COMPUTATIONAL EVALUATION OF AIRFOILS WITH GURNEY FLAP

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Abstract

The Reynolds averaged incompressible flow solver implementation in open source CFD tool OpenFOAM is validated against flow over airfoil with gurney flap. The study is carried out by referencing the experimental data available in the literature for various airfoils that are suitable to be utilized in rotorcraft designs. The effects of gurney flap installation on the force and moment generation, velocity profile at the wake and pressure distribution on the airfoil are captured accurately compared to test results. The variation of the performance of the airfoils due to gurney flap installation is evaluated by commercial CFD software for different flow conditions in which Mach number varies from 0.3 to 0.9.

1. INTRODUCTION

Gurney flaps are small straight planar devices implemented at the trailing edge of the profiles, to gain higher lift. The two counter-rotating vortices formed downstream of the profile due to the separation occurred just upstream of the gurney flap modifies the Kutta condition at the trailing edge and enhances the lift characteristics. Dan Gurney and Robert Liebeck firstly introduced this miniature trailing device to improve the down force generation by race cars [1]. Gurney flaps are then used to enhance the maximum lift coefficient of airfoils and wings [2], and to improve the performance of the wind turbines [3].

The gurney flap installation also has potential in rotorcraft applications. Some potential improvements by deployable gurney flap designs on rotors are; autorotative characteristics enhancements [4], reduction of the peak-to-peak variations in hub loads[5], increment in figure of merit at higher thrust coefficients[6], extension of flight envelope by introducing a geometric profile compatible to both of high lift and transonic flow constraints[7]. Moreover gurney flaps are applied to the horizontal and vertical stabilizers of helicopters to increase the performance for high-powered climbs and high speed level flights [8].

Recently, an individually controlled rotor blade by the actuation of the small gurney flaps has become an attractive research area. Since gurney flaps have small area and weight their power requirement for actuation is low. Hence gurney flaps have taken lots of interest for their applicability in active control of rotor blade vibration. The demonstration and evaluation of the capabilities of active gurney flaps through the design of innovative rotor blades has also been studying by the European Commissions' FP7 Cleansky-Green Rotorcraft Project.

Advanced computational tools that can supply high fidelity aerodynamic models are required to evaluate the potentials of innovative rotor blade designs. Open source CFD tool OpenFOAM has promising features in terms of turbulence modeling, dynamic meshing and variety of available schemes. OpenFOAM has a big potential to be used as baseline for the development of the flow solver tailored specially for rotary wing aerodynamics. This study mainly aims to validate the available flow solvers in OpenFOAM for the evaluation of the flow over airfoil equipped with gurney flap.

2. FLOW SOLVER

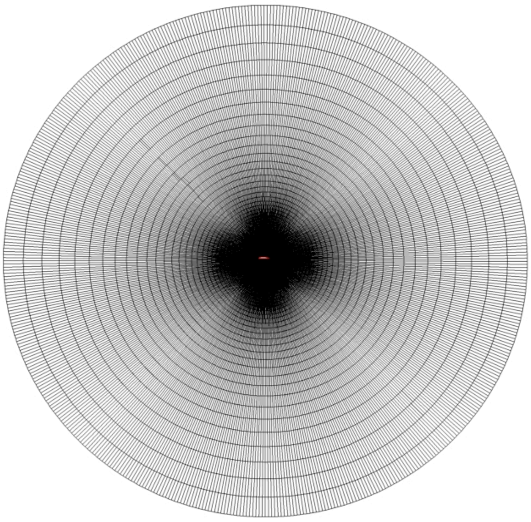
OpenFOAM is an open source library that includes numerous C++ classes for finite volume, finite element, and Lagrangian particle tracking. It also offers various solvers for different flow problems, however one of the main strength of the OpenFOAM is that new solvers and utilities can be created with a small effort by managing the available C++ classes. The usage of C++ in OpenFoam development enables advanced error checking, efficient memory management and robust utility executables.

OpenFOAM provides wide range of turbulence modeling options. RANS, URANS, DES and LES approaches are available with varying models. In industrial applications the time efficiency of the analyses are as important as capturing the complex details of the flow physics. Hence it is common in early stages of the designs of new rotors to perform aerodynamic analysis with simplified models. The simulation of the aerodynamics of the rotors by actuator disks or blade element momentum type boundary conditions are common simplified applications which requires database for aerodynamic sections utilized in the design of the rotor blades. In this study, evaluation of capability of commercial or open source CFD software in generation of accurate aerodynamic database for new designs applicable to rotorcrafts is aimed. Consequently RANS turbulence modeling is chosen as main approach for analysis airfoils with gurney flaps.

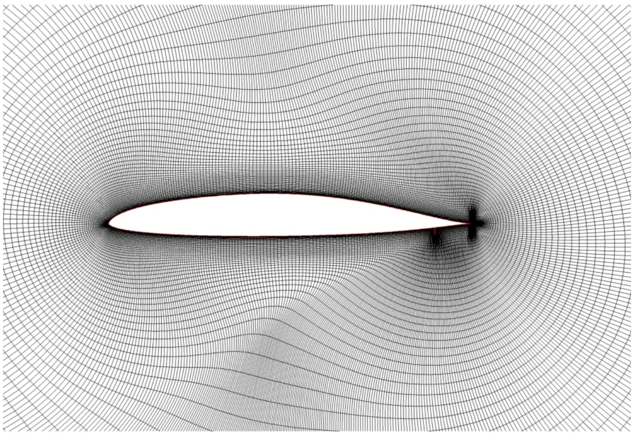
This paper will mainly present validation results evaluated by the incompressible RANS solver simpleFoam available within the official OpenFOAM distribution. SimpleFoam is a segregated solver based on SIMPLE pressure-velocity coupling algorithm. Analysis performed by the available compressible solvers did not exhibit consistent results in transonic regimes therefore the evaluation of the gurney flaps in transonic regimes is applied by coupled solver of the commercial software Fluent. This work will be extended in near future with the validation of the solvers tailored by the authors for different aerodynamic problems in rotorcraft applications.

3. GEOMETRY AND MESH

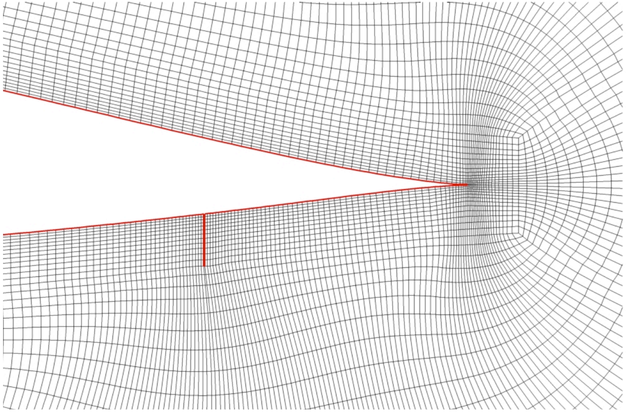
Various airfoils, applicable to rotorcraft applications, are analyzed with gurney flap configurations and evaluated results for airfoils at incompressible flow conditions are presented in this paper to demonstrate the capabilities of the open source solver. The height and chordwise location of the gurney flap are varied as design parameters. The numerically evaluated performance variations with respect to those design changes are compared to the ones captured by experiments in previous works available in literature.



a) far-field



b) near airfoil



c) mesh with 30<y+<50 near the trailing edge, Gurney flap installed at x/c = 0.9

Figure 1 Grid constructed around S903 airfoil

The wind tunnel measurements for NACA4412 and S903 airfoils are available for 2.2x10^6 [2], 1x10^6 Reynolds numbers, respectively[7]. Both experimental data presents the force, moment coefficient variation and pressure distribution change on the airfoil for different gurney flap heights and locations. The NACA 0012 airfoil equipped with the height of %2 chord length is analyzed computationally and evaluated velocity distribution in the wake is compared with the experimental data[9]. The NACA 23012 airfoil is analyzed for wide range of Mach numbers from 0.3 to 0.9 to figure out the variation of effect of Gurney flaps by changing Mach numbers.

Computational meshes are generated by the utilization of the commercial software POINTWISE. Highly orthogonal mesh over the airfoils is constructed by hyperbolical extrusion. Near wall treatment applications available in OpenFOAM are tested with meshes generated with varying first wall height parameters. The high Reynolds near wall treatment is utilized by the wall functions which output most accurate results with meshes whose y+ values vary from 30 to 50. For low Reynolds near wall treatment meshes with y+ values lower than 1 are generated. Figure 1 depicts an example grid used for analysis of s903 airfoils

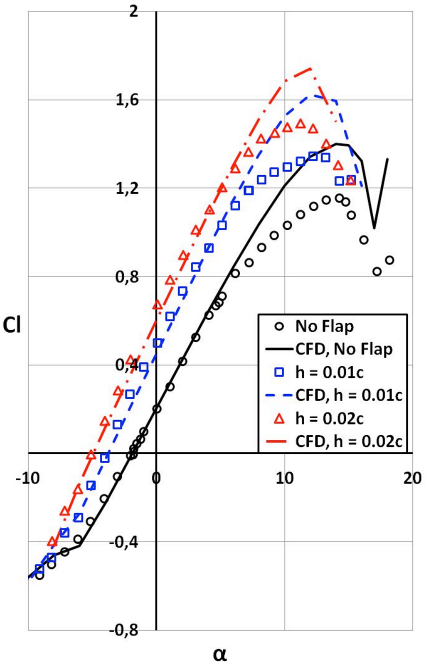
4. RESULTS

The variation of the lift, drag and moment coefficients by angle of attack are evaluated for the S903 and NACA 4412 airfoils equipped with gurney flaps by fully turbulent flow assumption for different flap heights. The solutions performed by k-kl-omega transition model at low angle of attack conditions, which are utilized with low Reynolds near wall treatment, resulted in fairly good drag estimation for S903 airfoil, which was experimentally tested at wind tunnel with low inlet turbulent intensity without trips. However consistent results for higher angle of attack cases could not be evaluated with that transitional turbulent model for varying computational mesh and varying boundary conditions. Moreover stall conditions are calculated prematurely when the k-kl-omega model is utilized and at high angle of attack cases convergence characteristics of the steady solver was very poor.

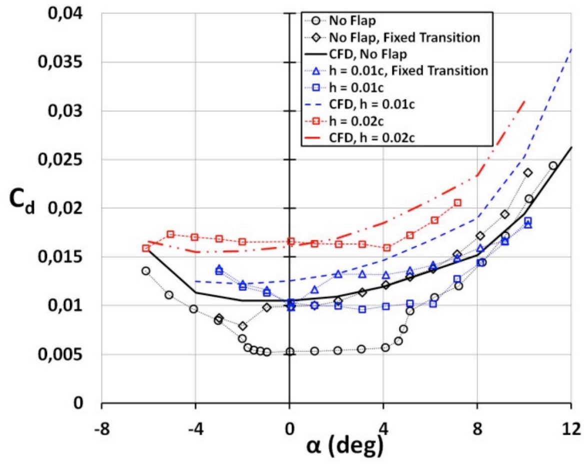
The Spalart Allmaras and kw-SST models are utilized with both of low and high Reynolds near wall treatment approach by varying the mesh resolution and the boundary conditions on the airfoil. Performing various simulations with varying meshes it was concluded that usage of wall functions for meshes whose y+ values are in between 30 to 50 can capture the force and moment coefficients of an airfoil satisfactorily although drag coefficient is evaluated higher compared to experiments due to the fully turbulent flow assumption.

Figure 2 presents comparison of evaluated force and moment coefficients by wind tunnel tests for s903 airfoil. The results are calculated by kw-SST turbulence model using the wall functions. The lift coefficient variation is captured acceptably well and effect of gurney flap height is reflected similar to the outputs of the wind tunnel tests. Computations predicted higher lift coefficient values at angle of attacks close to stall conditions. The applied turbulence model performed satisfactorily to capture drag coefficients, which are in agreement with the wind tunnel tests where transition is fixed. However, for free transition cases more effort is required in near wall physics modeling to evaluate accurate drag forces. The deficiency in the drag results compared to tunnel data also affected the accuracy of the moment coefficient predictions.

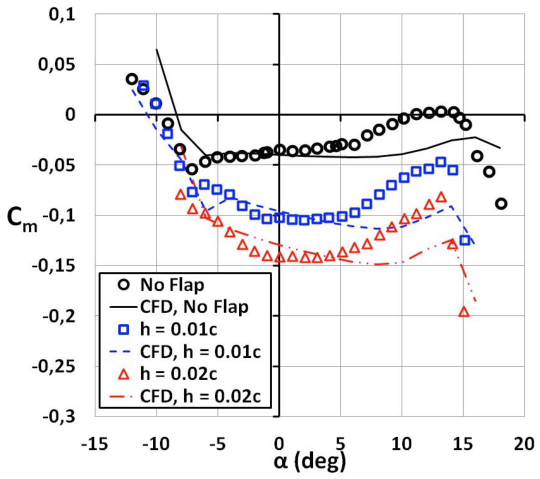
Figure 3 shows the variation of the additional maximum lift coefficient due to the gurney flap installation for different flap sizes and locations. Two different gurney flap heights, which are equal to 0.01c and 0.02c, are tested at three different locations. The computationally evaluated variation of the maximum lift coefficient shows very good agreement with the results obtained from wind tunnel tests. Figure 4 presents variation of pressure coefficient through the chord for s903 airfoil equipped with gurney flap whose height is 2% chord length. The evaluated results are compared with wind tunnel tests for two different cases where flaps are installed to the trailing edge and 90 percent chord locations. In each case, computationally evaluated pressure distribution shows good agreement with the wind tunnel tests.



a) varition of lift coefficient



b) varition of drag coefficient



c) varition of moment coefficient

Figure 2 Effect of gurney flap on force and moment coefficients of S903 airfoil

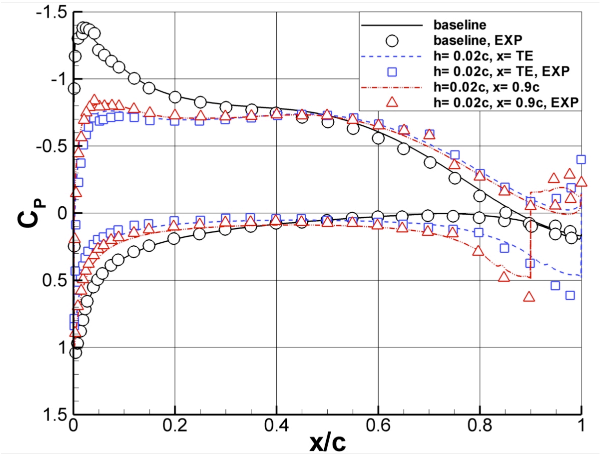


Figure 3 Effect of gurney flap on Cp distribution on S903 airfoil

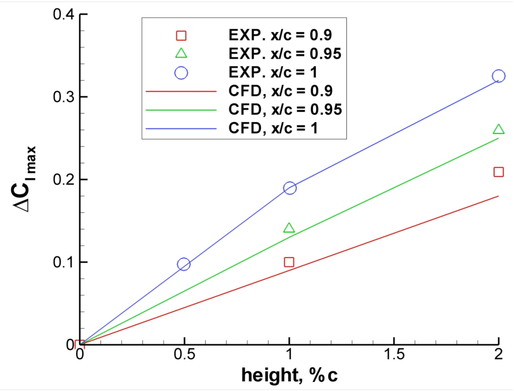
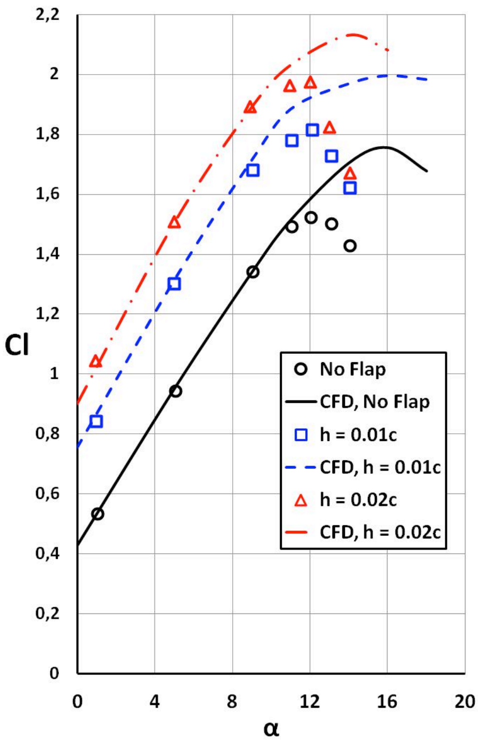
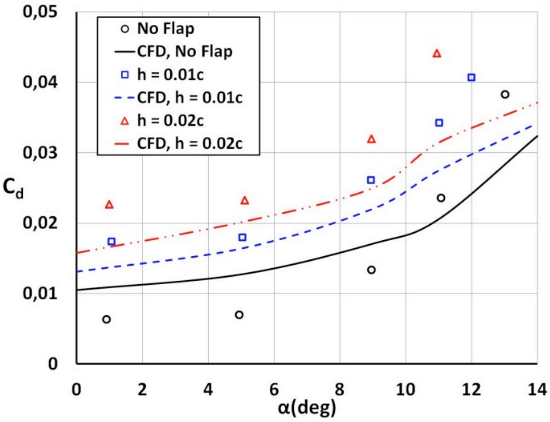


Figure 4 Effect of gurney flap on C_{lmax} for S903 airfoil

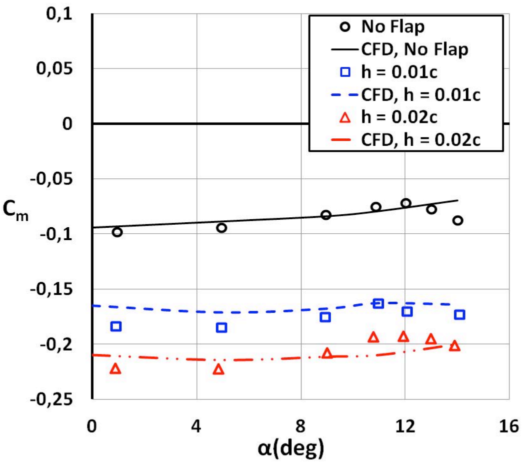
Figure 5 depicts the comparison of numerical results evaluated for NACA 4412 airfoil with wind tunnel data. The effect of gurney flap installation at the trailing edge is investigated for two different gurney flap heights. Similar to results evaluated for S903 airfoil, the variation of the lift coefficient is predicted in agreement with the experiments for baseline airfoil and ones equipped with gurney flaps whose heights are 1% and 2% chord length. There are some deficiencies in calculated drag and moment coefficients due to the followed near wall treatment approach. Figure 6 presents the pressure coefficient comparison between the experimental data and present computation of NACA 4412 airfoil with 1 % chord height gurney flap. The numerical results are in well agreement with the experimental data. Figure 7 shows the comparison of the numerically evaluated results with experiments for the variation of the maximum lift coefficient of NACA4412 airfoil equipped with different size of gurney flaps at the trailing edge. Numerical calculations capture the effect of the gurney flap installation on the lift coefficient almost exactly.



a) varition of lift coefficient



b) variation of drag coefficient



c) variation of moment coefficient

Figure 5 Effect of gurney flap on force and moment coefficients of NACA 4412 airfoil

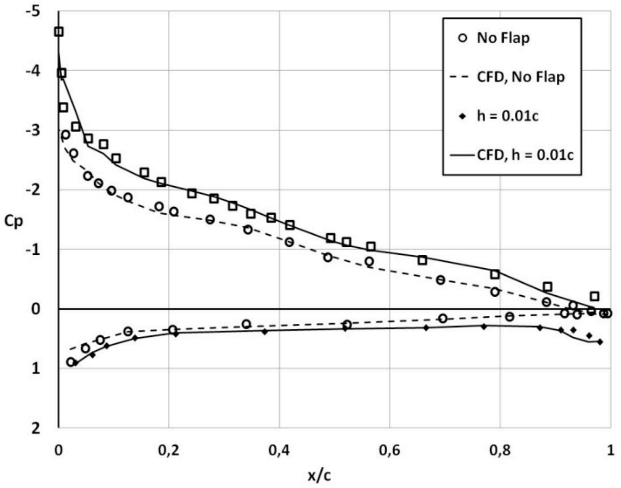


Figure 5 Effect of gurney flap on Cp distribution on NACA 4412 airfoil

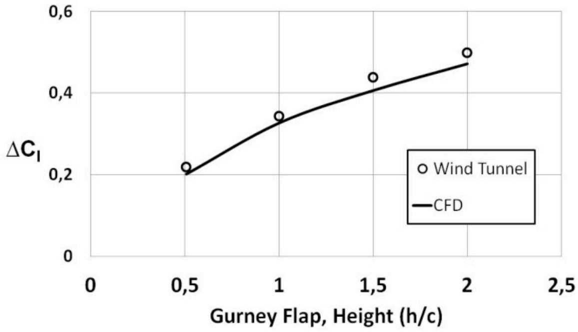


Figure 6 Effect of gurney flap on C_{lmax} for NACA 4412 airfoil

Besides comparing the evaluated force and moment coefficients with experimental values for validation purpose, the evaluated velocity profile at the downstream of the gurney flap installed on the NACA 0012 airfoil is also judged against test data. Figure 7 presents the velocity profiles evaluated at 0.7 chord length downstream of the NACA 0012 airfoil at zero angle of attack flow conditions. The height of the gurney flap is equal to the 2 percent of the chord length. The numerical evaluations are performed with k-kl-omega turbulence model with a mesh whose y+ value is lower than 1. The numerically calculated velocity profile behind the baseline and gurney flapped airfoils compares very well with the experimental data. The vertical shift in the velocity profile due to the gurney flap is captured satisfactorily.

The incompressible flow solver simpleFoam predicted the characteristics of the airfoils equipped with gurney flaps successfully. However using the available segregated compressible solvers in the OpenFOAM software, consistent results could not be obtained at transonic flow regimes. The effects of gurney flap installation on airfoil at wide range of subsonic and transonic Mach numbers are evaluated by utilizing the coupled solver of the commercial software Fluent.

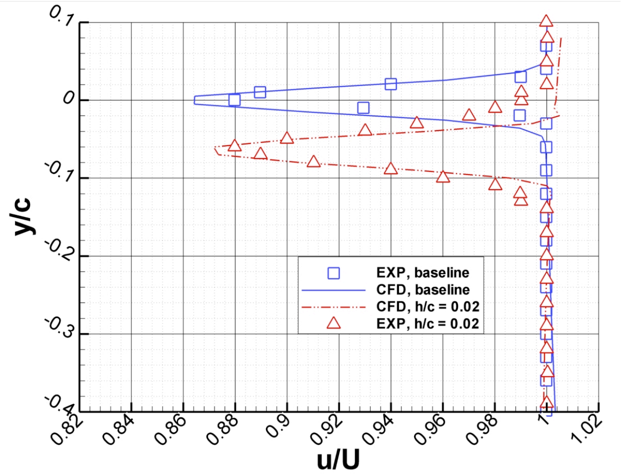


Figure 7 Velocity profile in the wake of NACA 0012

The airfoil sections of the rotor blades are exposed to varying Mach numbers during the operation. Hence effects of gurney flaps on the airfoil performance should be examined for varying flow conditions, to be able to have some insight for the effect of those devices on the resultant performance of the rotor. Figure 8 presents the variation of the lift coefficient of NACA23012 airfoil by angle of attack for different mach numbers. Similar to incompressible conditions, the gurney flap enhances the lift production in the compressible regime also. The gain of lift improved when the height of the flap is increased from 1 percent chord to 2 percent chord length. Figure 9 presents the effect of gurney flap installation on the NACA23012 airfoil in terms of change of lift to drag ratio at wide range of flow conditions with varying Mach number. Evaluated numerical results show that gurney flap whose height is 2 percent of the chord length does not introduce any lift to drag ratio improvement for Mach numbers below 0.7 whereas for higher Mach numbers it enhances the performance. Deeper evaluations for the effects of gurney flaps at varying flow conditions faced by rotors will be performed in near future with a developed coupled solver in OpenFOAM which can handle wide range of flow speeds in compressible regime.

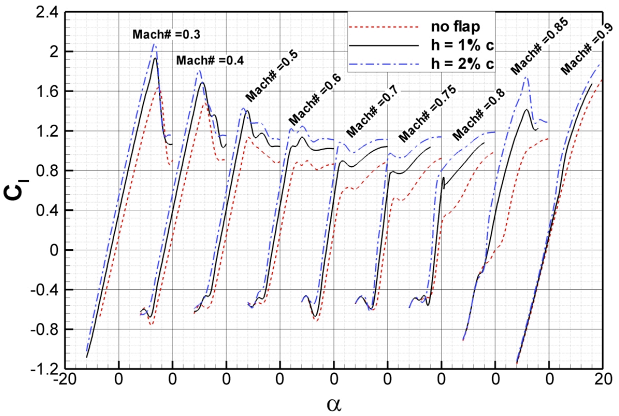


Figure 8 Effect of gurney flap on lift coefficient of NACA 23012 airfoil for varying Mach numbers

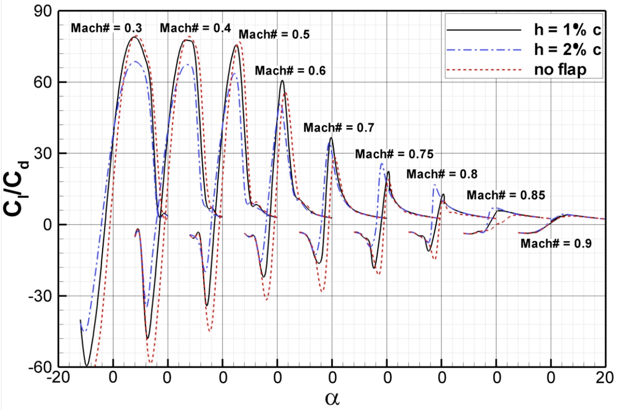


Figure 9 Effect of gurney flap on lift to drag ratio of NACA 23012 airfoil for varying Mach numbers

CONCLUSION

The simulations performed up to now demonstrated that OpenFOAM is valuable open source tool that has potential for numerical evaluation of new aerodynamic designs with satisfactory accuracy. However improvements are required in the field of turbulent modeling with transition capturing and compressible flow solution with a coupled solver. In both fields the community using open source software has made some progress already. The authors are planning to tailor the available libraries in OpenFOAM for an efficient solver applicable to rotorcraft aerodynamics. Detailed design alternative evaluation studies and validation efforts will be performed with customized OpenFOAM solvers in near future.

REFERENCES

[1] Liebeck RH. “Design of subsonic airfoils for high lift,” *Journal of Aircraft*, 1978, Vol. 15, No. 9, pp. 547–61.

[2] Storms, B. L., Jang, C. S., “Lift Enhancement of an Airfoil Using a Gurney Flap and Vortex Generators,” *Journal of Aircraft,* Engineering Note, Vol. 31, No. 3, May-June 1994, pp. 542-547.

[3] Kentfield, J. A. C., “Theoretically and Experimentally Obtained Performances of Gurney-Flap Equipped Wind Turbines,” *Wind Engineering*, Vol. 18, No. 2, March 1994, pp. 63-74.

[4] Min, B. Y., Sankar, L. N., and Yu, Y. H., “Computational Studies of the Effects of Gurney Flaps on the Autorotative Performance of Rotors in Descent Flight,” AHS Aeromechanics Specialists Meeting [CD-ROM], AHS International, Alexandria, VA, Jan. 2008

[5] Min, B. Y., Sankar, L. N., Rajmohan, N. and Prasad, J. V. R., “Computational Investigation of Gurney Flap Effects on Rotors in Forward Flight”, *Journal of Aircraft, Vol. 46, No. 6,* November–December 2009, pp. 1957-1964

[6] Thiel, M. R., Lesieutre, G. A., Maughmer, M. D., Koopmann, G. H., “Actuation of an Active Gurney Flap for Rotorcraft Application,” AIAA 2006-2181, May 2006.

[7] Kinzel, M. P., “Miniature Trailing-Edge Effectors for Rotorcraft Applications,” M.S. Thesis, Department of Aerospace Engineering, The Pennsylvania State University, University Park, PA, Aug. 2004

[8] Roesch P, Vuillet A. New designs for improved aerodynamic stability on recent Aerospatiale helicopters. Vertica 1982;6:145—64

[9] Wang, J. J., , Li,Y.C., Choi, K.-S., “Gurney flap—Lift enhancement, mechanisms and applications,” Progress in Aerospace Sciences, Vol. 44, Issue 1, January 2008, pp 22-47