Annals of the Academy of Romanian Scientists
Series on Engineering Sciences
ISSN 2066-8570 Volume **15**, Number **1**/**2023**

COMPUTATIONAL STUDIES OF HELICOPTER AERODYNAMICS

Marcel ILIE[1], Augustin SEMENESCU[2]

Rezumat. *Prezentul studiu are ca scop analiza aerodinamicii elicopterului și, în particular, fenomenul de interacțiune dintre vârtej și elicea rotorului. Studiile computaționale sunt efectuate cu ajutorul metodei large-eddy simulation, pentru fluide subsonice și incompresibile, pentru un număr Reynolds* $Re=1.3x10^6$*. Aerodinamica elicopterului este dominată de fenomenul interacțiunii dintre vârtej și elicea rotorului, care este responsabil pentru vibrații și zgomotul elicopterului. În timpului zborului cu elicopterul, un vârtej este format la capătul elicei și interacționează cu a doua elice în mișcare, generând fenomenul de interacțiune dintre vârtej și elice. Studiul arată că interacțiunea dintre vârtej și elice cauzează oscilații ale coeficienților aerodinamici. Datorită fenomenului de turbulență, aceste oscilații prezintă o variație neliniară.*

Abstract. *The present research concerns the helicopter aerodynamics and the blade-vortex interaction phenomenon. The computational studies are carried out using the large-eddy simulation approach for subsonic incompressible flow of Reynolds number* $Re=1.3x10^6$*. The helicopter aerodynamics is dominated by the blade-vortex interaction (BVI) phenomenon which is responsible for noise and vibrations. During the helicopter flight, a tip-vortex filament is formed and its interaction with the advancing blade causes the blade-vortex interaction phenomenon. The study shows that the blade-vortex interaction causes oscillations of the aerodynamic coefficients. Due to the turbulence phenomenon, the oscillations exhibit a non-linear behaviour.*

Keywords: helicopter aerodynamics, modeling, finite-differences, large-eddy simulation

DOI https://doi.org/10.56082/annalsarscieng.2023.1.54

1. Introduction

In spite of extensive years of studies and research, the helicopter aerodynamics still poses significant experimental and computational challenges. Therefore, experimental studies of helicopter aerodynamics are costly and require specialized facilities such expensive wind-tunnel experimental setups. Moreover, the rotating-

---

[1] PhD, Assistant Professor: Dept. of Mechanical Engineering, Georgia Southern University, Statesboro, GA 30458, USA, e-mail: milie@georgiasouthern.edu

[2] PhD, Professor, Dept. of Material Sciences, University Politehnica, Bucharest, Romania, augustin.semenescu@upb.ro; Corresponding Member of Academy of Romanian Scientists

frame of reference brings additional challenges due to the fact that the wind-tunnel setup must account for the centrifugal forces and rotational motion. On the other hand, the experimental setup of rotational frame of reference pose challenges associated with the measurement of the flow variable such as pressure and velocity.

One of the main challenges in the rotorcraft aerodynamics is posed by the blade-vortex interaction (BVI) phenomenon, as schematically presented in Figure 1.

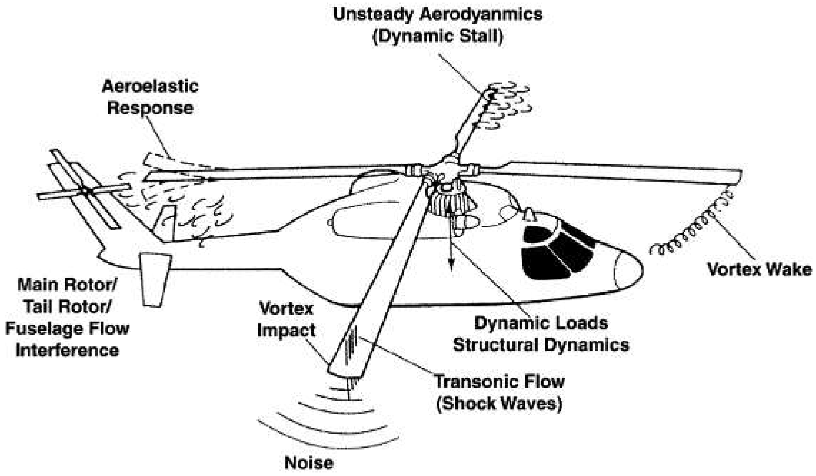


Fig. 1. Helicopter aerodynamics [20]

The blade-vortex interaction phenomenon is the main source of noise and vibrations in rotorcraft. Rotorcraft vibration affect the flight stability and safety of the operation. Moreover, for military helicopter noise plays a critical role in the fulfilment of the mission and thus, its mitigation is of critical importance.

The fluid dynamics associated with the BVI is also complex and involves boundary-layer separation, dynamic stall and vortex wake, as shown in Figure 1. Therefore, a good understanding of the fluid dynamics of the fluid flow associated with the rotorcraft aerodynamics would improve the life span of the rotorcraft and reduce the operational and maintenance costs. As already mentioned, the experimental studies of rotorcraft aerodynamics are challenging and costly and therefore, computational studies are more feasible and allow the repeatability of the experiment in a shorter time at minimum cost.

The present study concerns the feasibility of the computational approaches in the prediction of the fluid dynamics of helicopter aerodynamics. One of the main challenges for the computational approaches is to capture the highly-turbulent encountered in the helicopter aerodynamics. The rotorcraft aerodynamics is an unsteady phenomenon and therefore, computational methods that can simulate the unsteady phenomena must be sought.

2. Background

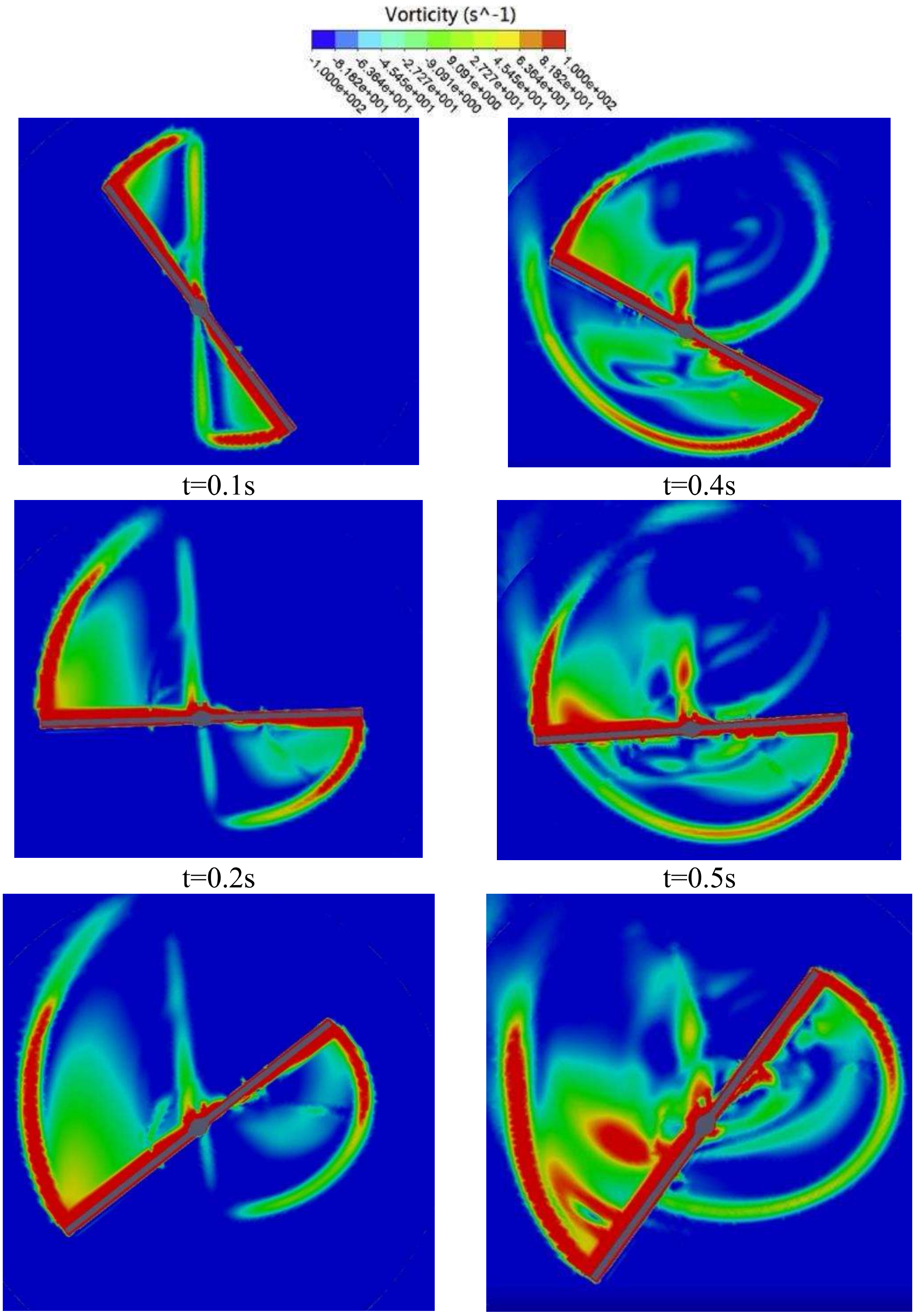
Generally, the numerical computations of rotorcraft aerodynamics pose significant challenges due to the flow complexity and computational costs. [5, 7]. Studies showed that the numerical approach based on the Reynolds-averaged Navier-Stokes (RANS) pose significant challenges in the computation of high-Reynolds number flows and vortex dominated flows such as the case of helicopter aerodynamics [5]. Direct numerical simulations (DNS) also pose computational challenges due to the high-resolution grid size required by the DNS. Therefore, the direct-numerical simulations also pose computational challenges due to the high requirements of the computational capabilities. On the other hand, the large-eddy simulation approach requires a lower computational capability, while providing a time-efficient accurate solution. Therefore, in the present study we will employ the large-eddy simulation approach for the computations of helicopter aerodynamics.

3. Modeling and algorithms

In the present research the computational studies are carried out using the large-eddy simulation (LES) approach. For more details on the computational modeling using LES, the reader is referred to [6].

4. Results and discussion

Figure 4 presents the vorticity magnitude of the flow field associated with the rotorcraft blade-vortex interaction phenomenon, at different instants in time. The analysis is performed for two-blade rotor design. However, the computational model can handle rotor with multiple blades.



t=0.1s t=0.4s

t=0.2s t=0.5s

t=0.3s t=0.6s

Fig. 2. Vorticity magnitude

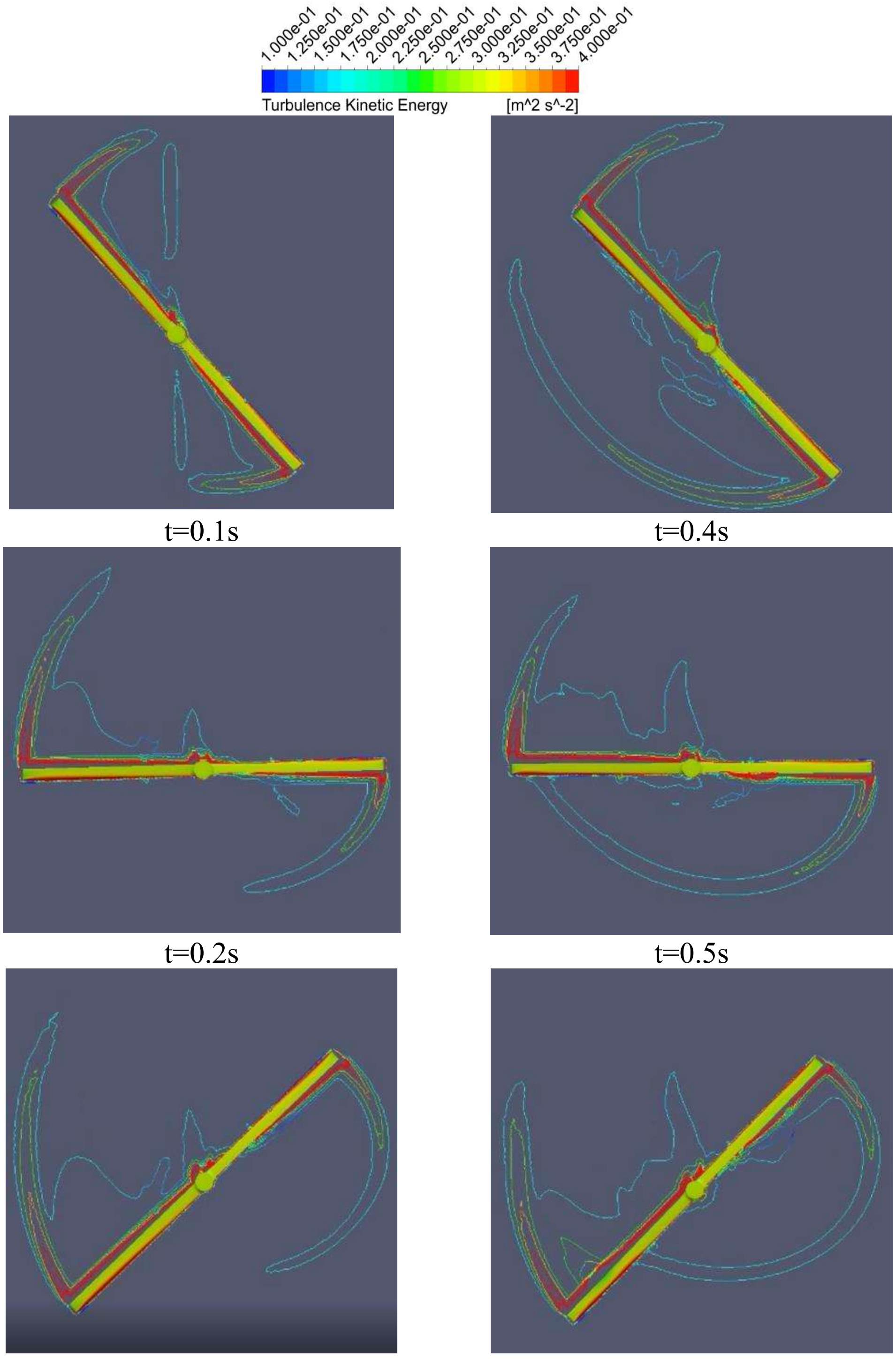
The analysis shows the formation of the tip vortex as the rotor starts to spin. The analysis of the vorticity field shows that its magnitude exhibits largest values at the tip of the blade and this is due to the large pressure difference between the upper and lower surfaces of the blade.

The fluid nature tries to balance the pressure at the two surfaces of the blade and thus, it escapes at the tip of the blade generating large flow disturbances. It is worth mentioning here that the rotor spins in the trigonometric direction. Therefore, we call the left-hand side blade the advancing-blade while the blade on the right-hand side is the retreating blade.

As the rotorcraft blades continue to rotate, the vorticity magnitude increases as shown in Figure 2, at instant t=0.1s. The rotating blade cause disturbances of the flow field which resembles a circular path as seen in Figure 2. It is also worth mentioning here that interaction between the incoming flow and rotor hub causes additional disturbances of the flow field. Further on, the advancing–blade interacts with the wake generated by the previous blade, and this represents the blade-vortex interaction phenomenon. The blade-vortex interaction phenomenon causes further disturbances of the flow field and thus, an increase of the vorticity magnitude is observed. It is important to mention here that the blade-vortex interaction occurs along the span of the blade. However, the most significant blade-vortex interaction occurs in the 25% of the span of the blade measured from the tip of the blade. As the vortex filament moves towards the hob of the blade, the blade-vortex interactions become weaker and weaker and thus, the vortex-filament dissipates.

A good insight into the magnitude of the turbulence and flow disturbances can be obtained from the analysis of the turbulence kinetic energy (TKE). Therefore, Figure 3 presents the turbulence kinetic energy at different instants in time. The analysis of the turbulence-kinetic energy shows that the largest turbulence disturbances are encountered in the near-blade region. Similar to the vorticity field the tip of the blade exhibits the largest turbulence kinetic energy levels. The wakes of the two blade also generate high levels of turbulence as shown in Figure 3. It is worth to mention here that the turbulent level is also large in the regions that enclose the vortex-filament path.

It is expected that the turbulence kinetic energy would impact the blade's vortex-filament in a particular manner and thus, it would impact the aerodynamics of the rotorcraft. It is expected that the perpetual blade-vortex interactions the aerodynamic coefficients lift and drag would exhibit an oscillatory behavior based on the instant of the blade-vortex interaction.

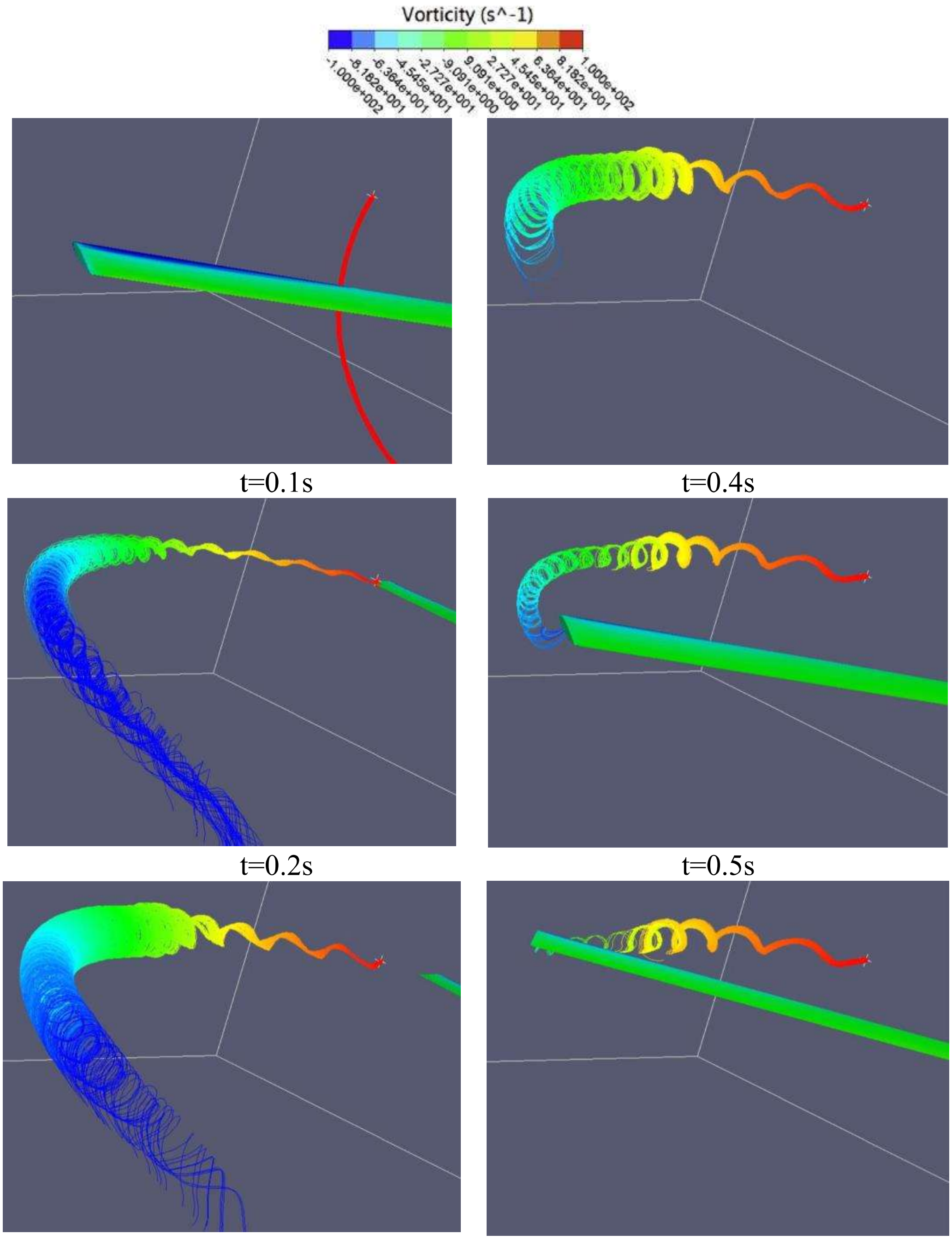


t=0.1s t=0.4s

t=0.2s t=0.5s

t=0.3s t=0.6s

Fig. 3. Turbulence kinetic energy



t=0.1s t=0.4s

t=0.2s t=0.5s

t=0.3s t=0.6s

Fig. 4. Blade-vortex interaction

Therefore, the aerodynamic coefficients would exhibit maximum and minimum values defined by the blade-vortex interaction phenomenon.

Figure 4 presents the transient unsteady behavior of the vortex filament, at different instants in time. Therefore, Figure 4, instant t=0.1s, presents the moving blade on a previously undisturbed flow path. As the blade passes the interrogation point, a vortex-filament is generated in the wake of the blade. As the time elapses, the vortex-filament increases in size and strength as shown in Figure 4, at instant t=0.3s. Figure 4, instant t=0.5s presents the interaction of the second with the vortex-filament generated by the first advancing blade, and this interaction represents the blade-vortex interaction phenomenon.

It is expected that the interaction between the rotorcraft blade and the vortex filament generates disturbance of the aerodynamic coefficients and this analyzed in the following. First the aerodynamic coefficients lift and drag are defined in the following. Therefore, the lift coefficient is defined as:

$$c_l = \frac{L}{\frac{1}{2}\rho_\infty U_\infty^2 l} \tag{1}$$

while the drag coefficient is given by:

$$c_d = \frac{D}{\frac{1}{2}\rho_\infty U_\infty^2 l} \tag{2}$$

In equations 1 and 2, L represents the lift force, while D represents the drag force ρ_∞ represents the flow density and U_∞ represents the free-stream velocity and l is the characteristic length.

Figure 5 presents the time-varying lift coefficient associated with the blade-vortex interaction. The analysis shows that the lift coefficient exhibits an oscillatory behavior due to the blade-vortex interaction phenomenon. However, the lift does not follow a smooth path but rather an inconsistent behavior and this is due to the non-linear behavior of the turbulence phenomenon.

Figure 6 presents the time-varying drag coefficient associated with the blade-vortex interaction phenomenon. The analysis shows that there is an increase of drag coefficient in the first part of the blade-vortex interactions and it is stabilizing as the BVI phenomenon develops further reaching an average value of 0.6.

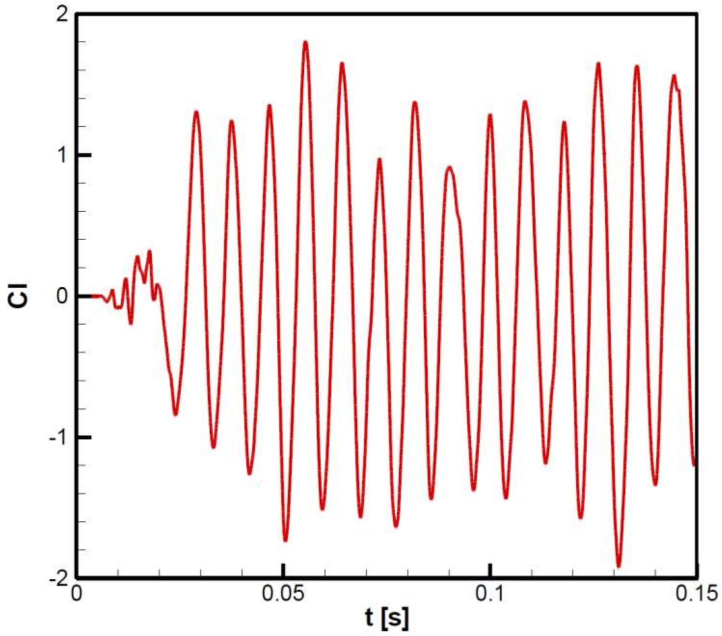


Fig.5. Time-varying lift coefficient

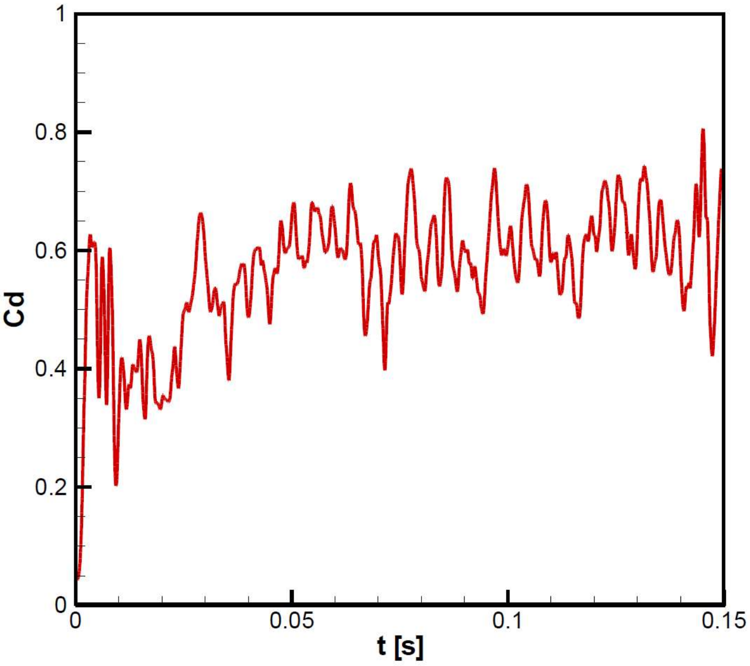


Fig.6. Time-varying pressure

Conclusions

A computational model is developed for the aerodynamic computations of helicopter aerodynamics in a rotating-frame of reference, using the large-eddy simulation (LES) computational approach. The analysis reveals that the large-eddy simulation approach captures very well the flow physics of the helicopter aerodynamics and aerodynamic coefficients. The analysis reveals the presence of the vortex-filament developed in the wake of the advancing-blade. The size and strength of the vortex filament increase with the time. The interaction between the vortex-filament and next advancing blade generates the blade-vortex interaction phenomenon. The BVI generates large disturbances of the flow field and implicitly of the aerodynamic coefficients. Therefore, the aerodynamic coefficients lift and drag exhibit an oscillatory behavior due to the BVI phenomenon. Also, due to the turbulence phenomenon, the oscillations of the aerodynamic coefficients exhibit a non-linear behavior. The study also shows that the large-eddy simulation computational approach is suitable for the computations of high-Reynolds number flows in a rotating-frame of reference.

REFERENCES

[1] Abelló, J. C., and George, A.R., 1999. Rotorcraft BVI Noise Reduction by Attitude Modification, 5th AIAA/CEAS Aeroacoustics Conference, Bellevue, Washington, May, 10-12

[3] Abello, J., George, A., 2003. Wake Displacement Study of Attitude and Flight Parameter Modifications to Reduce Rotorcraft Blade-Vortex Interaction (BVI) Noise, 9th AIAA/CEAS Aeroacoustics Conference, Hilton Head, SC, May 12-14

[4] Caradonna, F. X., Kitaplioglu, C., and McCluer, M., 1999, An Experimental Study of Parallel Blade–Vortex Interaction Aerodynamics and Acoustics Utilizing an Independently Generated Vortex," NASA Ames Research Center, TM 199208790, Moffett Field, CA

[5] M. Ilie, A. Semenescu, G. Liliana Stroe, S. Berbente, Numerical Computations of the cavity flow using the potential flow theory, Annals of the Academy of Romanian Scientists Series on Engineering Sciences, Volume 13, Number 2/2021, ISSN 2066-8570

[6] M. Ilie. "A computational model for cardiovascular hemodynamics and protein transport phenomena", Health and Technology, 2021

[7] M. Ilie, Augustin Semenescu, Matthew Chan. "Computational studies of turbine- stage, with variable inlet temperature; comparison between LES and IDDES", AIAA AVIATION 2021 FORUM, 2021

[8] M. Ilie, Matthew Chan, Jackson Asiatico. "Combustion instabilities in backward-step premixed reacting flows; computational studies using LES", AIAA SCITECH 2022 Forum, 2022

[9] Chen WL, Xin DB, Xu F, Li H, Ou JP, Hu H. Suppression of vortex-induced vibration of a circular cylinder using suction-based flow control. J Fluids Struct, 42:25–39, 2013

[10] J.C. Leong, N.M. Brown, F.C. Lai, Mixed convection from an open cavity in a horizontal channel, International Communications in Heat and Mass Transfer 32, 583–592, 2005

[11] Cattafesta L, Sheplak M. Actuators for active flow control. Ann Rev Fluid Mech, 43:247–72, 2011

[12] Choi KS, Jukes TN, Whalley RD. Turbulent boundary-layer control with plasma actuators. Philos Trans R Soc A,369:1443–58, 2011

[13] Genç MS, Açıkel HH, Akpolat MT, Ozkan G, Karasu I., Acoustic control of flow over NACA2415 airfoil at low Reynolds numbers. J Aerosp Eng, 29(6), 1-19, 2016

[14] Gissen, A.N., Vukasinovic, B., McMillan, M.L., Glezer, A., Distortion management in a boundary layer ingestion inlet diffuser using hybrid flow control. J. Propul. Power 30, 834–844, 2014

[15] Horner, M., Galbraith, R., Coton, F., 1996. Examination of Vortex Deformation during Blade-Vortex Interaction, AIAA Journal, Vol. 6, 1188-1194.

[16] Johnson, W., 1989. Calculation of Blade–Vortex Interaction Airloads on Helicopter Rotors, Journal of Aircraft, Vol. 5, 470-475.

[17] Jones G, Santer M, Debiasi M, Papadakis G. Control of flow separation around an airfoil at low Reynolds numbers using periodic surface morphing. J Fluids Struct, 76:536–57, 2018

[18] Jones G, Santer M, Papadakis G. Control of low Reynolds number flow around an airfoil using periodic surface morphing: a numerical study. J Fluids Struct, 76:95–115, 2018

[19] Gaetani, Paolo & Persico, Giacomo & Dossena, V. & Osnaghi, Carlo. (2007). Investigation of the Flow Field in a High-Pressure Turbine Stage for Two Stator-Rotor Axial Gaps—Part I: Three-Dimensional Time-Averaged Flow Field. Journal of Turbomachinery. 129. 10.1115/1.2472383.

[20] Kenneth S.Brentner, F. Farassat, Modeling aerodynamically generated sound of helicopter rotors