INVESTIGATION ON THE EFFECT OF HYDRODYNAMIC MEMS ON AIRFOIL

András Nagy*, József Rohács*, Tamás Régert**
***Budapest University of Technology and Economics, Department of Aircraft and Ships,**
****Budapest University of Technology and Economics, Department of Fluid Mechanics**
H-1111 Budapest, Hungary

Keywords: *Flow control, Airfoil, MEMS, CFD*

Abstract

This paper is about 2 investigations, in which the effect of the hydrodynamic Mini Electro-Mechanical Systems (MEMS) on airfoil has been investigated. The selected airfoil has been the NACA4415 with some modifications. In the first part of this paper the effect of the hydrodynamics Helmholtz resonator used near the leading edge of the airfoil has been investigated under steady and unsteady condition. In the second part, the mini tailing edge (mini-TE) flap (some called Gurney flap) has been investigated. The results have shown that the devices applied here are unsuitable to use as High Lift Device (HLD) in the way applied here. But it has been found that in some other applications they are able to generate positive effects, for instance they are able to increase the gliding ratio at lower angle of attack (typically under 4 degree).

1. Introduction

The most recent achievement in science and technology is to develop, analyze and use micro and Mini Electro-Mechanical Systems (MEMS) [10, 11, 12]. The technology called MEMS opens several possibilities in aeronautical engineering, too. Nowadays intensive researches are going on in connection with MEMS technologies. Theoretical and experimental researches are in progress on changing aerodynamics parameters of airflow by MEMS [13, 14, 15, 9]. In the recent paper, the emphasis has been laid on studying the feasibility of controlling airflow around the airfoil NACA 4415 by small size elements, by which the force distribution can be controlled.

The effect of jet close to the leading edge at the upper surface of the airfoil has been investigated by numerical manner. The first investigation has been performed on blowing out air into cross flow (static jet). The results showed that this device can improve drag coefficient significantly at low angle of attack. As the outlet gap of jet stream is closer to the leading edge, the lift coefficient can not decay significantly. In the second stage of the investigation the blowing is unsteady, MEMS with moving membrane have been used. The MEMS can only affect the boundary layer because of its micro size [7].
The third stage of this paper the effect of the Gurney flap has been investigated. There are a lot of article in which this device has been investigated [e.g 17]. The new idea in this paper is the investigation on the effect of oscillating mini TE-flap.

The results of this article are to be regarded as preliminary investigation. Any conclusion can only be drawn after comparison with the results of wind tunnel experiments [e.g 3, 4].

2. Investigation of the effect of static jet close to the leading edge at the upper surface of the airfoil

The CFD software applied here is the Fluent 6.2.16. For all the computations published in this paper the selected turbulence model is the SST k-ω, which is the only one in Fluent that is able to catch the point of laminar-turbulent transition correctly [2]. The turbulent length scale is set to 2 mm and the turbulent intensity is set to 1 % on velocity inlets [5, 1].

2.1 The model

The computational model and its mesh are shown in Figure 2. Structured mesh has been applied, which has 44871 cells. The size of the first cell next to the airfoil is 0,03% of the chord length in order to resolve the boundary layer enough for the turbulence model. The velocity of the jet is chosen to be 30 m/s, the airflow velocity is chosen to be 20 m/s. The Reynolds number can be determined by the mentioned data, thus Re = 400000. All cavities for the jets are normal to the chord line of the airfoil as it is manifested in Figure 2. Only one of the cavities is enabled at the same time, the others are disabled. This way it is enough to create only one model for the investigation which shows the difference between the different locations. The effect of the simultaneous use of multiple jets is not investigated in this work.

The reference values are:

- Wing area: $A = 0{,}24\ m^2$
- Velocity: v = 20 m/s
- Pressure: p=101325 Pa

The boundary conditions of the whole numerical space are shown in Figure 1. The angle of attack can be set by the direction of the velocity inlet. At the outflow only the diffusion terms of the equations are set to zero, the convective terms and the pressure are extrapolated from the interior of the domain.

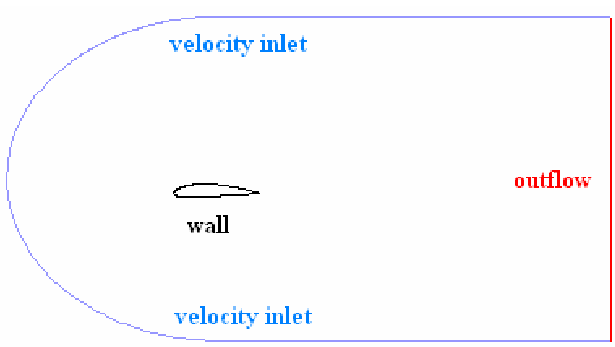

Fig. 1 Boundary conditions

The boundary condition near the 3rd cavity is shown in Figure 3.

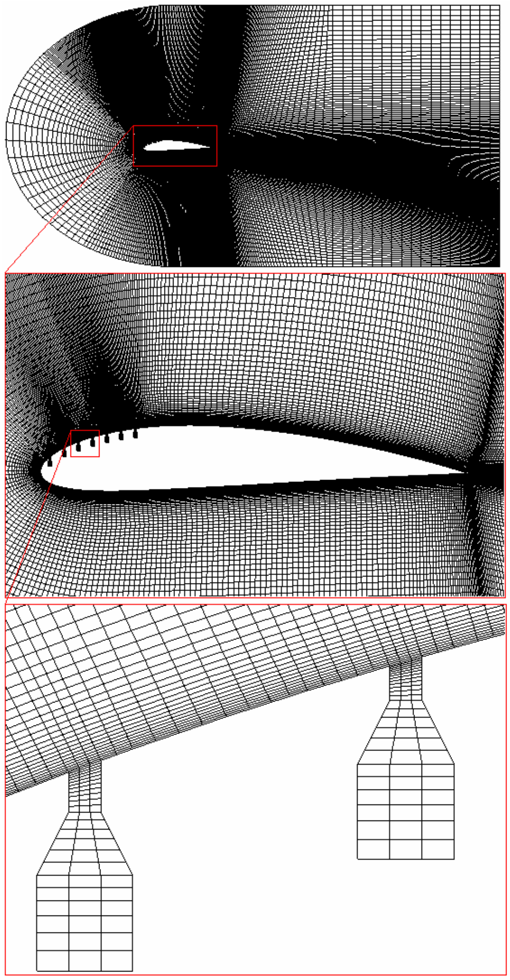

Fig. 2 The applied model and its mesh

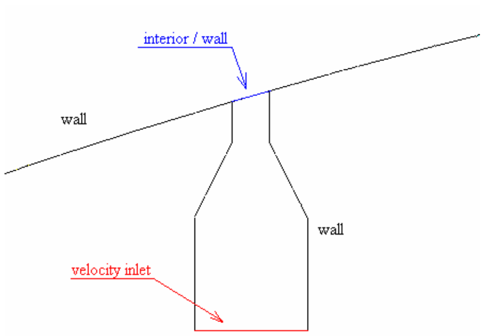

Fig. 3 Boundary conditions near the 3rd cavity

If the cavity given is enabled, the top of the cavity has interior boundary condition to pass the airflow smoothly, but in the other case (if it is disabled) it has no-slip condition.

2.2 Results

One of the results of this investigation is shown in Figure 5. The drag coefficient is reduced by the static jet on 2nd and 4th hole. At lower angles of attack (<3deg) the reduction is greater and there is an exact angle of attack at each hole, at which the drag is equal to the basic airfoil (where the curve intersects the red curve). Other result is shown in Figure 4. These figures (Fig.4 - Fig.5) are made with the same legend, which is shown in Figure 5.

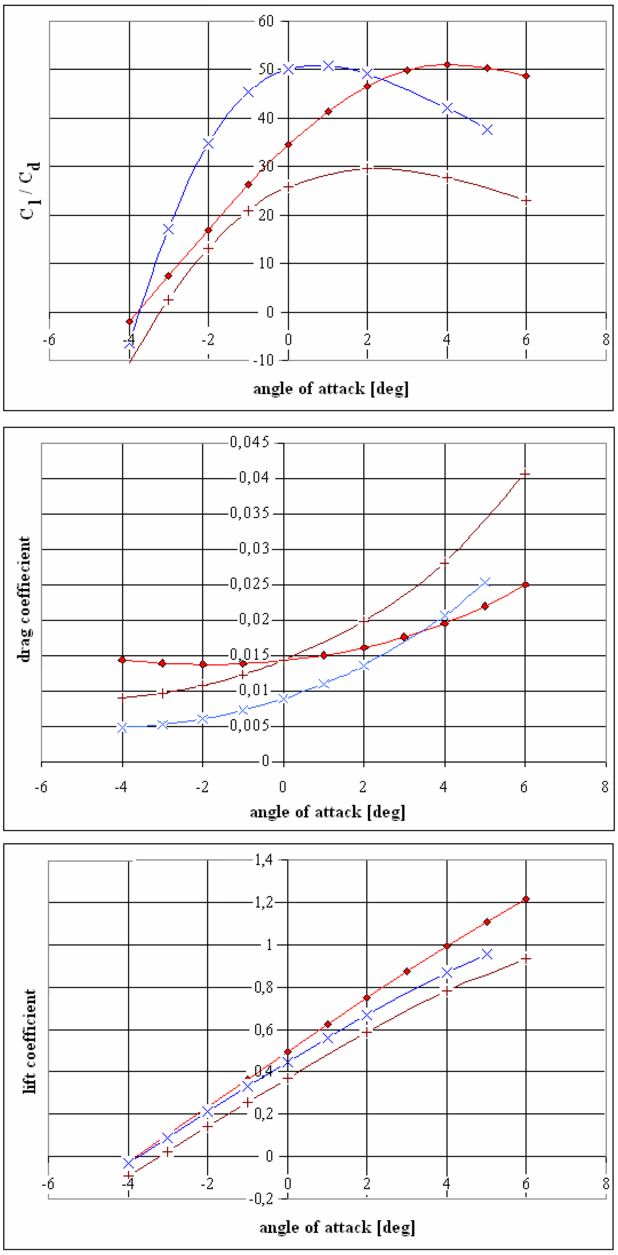

Fig. 4: Results of investigation of the effect of static jet, legend in Fig.5

It is also seen in Figure 4 that lift coefficient always decrease due to the application of the static jet.

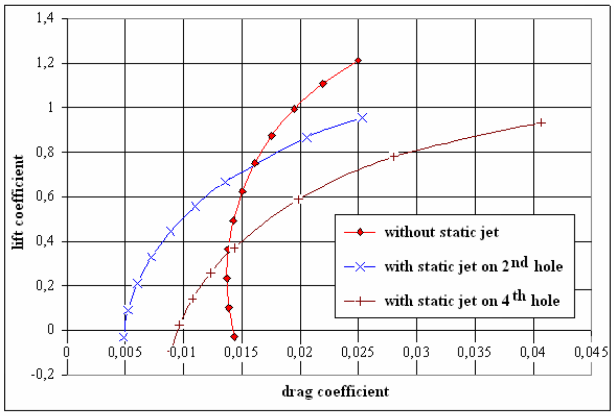

Fig. 5: Polar curve with and without static jet

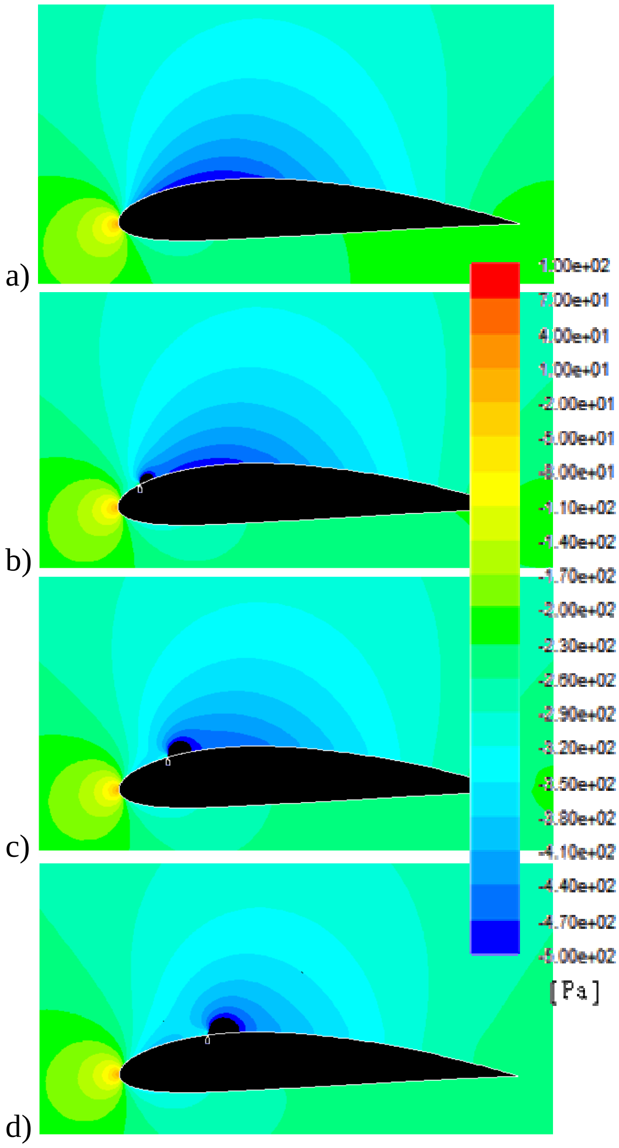

Fig. 6:
Static pressure distribution around NACA 4415 airfoil:
a) Without static jet; b) With static jet at 2nd cavity;
c) With static jet at 4th cavity; d) With static jet at 7th cavity

In Figure 6 the reason of dropping is shown at 2 degree angle of attack.
The problem is that the static jet deflects the flow in front of itself, the flow velocity is dropped, hence the static pressure is increased. It means that the lower pressure above the upper surface, which causes 2/3 of lift force, is reduced. It is clearly seen in Figure 6.
The reduction of the static pressure causes the reduction of the lift force. This can be seen in Figure 7, in which the static pressure is a function of the chord length.

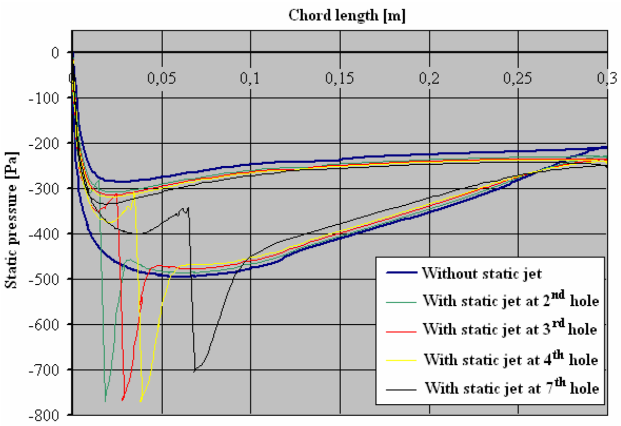

Fig 7: Pressure distribution around the airfoil as a function of chord length

It seems that this conception is unsuitable for building High Lift Devices (HLD). The effect of other HLD construction can be seen in other papers [e.g 6, 8]. The further from the leading edge the jet is, the more it reduces lift coefficient. At least the c_l/c_d quotient is bigger at the 2nd hole than at the basic airfoil at lower angle of attack (<2 deg), thus the next investigation (hydrodynamic Helmholtz resonator) is focused on this cavity.
It must be recognized that the applied model has the same effect than a deflector near the leading edge. In both cases a big lateral vortex is developed which can not be significantly big (relative to the chord length) because of the effect of the accelerated flow. The investigated construction can be imagined in 3D as a deflector or a jet from a slot run along the wing. But in 3D the flow is become 3D, so some cross vortex could be developed quickly.

3. 2D investigation of hydrodynamic Helmholtz resonator

The hydrodynamic Helmholtz resonator is a so-called zero-mass-device because it does not change the mass flow rate around the wing. It has a very simple build up which is shown in Figure 8, the piezo crystal is flexed by voltage and hence the membrane is flexed, too. It can reduce or improve the volume of the cavity and so a jet across the hole is evolved. In the first stroke, this construction sucks the air in and in the second stroke it blows it out.

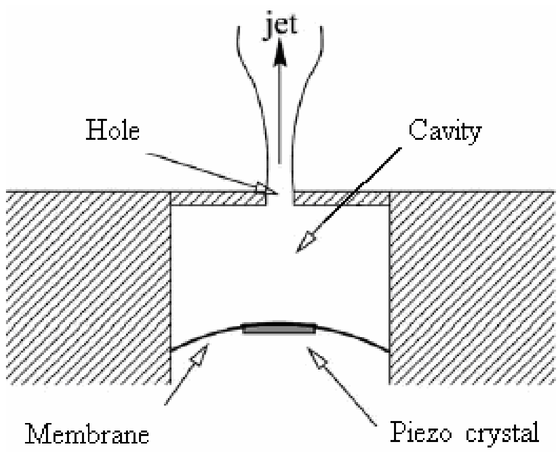

Fig. 8: The theoretical construction of hydrodynamics Helmholtz resonator [18]

3.1 The applied model and the results

The model of this device is the same as in chapter 2 (it is shown in Figure 2), but in this case the velocity inlet at the bottom of the cavity has got time dependent velocity profile. This function is shown in Figure 9.

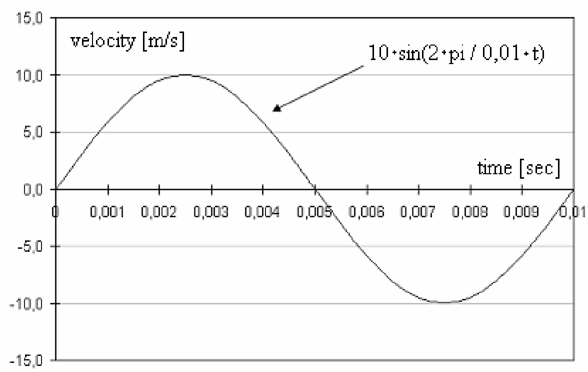

Fig. 9: One period of time depend velocity

The positive half-period is the blow out while the negative is the suck in, the resultant mass flow through the hole is zero. The operation frequency of the device is chosen to be 100 Hz. Results are shown in Figure 10 and 11. It can be seen in the first figure that the distance of the cavity does not affect its effect on the lift coefficient significantly. In the latter figure the dropping of the lift coefficient can be seen. It means this device is unsuitable to use as HLD.

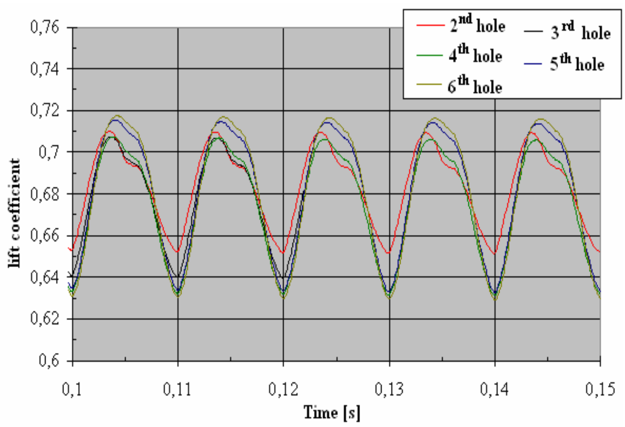

Fig. 10: Variation of the lift coefficient in time (5 periods), angle of attack: 2 deg

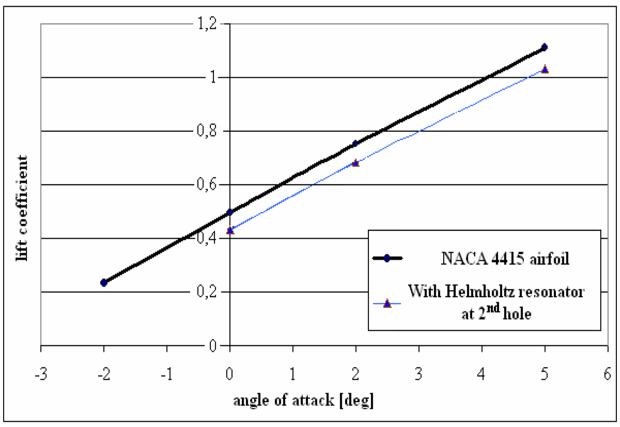

Fig. 11: c_l (α) curve with and without Helmholtz resonator

4. Mini flap at the trailing edge of the airfoil

A new model has been created for this investigation. The modified airfoil is shown in Figure 12. The mini flap at the trailing edge is also seen in the figure. It is built up by 6 elements which can be defined either as interior or wall. The size of each element is 1 mm.

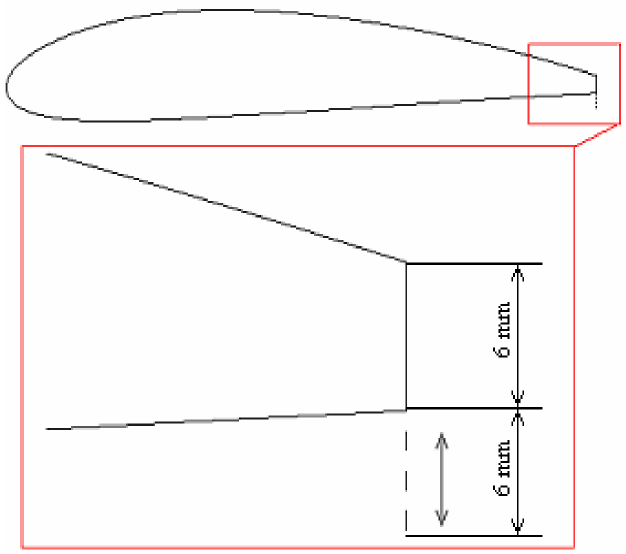

Fig. 12: Modified airfoil and the geometry of mini flap

4.1 The applied model

The model and its mesh are shown in Figure 13. Structured mesh has been used for the model, the number of the cells is 45520. The first investigation is to determine the effect of the mini flap when it is fully opened. In this part of the investigation flow velocity is set to 20 m/s, the Reynolds number is 345000. The size of the flap is 2% of the chord length, hence it operates inside the boundary layer. This way it does not cause too big drag force. This type of flap is usually called Gurney flap which is applied in aerodynamics, for instance to increase effectiveness of aileron on aircraft.

The use of the Gurney flap increases the loading along the entire length of the airfoil with a large increase in trailing-edge loading [16]. The Gurney flap is an intriguing device for high-lift design because of the mechanical simplicity of the device and its significant impact on aerodynamic performance. Subsonic aircraft could greatly benefit from the use of this simple flat-plate device.

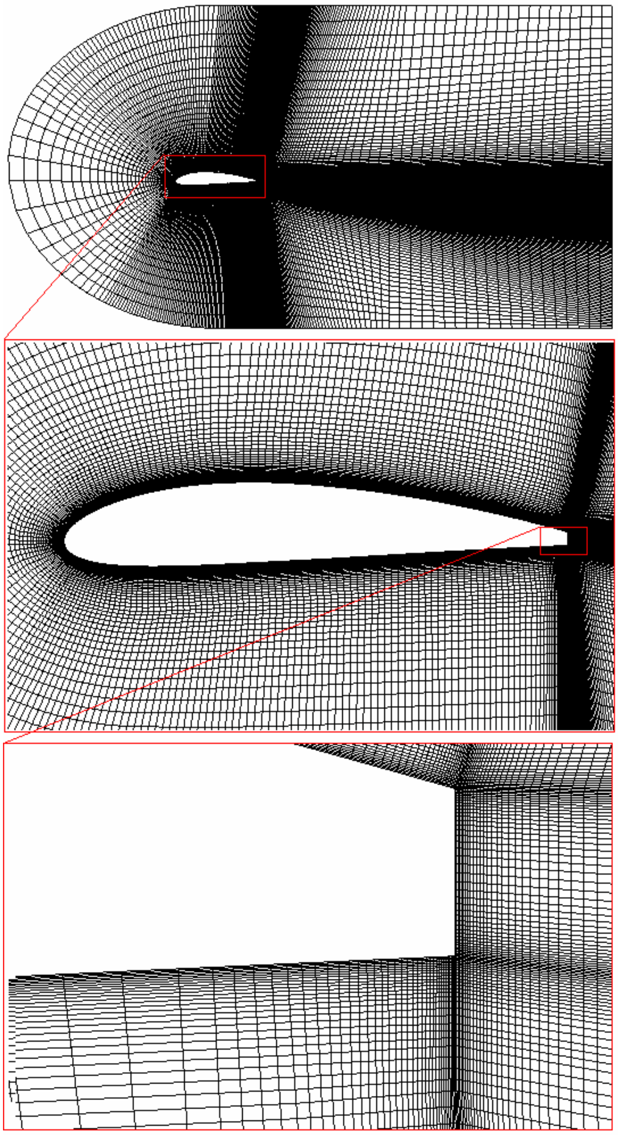

Fig. 13: Model and mesh for investigation of mini flap

4.2 Result

In Figure 14 the result of the fully opened mini flap is shown. It can be seen that both lift coefficient and drag coefficient are incremented in large measure. At 4 deg angle of attack lift coefficient is increased by 50% and drag coefficient is increased by 100% at the same angle of attack. This way lift force can be increased but for HLD this device is unsuitable because of drag increased considerably.

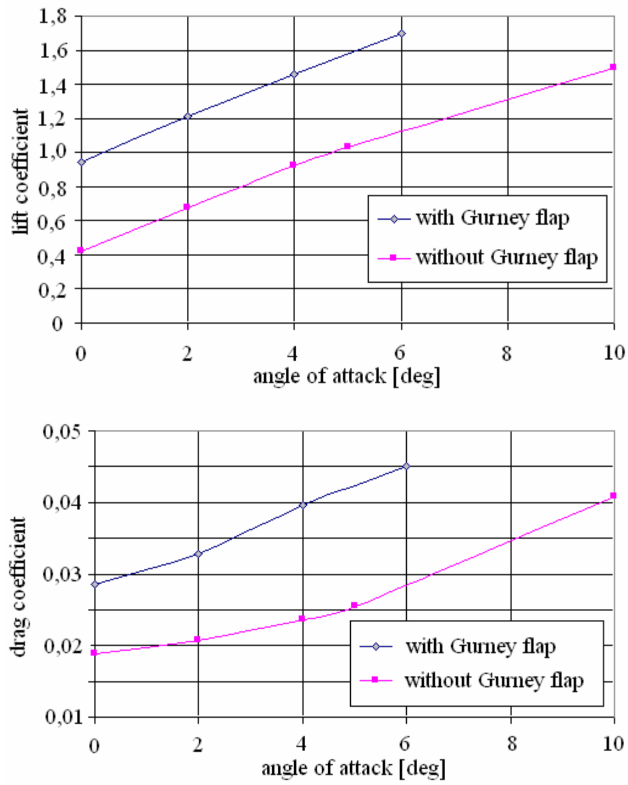

Fig.14 Result of the effect of Gurney flap:
Lift coefficient vs. angle of attack
Drag coefficient vs. angle of attack

Next, the effect of the oscillating mini TE-flap is investigated. The oscillation of the flap is realized by a journal file, which is built up from Fluent macros. So a journal file has been created and executed to do the unsteady investigation. The flowchart of the journal file is shown in Figure 15.

The results of this investigation are shown in Figure 16, in which the time depending of the lift coefficient is shown at 3 angles of attack (2, 5, 10 deg), with and without oscillating mini TE-flap. It can be seen that lift force is increased at all investigated angle of attack. The frequency of the oscillation is 42 Hz and flow velocity is 20 m/s. The first part of the diagram is the transition state of the iteration between the steady and the unsteady numerical space so it does not appear in the diagram because it is irrelevant in this paper. Hence the vertical axis does not intersect the horizontal axis in the pole, they intersect each other at the value 0.06 sec on horizontal axis.

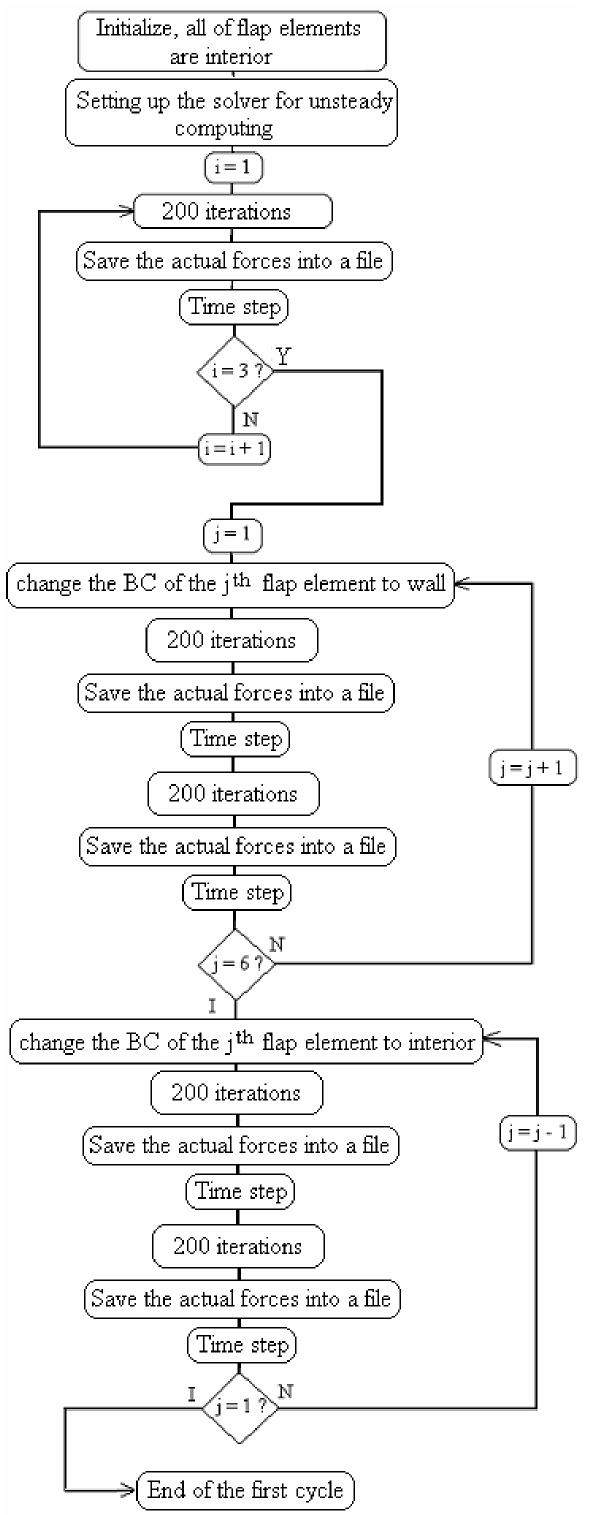

Fig. 15: Script file for investigation of oscillating mini TE-flap

There are 4 blue marks in Figure 16 (a, b, c, d), the static pressure distribution around the airfoil in these moments is shown in Figure 18. It consists of 4 figures (a, b, c, d) which are encoded by the same color.

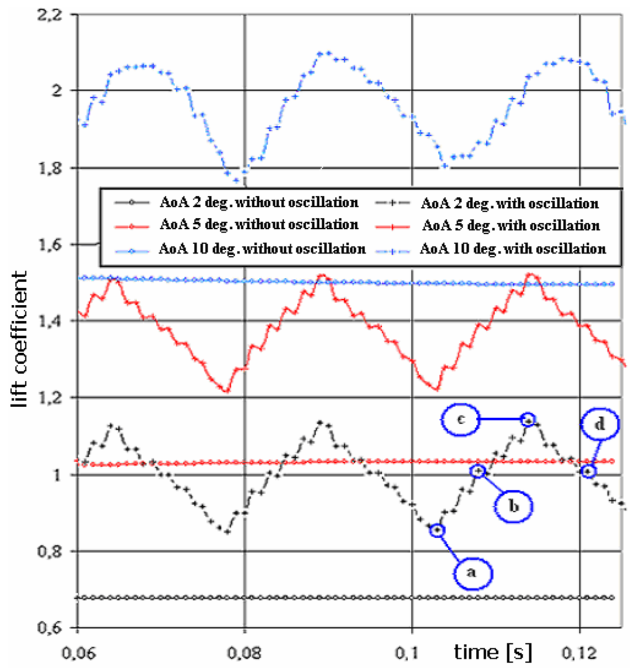

Fig. 16: Variation of the lift coefficient in time with and without oscillating mini TE-flap at 3 different angle of attack

It can be seen from the results that the oscillation of the mini TE-flap does not give positive effect.

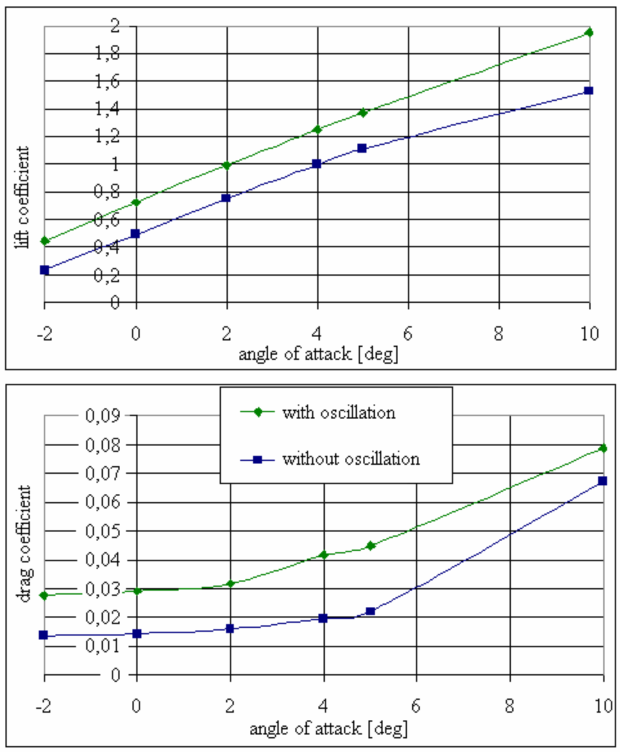

Fig. 17: Results of investigation of oscillating mini TE-flap effect
Lift coefficient vs. angle of attack
Drag coefficient vs. angle of attack

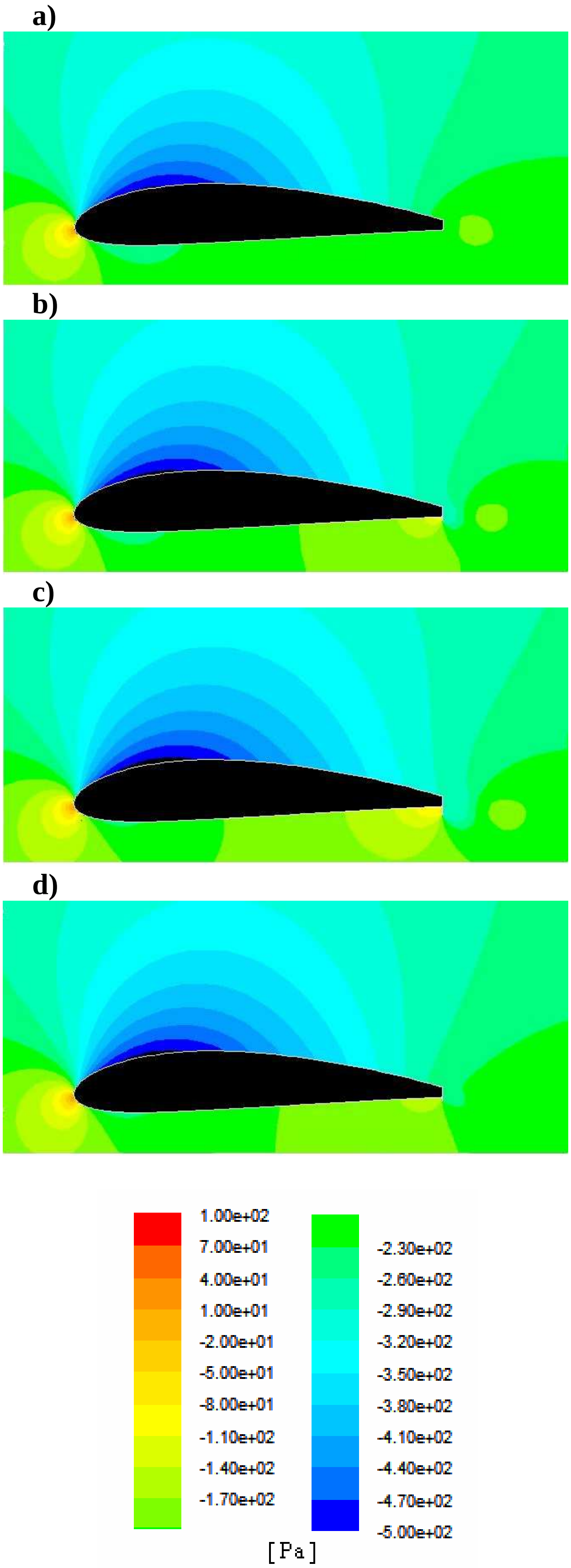

Fig. 18: The static pressure distribution around the airfoil at the marked moments of figure 16. The angle of attack is 2 degree.

Lift and drag coefficient caused by the oscillating mini flap are shown in Figure 17 at different angles of attack. Both lift coefficient and drag coefficient are increased, for instance at 4 deg the former by 25% the latter by 50%. It means that the oscillating mini flap can not be applied as a High Lift Device because of drag increased seriously, it is unprofitable economically.

In the previous part of this investigation the lift variation at the same frequency of oscillation and at various angles of attack is discussed. The frequency of oscillation of mini TE-flap was 42 Hz and it was fixed. In the next investigation the angle of attack is fixed to 2 deg and the effect of various frequencies of oscillation of mini TE-flap is discussed. The frequency investigated is 14Hz, 20 Hz, 42Hz and 83 Hz. The result is shown in Figure 19. It can be seen that the oscillation frequency does not affect lift force significantly. The highest frequency which is investigated is 83 Hz, the lowest is 14 Hz. The difference between the time-averaged lift coefficient in the two cases is just 6 %, so it seems that increasing frequency is redundant. The amplitude of the variation is about the same.

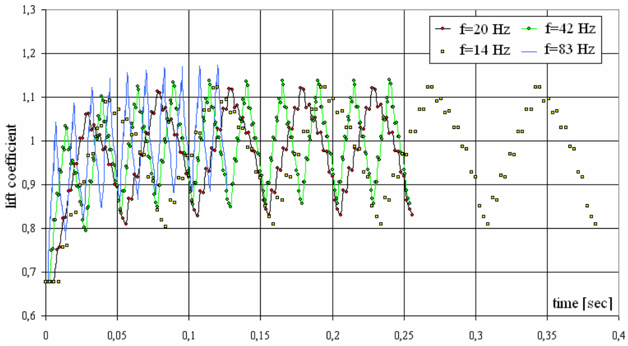

Fig. 19: The effect of the various oscillation frequency

5. Summary

In this article 3 different models were built for numerical investigation and they were investigated. All of them were based on the NACA4415 airfoil. For numerical investigation the CFD code used was the Fluent with Gambit, the turbulence model selected was the SST k-ω. The aim of the investigations was to find alternative opportunities to increase the lift of an airfoil at low speed. This function is being successfully done on conventional aircraft by High Lift Device (HLD), among others leading edge and trailing edge flaps.

The first investigation was about blowing out air into cross flow (static jet). The results showed that this device could not increase lift force, so it was unsuitable to use as HLD, however, the maximal glide ratio could be shifted to lower angle of attacks.

The next investigation was about the effect of hydrodynamic Helmholtz resonator close to leading edge. This is a MEMS device, which consumes extremely low power for operation. The results showed that it could not be used as HLD on the investigated place.

In the last part of the paper the mini flap at the trailing edge of the airfoil (mini TE-flap) has been investigated as a static opened flap and as an oscillating flap. Both investigations gave about the same result: lift force was increased but unfortunately drag was increased significantly, too. Although it was able to increase the lift force it was unsuitable as HLD. Operation frequency did not affect lift force seriously.

The results of this article are to be regarded as preliminary investigation. Any conclusion can only be drawn after comparison with the results of wind tunnel experiments.

6. References

[1] J.H. Ferziger, M.Peric : Computational Methods for Fluid Dynamics. *Springe*

[2] WILCOX D. C.: Turbulence Modelling for CFD. *DCW Industries ISBN 0963605151*, 1998.

[3] NACA Report No.824

[4] JAVAFoil software: http://colaco.freeshell.org/mhepperle/javafoil/jf_applet.htm

[5] Fluent manual, *Fluent Inc.* 2006

[6] Dr. W. Mason, http://www.aoe.vt.edu/~mason/Mason_f/ConfigAero.html *Department of Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University*

[7] S.R. Munshi, V.J. Modi, T. Yokomizo: Fluid dynamics of flat plates and rectangular prisms in the presence of moving surface boundary-layer control, *Journal of Wind Engineering and Industrial Aerodynamics*, 1997

[8] D. Cichy, J. Harris, and J. MacKay: Flight Tests of a Rotating Cylinder Flap on a North American Rockwell YOV-10A Aircraft. *NASA CR-2135*, 1972

[9] M. Amitay, A.E. Washburn: Active Flow Control on the Stingray UAV: Physical Mechanisms, *AIAA 2004-0745*, 2004

[10] MEMS clearinghouse, 2007 http://www.memsnet.org/

[11] Franck Chollet: A (not so) short introduction to MEMS. *Micromachines Centre, School of MAE, Nanyang Technological University of Singapore*

[12] M. Madou: Fundamentals of microfabrication. *2nd edition, CRC Press, Boca Raton*, 2002

[13] D. A. Lockerby, P. W. Carpenter, C. Davies: Numerical Simulation of the Interaction of Microactuators and Boundary Layers, *AIAA Journal*, 2002

[14] Guang Hong, C. Lee, Q.P. Ha, A.N.F. Mack, S.G. Mallinson: Effectiveness of synthetic jets enhanced by instability of Tollmien-Schlichting waves, *AIAA 2002-2832*, 2002

[15] D. A. Lockerby, P. W. Carpenter, C. Davies: Is Helmholtz Resonance a Problem for Micro-jet Actuators?, *University of Warwick*, 2006

[16] Jang, C.S.; Ross, J.C.; Cummings, R.M. (1998). "Numerical investigation of an airfoil with a Gurney flap". Aircraft Design 1 (2): 75-88.

[17] Manish K. Singh, K. Dhanalakshmi, S. K. Chakrabartty: Navier-Stokes Analysis of Airfoils with Gurney Flap,

[18] Ryan Holman, Yogen Utturkar, Rajat Mittal, Barton L. Smith, Louis Cattafesta: Formation Criterion for Synthetic Jets, *AIAA JOURNAL Vol.43 No.10*

Copyright Statement