Penerbit Akademia Baru

CFD Letters

Journal homepage: www.akademiabaru.com/cfdl.html
ISSN: 2180-1363

Comparison of Rod-Airfoil Noise Calculation between Large Eddy Simulation (LES) and Detached-Eddy Simulation (DES)

Open Access

Siti Ruhliah Lizarose Samion[1], Mohamed Sukri Mat Ali[1,*]

[1] Malaysia – Japan International Institute of Technology (MJIIT), University Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 12 October 2018
Received in revised form 4 December 2018
Accepted 13 January 2019
Available online 5 February 2019

Keywords:
Rod-airfoil, airfoil leading edge noise, computational aeroacoustic (CAA)

ABSTRACT

Airfoil Leading Edge noise is generated due to impingement of turbulent structures on the airfoil surface. The rod-airfoil configuration is a benchmark configuration for the Leading edge noise and their noise calculation by computer simulation has peen progressively investigated to acceptable compare with the experiment. This paper presents the noise results finding between two distinct simulation models and their comparison with the experimental results. The two simulation models are Large-eddy simulation (LES) and the Delayed Detached-Eddy simulation (DDES). The DES can provide good noise results with the correct number of meshing grids with shorter time-span if compared to the LES. This study proposes to use DDES results for further rod-airfoil noise analysis.

1. Introduction

The rod-airfoil configuration is a relevant benchmark case for the Airfoil-Turbulence Interaction Noise (ATIN) investigations. Jeong and Hussain [1] and Jacob *et al*., [2] were among the pioneer to introduce this rod-airfoil configuration. This is because at high Reynolds numbers, the rod sheds the well-known von Karman vortex street which acts as an oncoming turbulence disturbance onto the airfoil. Rod flows had been extensively studied since the early work of Strouhal [3] on Aeolian tones, and a complete review of this topic has been published by Zdravkovich [4]. However, although the von Karman street can be regarded as a gust, very few investigations concerning rod-airfoil configuration are reported in the literature.

Stapountzis *et al*., [5] and Cambanis [6] focused on airfoil in the near wake of a very large rod (rod diameter ≈ airfoil chord length) in the context of wind turbine. Jacob *et al*., [2] highlighted three strong dimensional effects responsible for spectral broadening around the rod vortex shedding frequency in the subcritical regime, and identified that the airfoil leading edge was the main contributor to the noise emission in a rod-airfoil configuration due to vortex-structure interaction. Further comparison done by Lorenzoni *et al*., [7] revealed the ability of rod-airfoil configuration to

* *Corresponding author.*
E-mail address: sukri.kl@utm.my (Mohamed Sukri Mat Ali)

predict reasonably well compared with the real case, especially the magnitude of the tonal peak of emission and the narrow band spectrum around it. Microphone array measurements have also been done to investigate the influences of the rod diameter and the streamwise gap between the rod and the airfoil leading edge on the broadband noise generation frequencies higher than the flow vortex shedding frequency [8], thus the rod-airfoil is fairly enough can be used as representation of airfoil-turbulence interaction noise case.

Moreover, further understanding on the details of the rod-airfoil interactions have been gained through numerical simulations too [9–13]. Berland *et al*., [14] found good agreement between calculation and experiment when they used direct noise calculation based on the compressible LES of the rod-airfoil configuration. The LES is preferable in most of high Reynolds three-dimensional numerical investigation as it is possible flow separation, partial reattachment, vortex shedding, various length scale of turbulence [15]. However the LES itself may need a very high computer capacitance with its requirement of too much grid resolutions. The Detached-Eddy Simulation (DES) however, gives less intense to the requirement of computer performance. The DES, originally proposed by Spalart et al. (1997), is a hybrid model that functions like RANS in the near-wall regions and like LES in detached flow zones, and hence combines advantages of both methods [16].

The DES in an aeroacoustic perspective allows to limit the necessary detail to frequencies below the largest frequency of interest. Rod-airfoil noise calculation studies using the DES model is farther not as much as the LES studies of rod-airfoil. Jeong and Hussain [1] is among the early one to implement DES for rod-airfoil flow. Their three-dimensional flow results depicted vortex-shedding downstream the rod. However, their results showed retarded formation of regular von Karman vortex street, but that was due to the spanwise effect and not the defect from DES model. Jacob *et al*., [2] and Greschner *et al*., [12] are amongst the more recent works did using the DES for the computation of rod airfoil noise at high Reynolds flow. Greschner *et al*., [12] needed 2.3 million cells to do the DES of rod-airfoil, which the LES with such meshing would not result in good outcomes. Their DES predicted the peak of shedding frequency almost accurately. The frequency is a little small and the magnitude is under-predicted by 1 to 5 dB for different observer positions. The whole broadband spectrum from the DES/FWH showed excellent agreement with the experiment. These proved that the DES is a capable tool for the prediction of far-field noise in the case of highly turbulent flow such as a rod-airfoil configuration [17].

In addition to the recent findings of rod-airfoil DES simulation, this study aims to provide a comparison of noise calculation from DES/Curle and LES/Curle models.

2. Computational Domain

Figure 1 shows the current problem geometry. The inlet and topbottom is 10.5D away from the rod of the diameter D. The gap between the rod and airfoil is 3.5D as agreed with the experiment [18] and the study of Li *et al*., [19] whom proved that at $G \geq 3.3\ D$, the airfoil experience fully developed vortex in the wake of the rod. The chord of airfoil is 9.5 D with the outlet is 20.5 D downstream of the airfoil. The span of the domain is 3.5 D. The Reynolds number taken in current simulation is Re=Uv/D=20,000 fixed both in DES and LES cases.

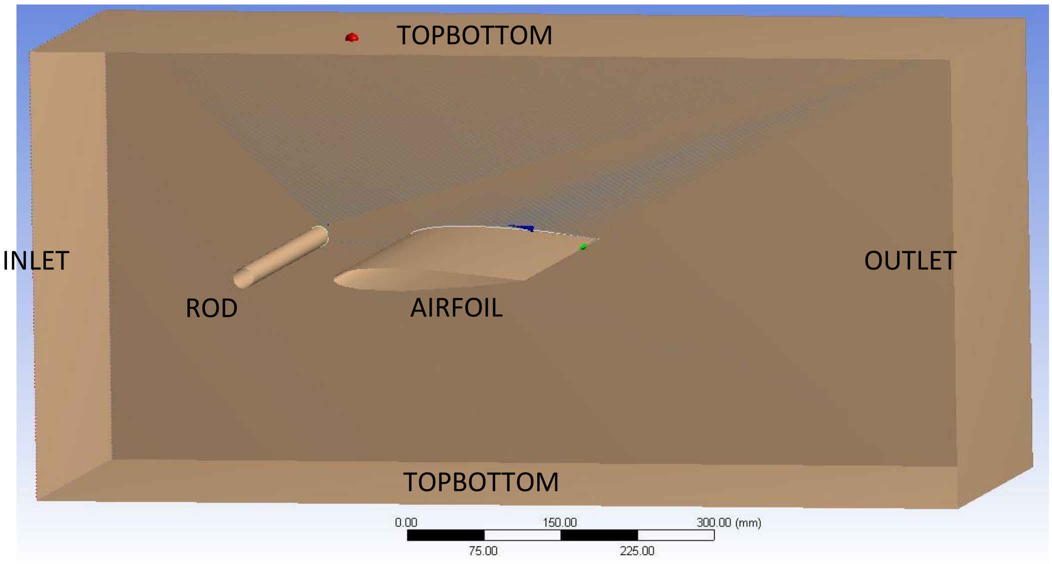

Fig. 1. Rod-airfoil configuration and the domain setting of current study

Figure 2 shows the close-up of meshing implemented in this study. The domain consists of approximately 3×10^6 grid cells. The vicinity mesh around rod and airfoil are treated with wall function, with smallest cell size near the wall is approximately 0.025D. The y+ is crucial and the y+ value of current study for rod is ${y^+}_{\text{rod}} \approx 49$ and the airfoil is ${y^+}_{\text{airfoil}} \approx 97$ which meet the requirement of $y^+ \approx 30$ to 300 with the use of wall function of the geometry wall [20].

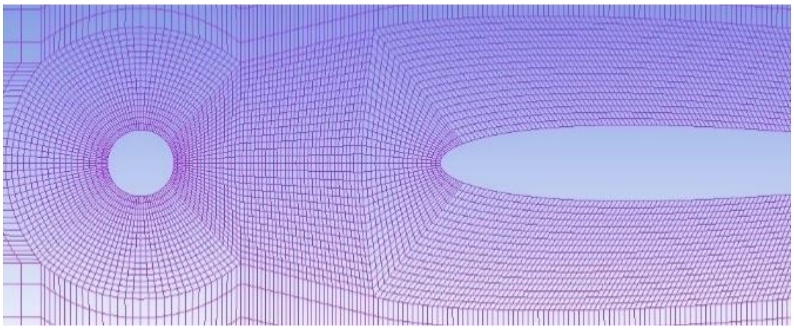

Fig. 2. Close-up of grid resolutions in the vicinity of rod-airfoil

3. Governing Equations

The noise of rod-airfoil uses hybrid calculation of noise source and the noise emission. The noise source is obtained from both the LES and DES, and noise emission uses the Curle's Analogy to calculate noise. Basically the flow is governed by Navier-Stokes and continuity equations taking the form

$$\frac{\partial U}{\partial t} + \nabla \cdot (UU) - \nabla \cdot \left[\left(\nu_\tau + \nu \right) \nabla U \right] = -\nabla p \tag{1}$$

$$\nabla \cdot U = 0 \tag{2}$$

where U is the velocity, t is the time, p is the pressure divided by a density and is the ν_τ turbulent eddy viscosity. The effect of turbulence on the flow behaviour is involved into a turbulent eddy viscosity calculated using the appropriate turbulent model.

3.1. Large Eddy Simulation (LES)

For LES model, turbulent eddy viscosity ν_τ is defined as

$$\nu_\tau = (C_S\Delta)^2|\overline{\boldsymbol{S}}| \quad (3)$$

where the$|\overline{\boldsymbol{S}}|$ is the magnitude of deformation rate tensor is

$$|\overline{\boldsymbol{S}}| = \frac{1}{2}\cdot\left[\left(\frac{\partial\overline{u_i}}{\partial x_j}\right)+\left(\frac{\partial\overline{u_j}}{\partial x_i}\right)\right] \quad (4)$$

The C_S is Smagorinsky constant, taken as C_S= 0.06 in current study, while the Δ defines the filtering scale.

3.2 Delayed Detached-eddy Simulation (DDES)

The DES model in current study is based on a modified eddy viscosity in the Spalart-Allmaras model and is calculated using the transport equation in the following forms

$$\frac{D\tilde{v}}{Dt} = P\nu - \epsilon\nu + \frac{1}{\sigma_\nu}\left[\nabla\big((\nu+\tilde{\nu})\nabla\tilde{\nu}\big) + c_{b2}|\nabla\tilde{\nu}|^2\right] \quad (5)$$

where $P\nu$ is production term and $\epsilon\nu$ is destruction term for the reduction of the stresses in the vicinity near the solid walls. The production term includes further a scalar quantity $\tilde{S}$ which is expressed by a magnitude of vorticity S plus a near wall correction and it can be modeled as in the Spalart Allmaras model (Spalart (1994)) as following

$$P\nu = c_{b1}\tilde{S}\tilde{\nu} \quad (6)$$

$$\tilde{S} = S + \frac{\tilde{\nu}}{\kappa^2 d^2} f_{v2} \quad (7)$$

The desired turbulent eddy viscosity ν_τ is calculated by the modified turbulent viscosity using the relation taking the form of

$$\nu_\tau = \tilde{\nu}\cdot f_{v1} \quad (8)$$

The lengrh scale in DES is redefined from the LES and represented as

$$\tilde{d} = \min(l_{RANS}, l_{LES}) = \min(d, C_{DES}\Delta) \quad (9)$$

where $\Delta = \max(\Delta x, \Delta y, \Delta z)$ is maximum grid spacing which is appropriate choice for homogenous grids, especially (Nikitin (2000)). The recommended value for adjustable parameter C_{DES} is 0.65. As to suppress the negative effect of unphysical behavior in the attached boundary layers of general DES, the formulation is further modified into DDES model. A new function f_d was additionally appended to the definition of the characteristic length scale $\tilde{d}$. Hence the dissipation length scale is

$$\tilde{d} = d - f_d \max\{0; d - C_{DES}\Delta\} \tag{10}$$

where

$$f_d = 1 - \tanh[(8r_d)^3] \tag{11}$$

and

$$r_d = \frac{v + v_t}{\sqrt{\partial x_j u \, \partial x_i u_i} \kappa^2 d^2} = \frac{\tilde{v}}{\kappa^2 d^2} \tag{12}$$

3.2. Acoustic Calculation

The sound calculation utilizes the Curle's solution [21] from Lighthill Acoustic Analogy. The Lighthill's Acoustic Analogy [22] is

$$\left(\frac{\partial^2}{\partial t^2} - {c_0}^2 \nabla^2\right)(\rho - \rho_0) = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}(x, t) \tag{13}$$

Eq. 13 is an inhomogenous wave equation derived from the rearrangement of Navier-Stokes equations. The T_{ij} is Lighthill's stress tensor,

$$T_{ij} = \rho u_i u_j - \tau_{ij} + \delta_{ij}\big((p - p_0) - c_0^2(\rho - \rho_0)\big) \tag{14}$$

where the first term in the right hand side is the Reynolds stress tensor, the second term is viscous stress and the δ_{ij} is Kronecker delta. Curle's theory consider a compact body present in the flow (i.e. the rod-airfoil). Compact sound source is considered when the body dimension is very small compared to the wavelength of emitted sound. The final solution of a Curle's equation to obtain sound pressure p' [Pa] in three-dimension is

$$p'(x, t) = \frac{1}{4\pi c_0} \frac{\partial^2}{\partial x_i x_j} \int \frac{T_{ij}}{r} dV - \frac{1}{4\pi} \frac{\partial}{\partial x_i} \left[\frac{F_i}{r}\right] = \frac{1}{4\pi c_0^2} \frac{x_i x_j}{x^3} \int \frac{\partial^2 T_{ij}}{\partial t^2} dV - \frac{1}{4\pi c_0} \frac{x_i}{r^2} \left[\frac{\partial F_i}{\partial t}\right] \tag{15}$$

where the sound source $\frac{\partial F_i}{\partial t}$ and $\frac{\partial^2 T_{ij}}{\partial t^2}$ are obtained from the flow calculation, whether from DES model or the LES model in this study and the. However, the sound from the first term (i.e. the quadrupole sound derived from the stress tensor of the system) is neglectable due to its too small contribution. $\frac{\partial F_i}{\partial t}$ on the other hand is derived from the lift force acting on the rod and airfoil bodies. The sound due to drag force is small and not dominant as similarly found in Ali et al., [23]. The sound pressure will be used in the following equation to obtain the sound pressure level in decibels.

$$SPL = 20 \log\left(\frac{p'}{p'_{\mathrm{ref}}}\right) \quad [\mathrm{dB}] \tag{16}$$

To consider the spanwise effect, a span correction is used in current study [13]. The overall sound pressure level $OASPL$ [dB] is calculated using the integral of sound spectra over a range of frequency, by the following [24]

$$OASPL\ [\mathrm{dB}] = \int_{St=0.1}^{St=1.1} SP\ (St)\ d\ St \tag{17}$$

4. Findings and Discussion

LES is expected to describe major structures of the turbulent flow responsible of the broad acoustic spectrum, but DES is far than enough to provide the sources and consequently provide good noise source for acoustic analogy to be implemented. The finding of this study distinguishes the advantages of taking DES model as the medium to calculate the noise source instead of the highly-intense LES computation.

4.1. Acoustic Results

The sound generation from current cases are presented in the density spectrum as shown in Figure 3. The calculation results are also compared with the rod-airfoil experimental results obtained in the anechoic wind tunnel of the author's previous finding [18]. The sound calculated from the DDES model shows very good agreement with the experiment if compared with the LES model. Also, the OASPL of experiment is 47.27 dB, but the OASPL from LES is 49 dB and DDES is 47.57 dB. Instead, the LES results show over prediction from the experiment in both the PSD trend and the overall sound pressure. This may be due to too few grid resolutions for an LES to capture the smaller eddies present in the flow and this lead to the over prediction of turbulent structures of current LES. This can be explained further in the aerodynamic results section.

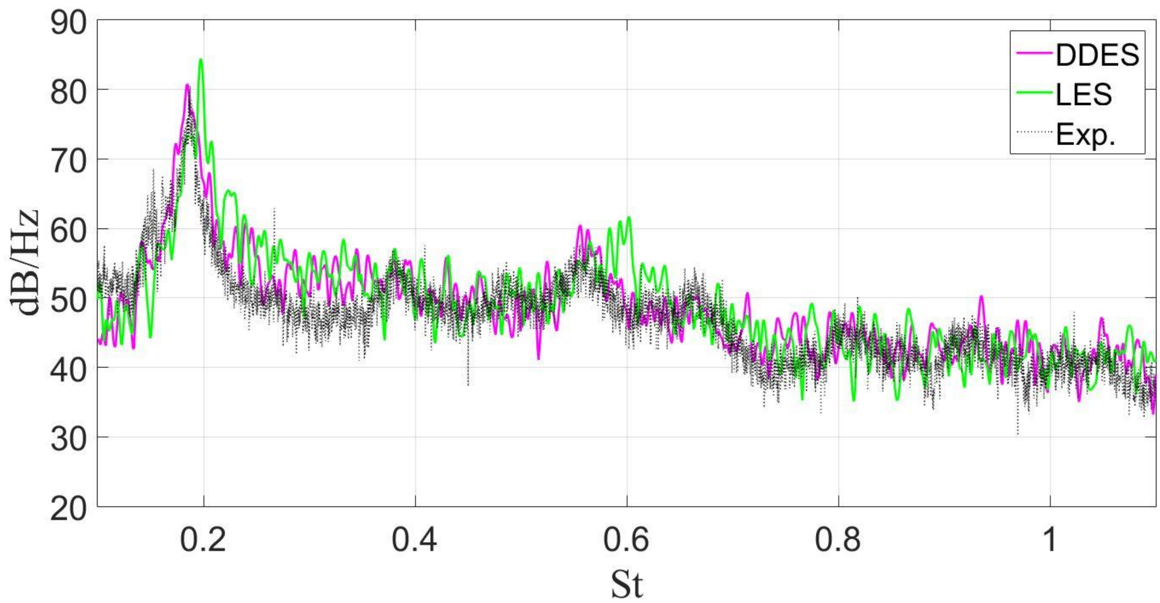

Fig. 3. Comparison of sound spectra of DDES, LES and the experiment

4.2. Aerodynamic Results

Acoustic emission from the rod-aifoil is the results of the aerodynamic behaviour around the bodies. The physics of the flow behaviour can be observed from the vorticity contour. Figure 4 shows the vorticity map from current simulation of DES and LES.

In general, both the simulations provide us with the recognizable vortex core. Also, the eddies are sufficiently distinct to be seen impinging at the leading edge, suitable enough for the study of leading edge noise investigation. However, the LES model is believed can provide a better performance with a more defined grid resolutions. This might be the reason of the over prediction of OASPL from LES/Curle as portrayed previously in Figure 3.

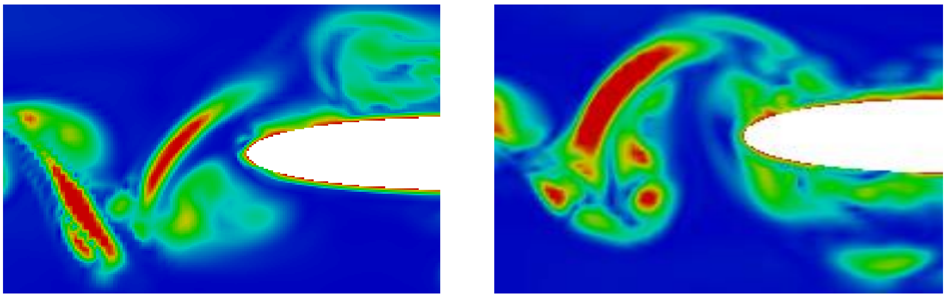

Fig. 4. Vorticity magnitude obtained from DES (LHS) and LES (RHS)

Figure 5 shows the flow visualization of an experimental investigation of Jacob *et al*., [2] whom did a rod-airfoil configuration in high-Reynolds number flow (Re=48,000), almost the same case of current study. Comparing current results with the experimental PIV results of vorticity contour, the agreement of flow visualisation by the DES (as represented in the Q map in Figure 6) is very good, both in terms of levels and shape of vortices impinging onto the airfoil. The DES results showed the cluster of eddies inside larger vertical structures and the severe deformations of vortices that impinge onto the airfoil. This result also proves leading edge as the intense sound source of this flow.

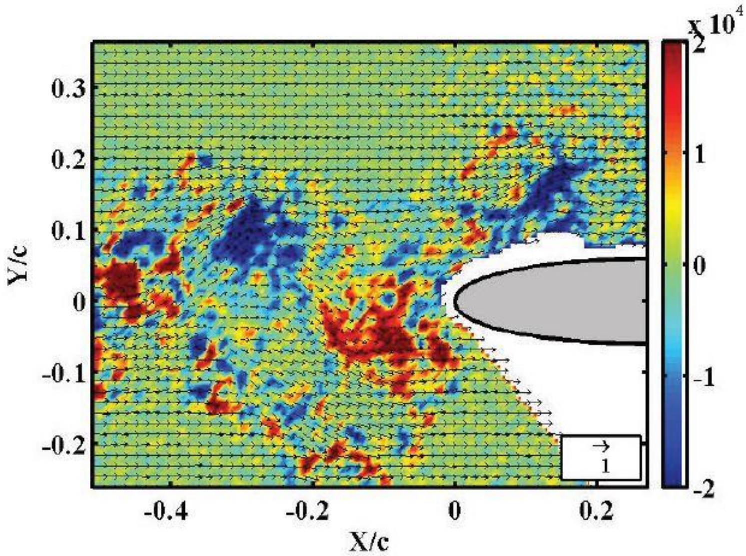

Fig. 5. Vorticity map from PIV measurement of rod-airfoil experiment obtained from Jacob et al., 2008

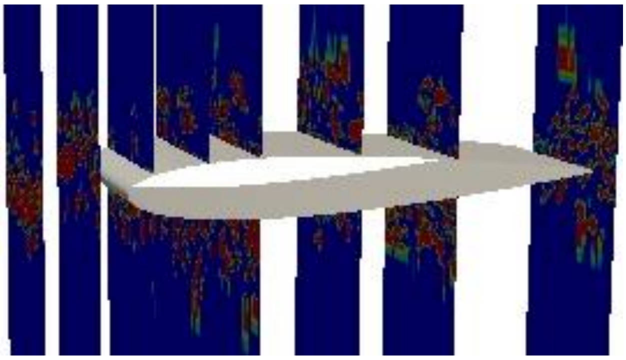

Fig. 6. Q-criterion obtained from DES

5. Conclusion

Current study argues on the acoustic calculation of high Reynolds flow around rod-airfoil configuration between the DES/Curle and LES/Curle methods. The DES/Curle and LES/Curle are compared with the available experimental data to access the reliability of the models for further airfoil leading edge noise study.

In summary, the DES/Curle is a suitable method for simulating the rod-airfoil interaction noise as it provides sufficient access to the resolved turbulent scales at minimal computational cost, if compared to the LES/ Curle. The eddies cluster and the turbulent structures are fairly sufficient from the DES/Curle, as need for a leading edge noise investigation. The acoustic results obtained from DES/Curle had also showed good agreement with that of the same case from the experiment. The results has provide excellent insights on the authentic performance of the DES/Curle hybrid method to be utilized in further airfoil-turbulence interaction noise in the future.

Acknowledgement
The author would also like to acknowledge University Technology of Malaysia for the grantment of Ainuddin Wahid Scholarship to financially support this study.

References

[1] Jeong, Jinhee, and Fazle Hussain. "On the identification of a vortex." Journal of fluid mechanics 285 (1995): 69-94.
[2] Jacob, Marc C., Jérôme Boudet, Damiano Casalino, and Marc Michard. "A rod-airfoil experiment as a benchmark for broadband noise modeling." *Theoretical and Computational Fluid Dynamics* 19, no. 3 (2005): 171-196.
[3] Strouhal, V. (1878) Ueber eine besondere Art der Tonerregung. Annalen der Physik und Chemie ; n5 (10) 216-251
[4] Zdravkovich, M. M. "Flow around circular cylinders volume 1: fundamentals." Oxford University Press, Oxford 19 (1997): 185.
[5] Stapountzis, H., K. Yakinthos, A. Goulas, S. Kallergis, and V. Kambanis. "Cylinder wake: airfoil interaction for application to a downwind HAWT." In EWEC-CONFERENCE-, pp. 172-175. 1999.
[6] Cambanis, V. P., and H. Stapountzis. "An experimental study and FLUENT simulation of the horizontal axis wind turbine (HAWT) blade-tower dynamic interaction." In 2nd Southeastern Europe Fluent Users Group Meeting. November, pp. 1-2.
[7] Lorenzoni, V., Moore, P. Scarano, F., Tuinstra, M.(2009) Aeroacoustic analysis of a rod-airfoil flow by means of time-resolve PIV. AIAA 3298.
[8] Giesler, Jens, and Ennes Sarradj. "Measurement of broadband noise generation on rod-airfoil-configurations." In 15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference), p. 3308. 2009.
[9] Casalino, Damiano, Marc Jacob, and Michel Roger. "Prediction of rod-airfoil interaction noise using the Ffowcs-Williams-Hawkings analogy." *AIAA journal* 41, no. 2 (2003): 182-191.
[10] Boudet, Jérôme, Nathalie Grosjean, and Marc C. Jacob. "Wake-airfoil interaction as broadband noise source: a large-eddy simulation study." *International Journal of Aeroacoustics* 4, no. 1 (2005): 93-115.
[11] Magagnato, Franco, Esra Sorgüven, and Martin Gabi. "Far Field Noise Prediction by Large Eddy Simulation and Ffowcs Williams Hawkings Analogy." In 9th AIAA/CEAS Aeroacoustics Conference and Exhibit, p. 3206. 2003.

[12] Greschner, Björn, Frank Thiele, Marc C. Jacob, and Damiano Casalino. "Prediction of sound generated by a rod–airfoil configuration using EASM DES and the generalised Lighthill/FW-H analogy." *Computers & fluids* 37, no. 4 (2008): 402-413.

[13] Seo, Jung H., and Young J. Moon. "Aerodynamic noise prediction for long-span bodies." *Journal of Sound and Vibration* 306, no. 3-5 (2007): 564-579.

[14] Berland, Julien, Philippe Lafon, Fabien Crouzet, Frédéric Daude, and Christophe Bailly. "A parametric study of the noise radiated by the flow around multiple bodies: direct noise computation of the influence of the separating distance in rod-airfoil flow configurations." In 17th AIAA/CEAS Aeroacoustics Conference (32nd AIAA Aeroacoustics Conference), p. 2819. 2011.

[15] Heidarzadeh, H., Farhadi, M. and Sedighi, K. "Convective Heat Transfer over a Wall Mounted Cube Using Large Eddy Simulation." *CFD Letters* 4 (2) (2012) 80-92.

[16] Spalart, PRaA, and S1 Allmaras. "A one-equation turbulence model for aerodynamic flows." In 30th aerospace sciences meeting and exhibit, p. 439. 1992.

[17] Michel, U., Eschricht, D., Greschner, B., Knacke, T., Mockett, C., and Thiele, F. (2010) Advances DES methods and their application to aeroacoustics. Progress inH ybrid RANS-LES Modeling, NNFM (111) 59-76.

[18] Samion, SRL., and Ali, MSM. (2018) Aerodynamic noise measurement in anechoic wind tunnel of rod-airfoil with leading edge serrations, *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 47 (1) 97-107.

[19] Li, Yong, Xun-nian Wang, Zheng-wu Chen, and Zheng-chu Li. "Experimental study of vortex–structure interaction noise radiated from rod–airfoil configurations." *Journal of Fluids and Structures* 51 (2014): 313-325.

[20] Kim, Won-Wook, Suresh Menon, Won-Wook Kim, and Suresh Menon. "Application of the localized dynamic subgrid-scale model to turbulent wall-bounded flows." In 35th aerospace sciences meeting and exhibit, p. 210. 1997.

[21] Curle, N. "The influence of solid boundaries upon aerodynamic sound." Proc. R. Soc. Lond. A 231, no. 1187 (1955): 505-514.

[22] Lighthill, Michael James. "On sound generated aerodynamically I. General theory." Proc. R. Soc. Lond. A 211, no. 1107 (1952): 564-587.

[23] Ali, Mohamed Sukri Mat, Con J. Doolan, and Vincent Wheatley. "The sound generated by a square cylinder with a splitter plate at low Reynolds number." *Journal of sound and vibration* 330, no. 15 (2011): 3620-3635.

[24] Chen, Weijie, Weiyang Qiao, Liangfeng Wang, Fan Tong, and Xunnian Wang. "Rod-airfoil interaction noise reduction using leading edge serrations." In 21st AIAA/CEAS aeroacoustics conference, p. 3264. 2015.