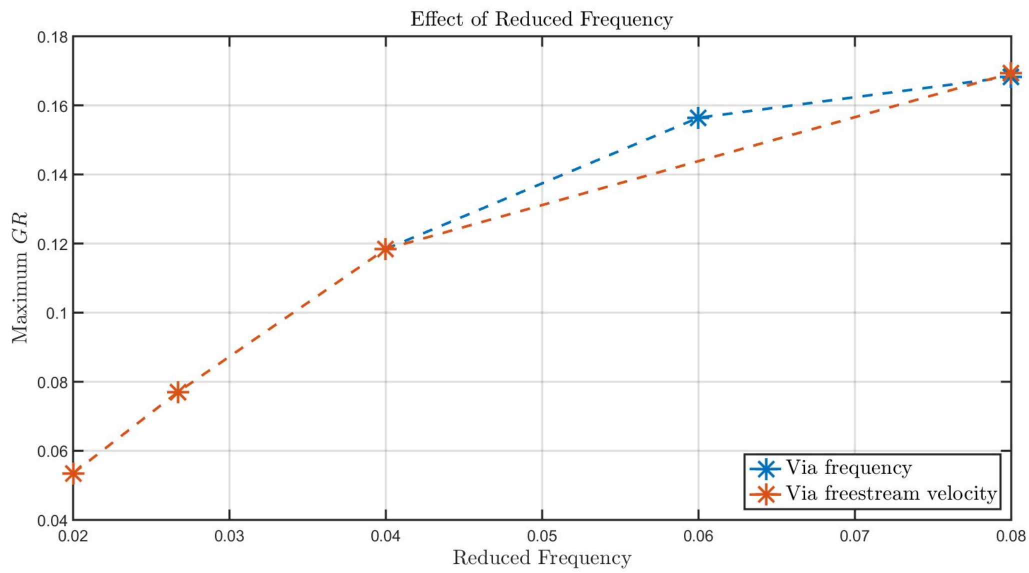

Figure 17: Effect of freestream velocity on gust ratio

The amplitude of GR as a function of the reduced frequency is plotted in figure 17. The same trend is obtained for both varying frequency and freestream velocity cases indicating that the gust amplitude is a direct function of the reduced frequency. As a result, varying the reduced frequency through pitching frequency and freestream velocity seems to be indifferent for the gust amplitude and shape, as long as the vanes undergo the same motion protocol.

CONCLUSIONS

This paper demonstrates the design and characterization of an artificial gust generator system. Based on the geometry of the wind tunnel and the blockage ratio limit of 10%, 8 cm chord length has been selected for the gust vanes, while the span covers the whole test section and is 33 cm. The vanes are mounted on a metal frame at the inlet of the test section as an extension. Several CFD analyses have been performed to conclude that a sinusoidal gust profile can be obtained at the center of the test section as the vanes undergo a sinusoidal motion. Amplitude of this gust can be increased by increasing reduced frequency. Decreasing the freestream velocity or increasing the pitching frequency results in no difference in the character of the resulting gust, provided that the final reduced frequency is the same.

FUTURE WORK

Two-dimensional two-component PIV measurements will be performed and compared with CFD results. Effect of varying freestream velocity, pitching frequency, separation of the vanes will be studied and resulting gust profiles will be analyzed. After the completion of full characterization of the gust generator, another one will be designed and placed in the Large Scale Wind Tunnel of METU Center for Wind Energy Research (RÜZGEM).

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