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CONTROL OF FLOW SEPARATION OVER NACA 0015 AIRFOIL USING SYNTHETIC JET ACTUATORS

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ABSTRACT: - In this paper the concept of active flow control using an array of synthetic jet actuators has been investigated. Synthetic jets are the one type of actuators that will be used in this research to introduce important modification to the pressure distribution levels that appear over the lifting surface of airfoil model when the flow separation exists. Two synthetic jet actuators arrays were used; the first one placed at 3% c and the second array located at 6% c on the upper surface of a NACA0015 airfoil. The experiments are conducted at Re=455000 in 8 different angles of attack 0º to 15º using the wind tunnel at University of Diyala. The first part of this paper concentrates on making comparison of the collected experimental data of the pressure distribution over NACA0015 airfoil at Re = 4.4×10^5 at angle of attack varied from 0.0 to 20 degrees without synthetic jet actuators (baseline case study) and previous experimental results as a baseline validation of the onset of flow separation location. Figure 3 and 4 clearly showed that the pressure distribution and the calculated lift were converged in the stall region at high angle of attack.

In the second part of this study we had utilized a NACA0015 airfoil of 300 mm chord length with a rounded leading edge of 20 mm diameter. 18 discrete synthetic jet actuators with 1.2 mm diameter is distributed along the lifting surface of the wing. This distribution is used to investigate the effect of jets and vertical structures on the characteristics of pressure coefficients (Cp) and flow separation over the airfoil. Pressure and lift coefficients have been measured and calculated by using surface pressure measurements technique that uses 29 pressure tapings over the lifting surface of the wing. A piezo-ceramic diaphragms technology of 15mm diameter have been used in the experiments and excited at a variety of frequencies (resonant frequency and vortex shedding separated flow frequency) in order to get the effective interaction between the synthetic jets and separated boundary layer which is the most significant parameter of producing the vertical structure that affects the flow separation. The results showed that at 3% c SJA location, the best enhancement in the lift was seen at Vp-p of 8 which increased by about 0.1. However, the overall results showed that maximum enhancement in lift of about 0.2 at 6% c.

Keywords—Flow Separation Control, Synthetic Jet Actuators, Airfoils

1-INTRODUCTION:

The performance of an airplane wing has a significant impact on the runway distance, approach speed, climb rate, payload capacity, and operation range. Since the beginning of human flight, many researchers and engineers have attempted to increase lift and reduce drag by changing aircraft structure or configuration. The performance of an airplane wing is often degraded by flow separation. Flow separation on an airfoil surface is related to the aerodynamic design of the airfoil profile. However, non-aerodynamic constraints such as material property, manufacturability, and stealth capability in military applications often conflict with the aerodynamic constraints, and either passive or active flow control is required to overcome the difficulty [1]. Flow control over airfoil is primarily directed at increasing the lift and decreasing the drag produced by the airfoil. This is usually achieved by manipulating the boundary and shear layer flows in order to minimize the separation region over the suction surface of the airfoil. Active flow control refers to the process of the expending energy in order to modify the flow [2]. This is distinct from passive techniques where flow control is provided without expending energy through means such as vortex generators have proven to be effective in delaying flow separation under some conditions. Advantages of active flow control include the ability to attain a large effect using a small, localized energy input, and to control complex dynamical processes; for example, the reduction of skin friction and hence viscous drag [3, 4] in turbulent boundary layers.

A synthetic jet actuator (SJA) is a jet generator that requires zero mass input yet produces non-zero momentum output. Developed in recent years, the synthetic jet actuator falls within the area of micro-electro-mechanical systems (MEMS) if the characteristic dimension or the diameter of the orifice, through which the jets are generated, is less than 1.0mm [3]. Advantages of using SJA include simple compact structure, low cost and ease of operation. The basic components of a SJA are a cavity and an oscillating material. A jet is synthesized by oscillatory flow in and out of the cavity via an orifice in one side of the cavity. The flow is induced by a vibrating membrane located on one wall of the cavity. There are many types of actuator that can be used in active flow control, such as thermal, acoustic, piezoelectric, electromagnetic and shape memory alloys. Here, a piezoelectric material is chosen to drive the oscillating diaphragm because of such desirable characteristics as such low power consumption, fast response, reliability, and low cost [5]. Flow enters and exits the cavity through the orifice by suction and blowing. On the intake stroke, fluid is drawn into the cavity from the area surrounding the orifice. During one cycle of oscillation, this fluid is expelled out of the cavity through the orifice as the membrane moves upwards. Due to flow separation, a shear layer is formed between the expelled fluid and the surrounding fluid. This layer of vorticity rolls up to form a vortex ring under its own momentum. By the time the diaphragm begins to move away from the orifice to pull fluid back into the cavity, the vortex ring is sufficiently distant from the orifice that it is virtually unaffected by the entrainment of fluid into the cavity. Thus, over a single period of oscillation of the diaphragm, whilst there is zero net mass flux into or out of the cavity, there is also a non-zero mean momentum flux flow control can be achieved using traditional devices such as steady [6] and pulsed [7] jets. The obvious benefit of employing SJAs as a flow control device is that they require no air supply and so there is no need for piping, connections, and compressors associated with steady jets.

The focus of the present paper is to investigate the lift enhancement mechanism using synthetic jets on NACA0015 airfoil, which has been frequently used as a model airfoil of various high lift systems [8, 9, and 10]. Various synthetic jets were applied to NACA0015 with two locations of synthetic jet actuators arrays were used; the first one is placed at 3% c and the second array is located at 6% c on the lifting surface of a NACA0015 airfoil , and the flow characteristics of separation control on the leading edge were examined.

Performance of the synthetic jet with a simple high-lift device under optimal flow control conditions was investigated. Furthermore, a multi-array synthetic jet was introduced as a way to reduce the amplitude of the jet peak velocity. And multi-location synthetic jets were also investigated as a remedy to cure unstable separated vortex flows on the airfoil suction surface. Finally, flow control combining multi-array and multi-location of synthetic jets was employed to provide a stable flow structure with a reduced jet peak velocity.

2. EXPERIMENTAL APPARATUS

The flow behavior over an airfoil section model was investigated and then aerodynamic pressure coefficients were calculated with the help of the pressure distribution over

NACA0015 model mounted inside wind tunnel. The subsonic wind tunnel used in current research is an open circuit type with a working cross section of (300mm x 300mm) as schematically shown in Figure 1. All experiments were conducted at Re = 455000 in 6 different angles of attack 6º to 15º using the wind tunnel facility at college of engineering , University of Diyala. A maximum flow speed of 36 m/sec had allowed the experiments on many aspects of incompressible air flow of subsonic aerodynamics were performed at satisfactory Reynolds number. The tunnel has a smooth contraction fitted with protective mesh screen to increase the flow uniformity inside the test section with working section constructed of clear Perspex. A model of wood of the NACA 0015 airfoil has been built locally. The data for this section were taken from NACA's lists of wings section [11, 12]. Moreover, its coordinate has been listed in Table 1.The wing section model specification has a cord (C=300mm) with a rounded leading edge of 20 mm diameter, the section length (b=300mm). A standard multi tubes manometer was used which consists of 30 manometers to measure the surface pressure distribution. The manometer connected with the stainless steel pressure tubes over the wing section model by a rubber snout. In this research, 29 pressure taps have been used on the upper and lower surface of the wing. Two synthetic jet actuators arrays were used: the first one was placed at 3% c with 9 discrete synthetic jet actuators which had 1.2 mm diameter and the second array was located at 6% c with 9 discrete synthetic jet actuators with 1.2 mm diameter on the upper surface of a NACA0015 airfoil as shown in Figure 2. The array of SJA was built at 3% of the chord length from the leading edge of the wing through nine holes with diameter of 16 mm and a depth of 2 mm in the flat plate metal. The distance between the first center holes to the neighbor center is 26 mm. The piezo-ceramic was fixed as a cushion inside the cavity which represents the oscillatory diaphragm for the synthetic jet actuators. The piezo-cermic diaphragms were connected together to the driving circuitry to excite them with different operation conditions with the help of signal generator. A 1.2 mm diameter orifice was drilled at the center of each synthetic jet actuators from the lifting surfaces of the wing. A piezo-ceramic technology of 15mm diameter was used in the present experiments at a variety of frequencies (resonant frequency and vortex shedding frequency)

2.1 CALCULATION AERODYNAMIC COEFFICIENT

There are a variety of ways to measure the lift on the airfoil. In the present experiments, the lift force, L, on the airfoil has been determined by integration of the measured pressure distribution over the airfoil's surface. The pressure distribution on the airfoil is expressed in dimensionless form by the pressure coefficient Cp as follow:

$$Cp = \frac{p_o - p_\infty}{0.5\ \rho\ U_\infty^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where p_o is the surface pressure measured at location i on the surface, p_∞ is the pressure in the free stream, ρ is air density, and $U\infty$ is the free-stream velocity given by

$$U_\infty = \sqrt{\frac{2\ (p_{Stagnation} - p_\infty)}{\rho}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

While $p_{Stagnation}$ is the stagnation pressure measured at the tip of the Pitot static tube. The vertical and axial force coefficients account through the integration of the pressure distribution along the chord as follows:

$$C_x = \int_0^1 \left(C_{p\ Lower} - C_{p\ Upper}\right).\ d(\tfrac{x}{c}) \ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$C_z = \int_{-\frac{zu}{c}}^{\frac{zu}{c}} C_p\ .\ d(\tfrac{z}{c}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Equations (3) ,(4) were solved numerically by using the method of Simpson numerical integration by using 12 slice on each of the upper and lower surfaces of the wing. Each of lift and drag coefficient caused by the pressure calculation through the following two equations:

$$Cl = Cx\ cos\alpha - Cz\ sin\alpha \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$Cd = Cx\ sin\alpha + Cz\ cos\alpha \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

3. RESULTS AND DISCUSSION

The results have been divided into two parts: Firstly, the pressure distribution and lift coefficients over NACA0015 (baseline case study) to investigate the onset of separation location. Secondly, the effect of an array of synthetic jets with two synthetic jet actuators arrays on the separation was examined. The objective of the first part of this paper concentrates on the finding the experimental data of the pressure distribution and plotting its curves which are presented over unactuated NACA0015 airfoil at angle of attack varied from 0.0 to 15 degrees without SJA (baseline case study) at Re = $4.4x10^5$. Moreover, a comparison had been made between lift coefficients for different angles of attack with the previous experimental data computed over NACA0015 airfoil [13, 14].

Figure 3 shows the pressure coefficient curves for the upper (Cpu) and lower surface (Cpl) of the wing plotted against the percent chord (x/c). At $\alpha = 0^o$ the Figures clearly illustrate that no lift was generated at this angle of attack as been expected from a symmetric airfoil without being different in the pressure which been generated. The existence of zero lift also validates the pressure measurement set up and ensures the accuracy of the readings obtained for other angles of attack. At $\alpha = 12^o$ the negative pressure gradient has been increased rapidly, therefore, the speed of the boundary layer relative to the wing falls almost to zero. Then, the fluid flow becomes detached from the surface of the wing, and instead takes the form of the wing tip vortices which become stronger with increase in angle of attack and the flow is further energized. This leads to lower pressures at the wing tips and the resultant drop in pressure coefficients .The sudden decrease in the pressure coefficients (towards lower negative values) also suggests the presence of the separation bubble in the plateau region.

Figure 4 shows the comparison of computed lift coefficients for different angles of attack with the previous experimental data computed over NACA0015 airfoil [13, 14]. Generally, the results were convergent and the experimental data is nearly close and acceptable. The lift coefficient varies along the chord at different angles of attack. For an angle of attack of 12^o, the flow is more likely to be separated at the trailing edge region of the suction surface. The computed results nearly agreed except near the region of stall. However, the general behavior near the post-stall region is captured nearly enough to understand the main characteristics of flow physics.

The second part is helping to understand the fundamental characteristics of a SJA as a function of excitation frequencies.in addition to that obtaining the optimal conditions for stall control and analyzing the merits of the use of synthetic jet actuators in flow separation control. Multi-synthetic jets were placed at 3% c on the upper surface of a NACA0015 airfoil. The two arrays of synthetic jet actuators have been introduced as a way to reduce the low momentum of the separated flow by suction phase or ejecting more momentum to complete the boundary layer of the separated flow.

Figure 5 shows the comparison of the computed aerodynamic coefficients of the experimental data for uncontrolled NACA0015 airfoil (baseline case study) and controlled with multi-synthetic jet actuators which were initially placed at 3% c on the upper surface of a NACA0015 airfoil. As expected, the enhancement of lift is proportional to the excitation amplitude of the sine wave Vpp (voltage peak to peak) that equipped to the piezo-ceramic diaphragms of synthetic jet actuator at constant frequency. The best enhancement of lift coefficient seen in value of Vpp =8 volt and frequency = 3.26 kHz as shown in Figure 6. The most likely reason of that is exciting the flow by SJA frequency near the resonant frequency of the diaphragm or near the vortex shedding frequency of the separated flow. At Vpp range from (2 to 8 volt) with constant frequency, a little improvement is observed in lift coefficients compared with uncontrolled airfoil when Multi-synthetic jets are placed at 3% c on the upper surface of a NACA0015 airfoil. The reason is that, the baseline flow is separating at the trailing edge of the suction surface region for the uncontrolled case due to Vpp and frequency mentioned above which was not providing sufficient jet momentum to disturb boundary layer of flow and prevent separated at the trailing edge. Hence, the SJA and separation point is not

the same or near position. The synthetic jet just disturbs the neighboring attached flow, which has a negative effect in both lift and drag. A relatively broad range of frequencies between f = 5 kHz and f = 8 kHz have been applied with a little effect on enhancing the post-stall lift coefficient with constant Vpp volt. The reason may be due to high frequencies could penetrate the boundary layer to much and no vertical structure can be produced.
Figure 7 similarly shows the same comparison between lift coefficients experimental data with and without SJA when multi-synthetic jets are placed at 6% c on the upper surface of a NACA0015 airfoil. At constant amplitude vpp = 8v, the improvement of aerodynamic coefficients is most visible when the frequency of the SJA is 3.26 kHz. The enhancement of lift and drag is most likely proportional to the excitation frequency of the SJA. Overall results show that the multi-synthetic jets placed at 6% c on the upper surface of a NACA0015 airfoil could improve the stall characteristics and thus increase the maximum lift coefficient. At a 12◦ angle of attack, the lift is remarkably increased when frequency is 3.26 kHz better than other frequency as shown in figure 8. However, a similar improvement can be observed at a SJA excitation frequency 3.26 kHz at different amplitude of sin wave signal from Vpp=2 volts to Vpp=4 volts.
Figure 9 shows the improvement of stall characteristics by increasing the lift coefficient. The best excitation values had been seen when Vpp=8v.The overall results when SJA placed at 6%c show the maximum enhancement in lift and drag when the separation point is nearly closer to the synthetic jets location. The effect of the synthetic jet is most visible when the location of the synthetic jet and the separation point is the same or very close together. However, the fact that the synthetic jets more likely to stay within the separated boundary layer and compensate the little momentum been lost due to the separation . Thus, the conditions for the maximum lift enhancement can be summarized as follows: the approximate frequency is 3.26 kHz; the location of the synthetic jet slot is equal or near to the baseline separation point. These results are similar to the conclusions obtained by other experimental studies [16].

4. CONCLUSIONS

Flow control on a NACA0015 airfoil using an array of synthetic jet actuators were investigated for various angles of attacks, jet frequencies and amplitude at a relatively high Reynolds number. The synthetic jet was able to push the separation point backward and thus change the global flow-field structure favorably. Consequently, stall characteristics and control surface performance were remarkably improved. For 3.26 kHz frequency, the small vortex did not grow enough to penetrate into the large separation vortex. The synthetic jet firmly attached the local flow and changed the circulation of the virtual airfoil shape. The maximum lift was obtained when the separation point coincided with the synthetic jet location and the amplitude is 8 volt. In addition, the separation control effect was proportional to the jet momentum. Thus, the performance of a multi-array synthetic jet was investigated to reduce the jet peak velocity. High frequency multi-location synthetic jet was proposed to control the unstable flow structure efficiently. As a result, desirable flow control effects were obtained by multi-array/multi-location synthetic jets which led the authors to investigate more about studying the effect of geometrical parameters of the synthetic jet actuators itself as orifice diameter, orifice thickness, cavity height and cavity diameter on the flow separation control.

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Table (1) a- Upper static pressure taps coordinate

Tap number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
x/c	0.05	0.1	0.17	0.2	0.23	0.27	0.3	0.36	0.39	0.42	0.46	0.49	0.53	0.58	0.62	0.69	0.75	0.81

b- Lower static pressure taps coordinate

Tap number	1	2	3	4	5	6	7	8	9	10	11
x/c	0.08	0.14	0.21	0.27	0.3	0.4	0.47	0.54	0.61	0.67	0.71

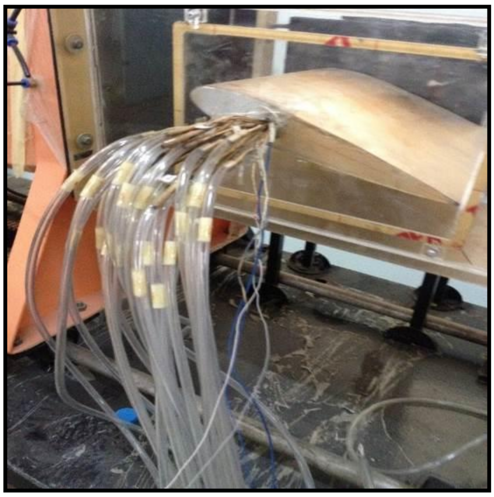

Figure 1.NACA0015 model mounted inside wind tunnel

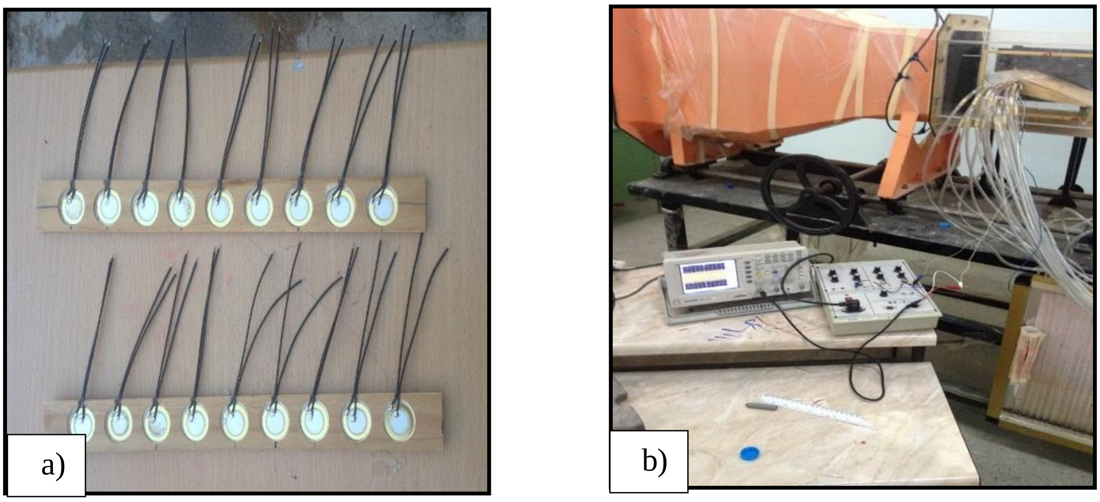

Figure 2. a) synthetic jet actuators arrays b) Experimental set-up

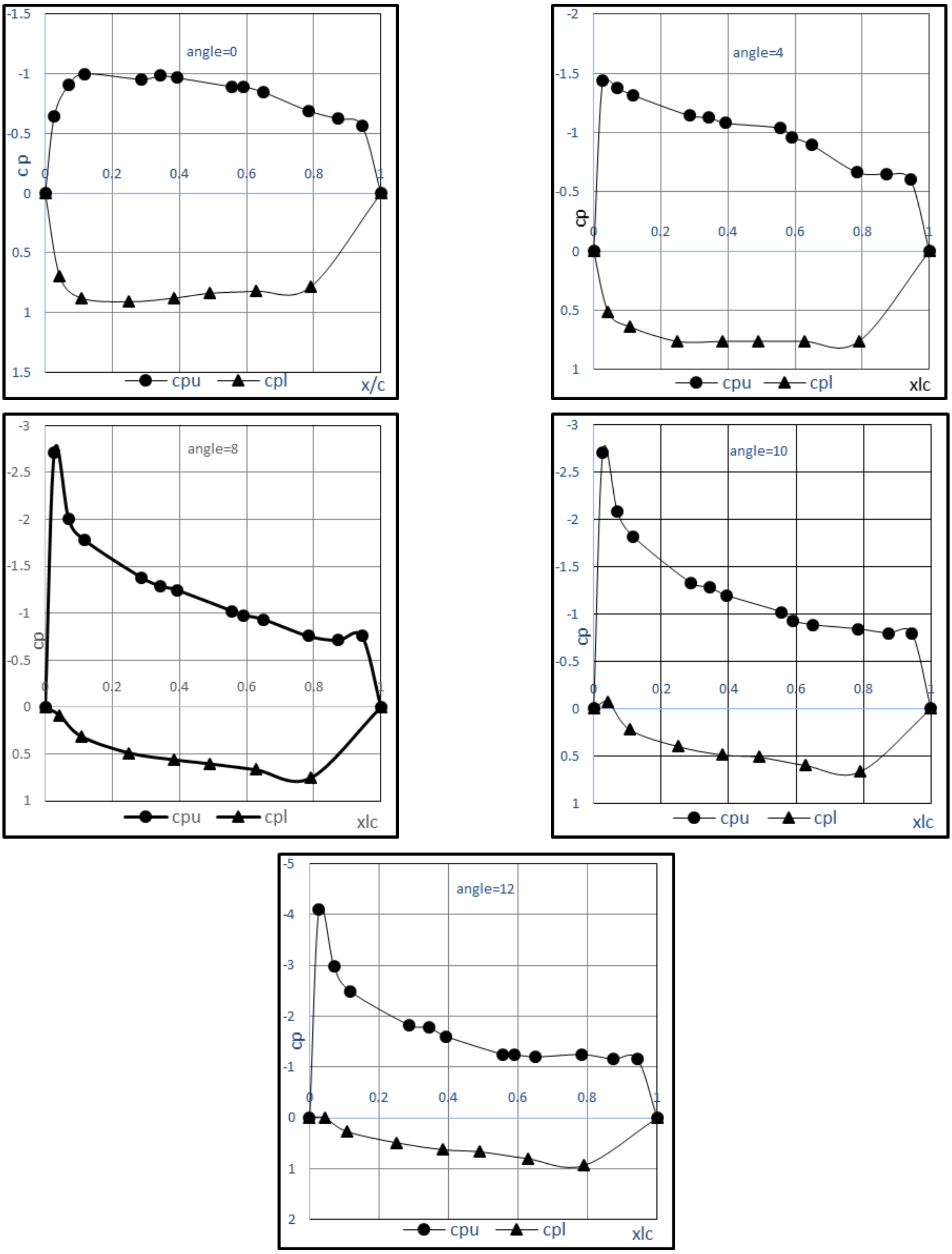

Figure 3. The pressure coefficient curves for the upper (Cpu) and lower surface (Cpl) of the wing

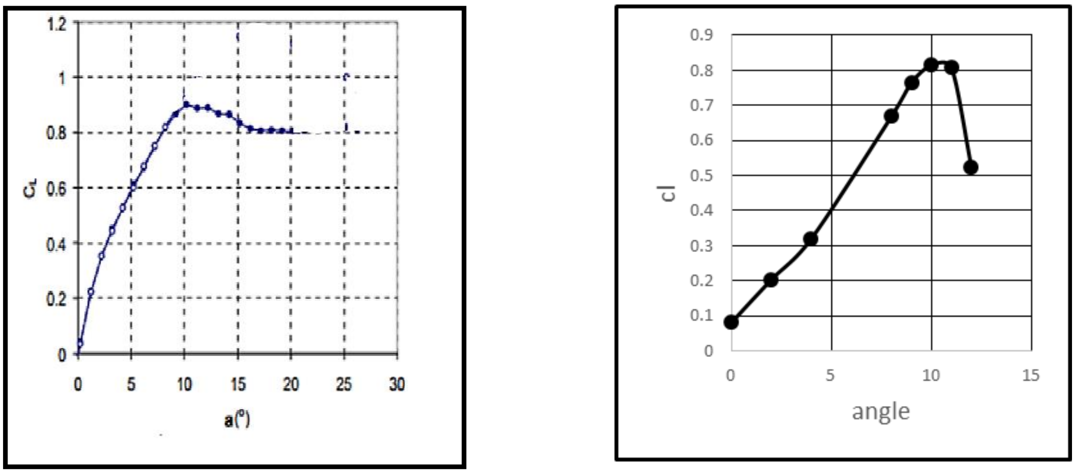

Figure 4. Comparison of experimental data for the lift coefficient over uncontrolled NACA0015 airfoil with the previous experimental data [13, 14]

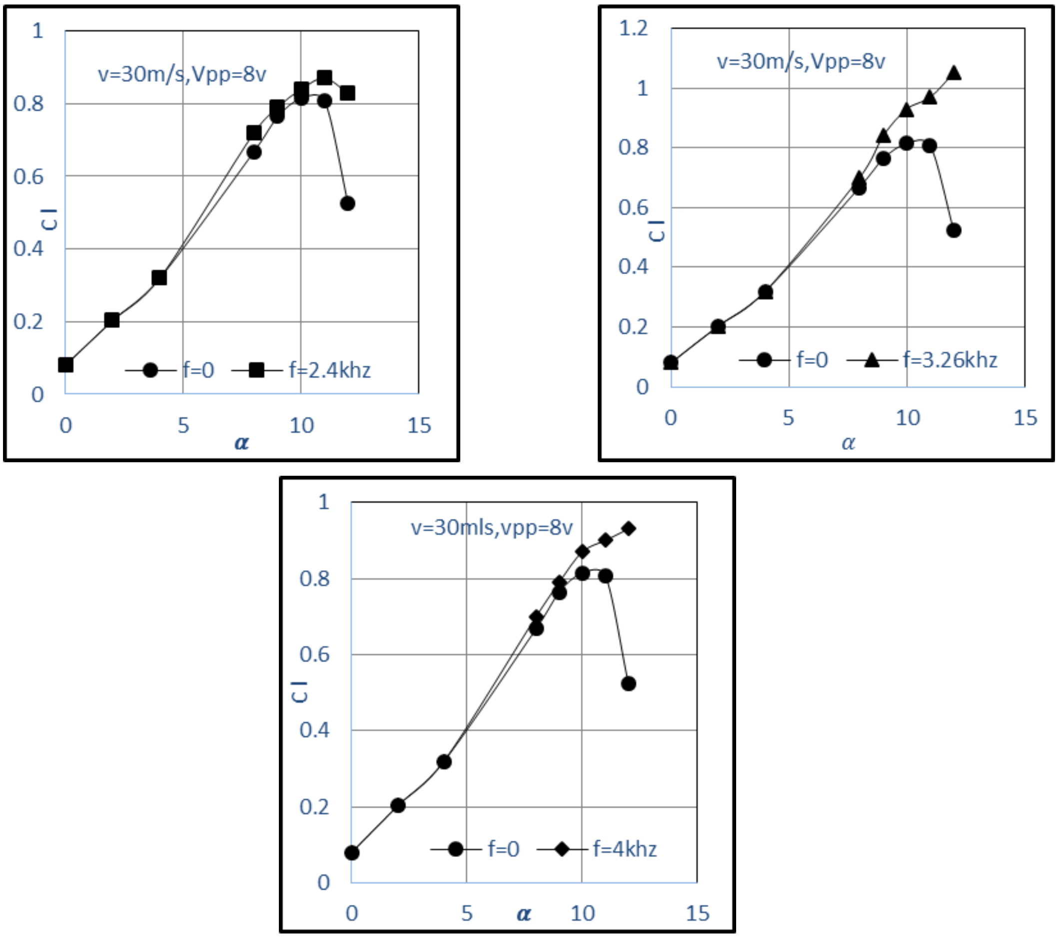

Figure 5. The lift coefficients experimental data with SJA frequency (f=0, 2.4, 3.26 and 4 kHz) are placed at 3% c.

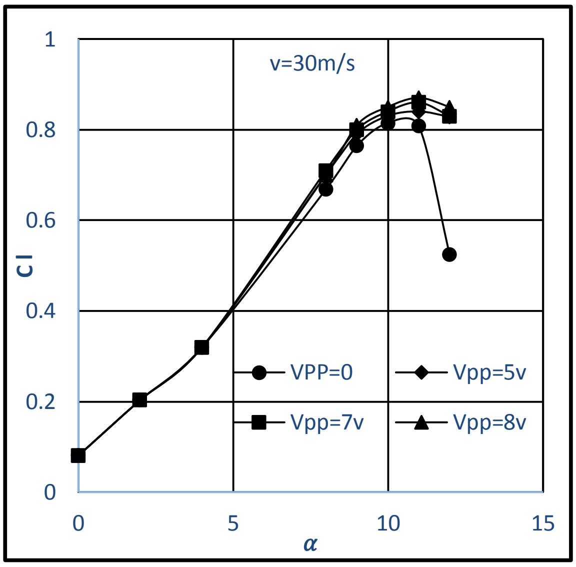

Figure 6.The comparison of computed aerodynamic coefficients experimental data at vpp=0v, 5v, 7v, 8v and f=3.26 kHz at 3%c.

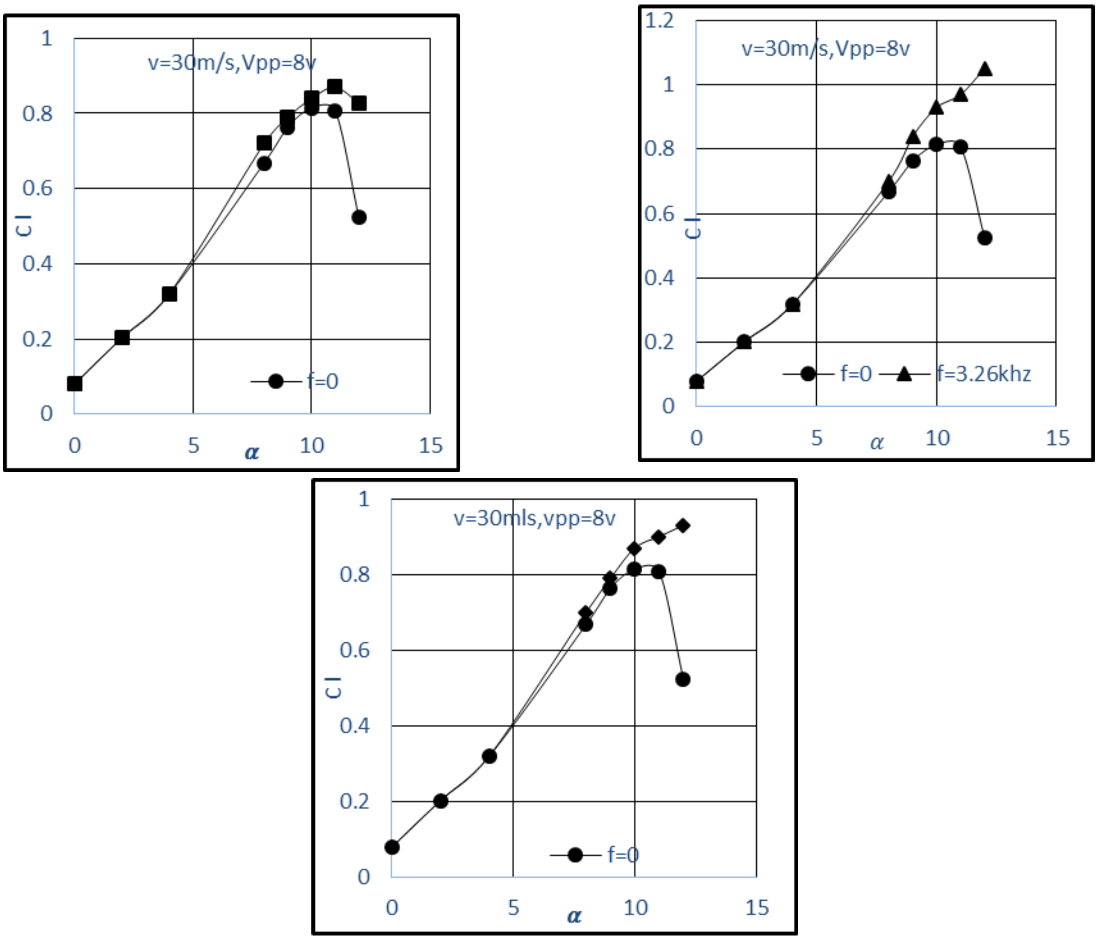

Figure **7.** Experimental data of lift coefficients with and without multi-synthetic jets are placed at 6% c at constant Vpp

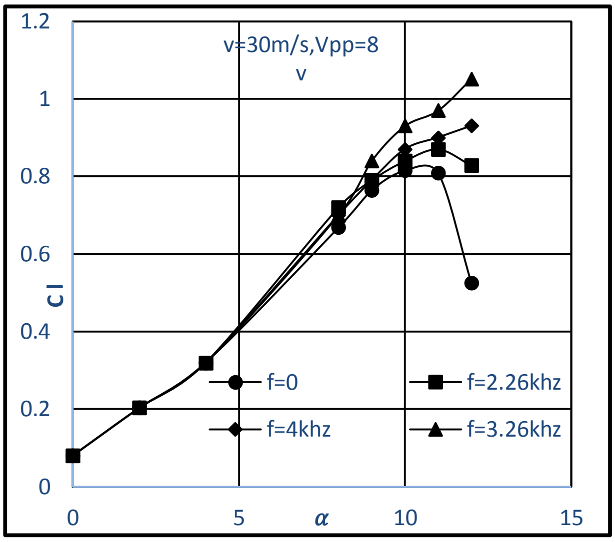

Figure 8. The best operational excitation parameters at 6% c.

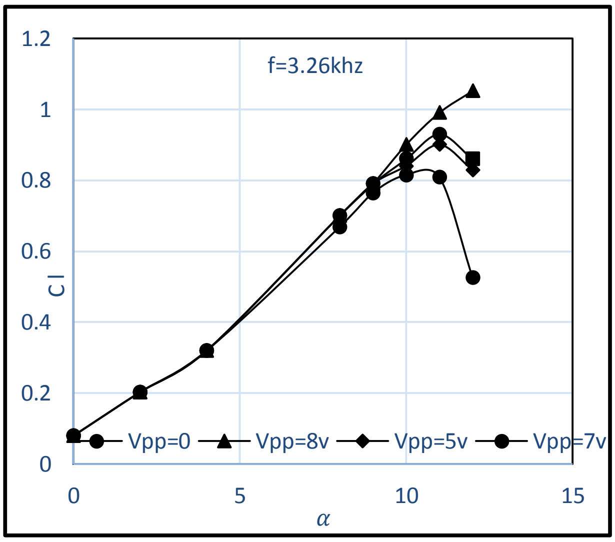

Figure 9. Comparison of lift coefficient at f=3.26 kHz and Vpp = 0, 5, 7 and 8 volts at 6% c.

السيطرة على انفصال الجريان على جنح NACA0015 باستخدام تقنية المحركات النفاثة الاصطناعية

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الخلاصة

يتناول البحث الحالي دراسة تأثير استخدام تقنية المحركات النفاثة الاصطناعية للسيطرة على انفصال الجريان حيث استخدم صفين من اجهزة النفث المصطنع، تم وضع الصف الأول على بعد 3% من مقدمة الجنح والصف الثاني على بعد 6% من مقدم الجنح. تمت التجارب عند عدد رينولد 455000 و 6 زوايا هجوم مختلفة تتراوح بين 6 و 15 درجة وجميع هذه التجارب أجريت في النفق الهوائي منخفض السرعة في جامعة ديالى / كلية الهندسة. تقنية المحركات النفاثة الاصطناعية هي واحدة من الوسائل المهمة للسيطرة على انفصال الجريان وتحسين الخواص الديناهوائية من خلال تعديل مستوى توزيع الضغوط على الاجنحة وبالتالي زيادة قوة الرفع وتأخير انفصال الجريان.

المحور الاول من البحث قدم مقارنة للنتائج العملية لتوزيع الضغوط ومعاملاتها على الجنح بين البحث الحالي مع نتائج بحوث عملية سابقة، عند زوايا هجوم تتراوح بين 0 و20 درجة ورينولد 440000 للتأكد من موقع الانفصال المحدد.

المحور الثاني من البحث ركز على دراسة تأثير استخدام 18 جهاز نفثي مصطنع داخل جنح ناكا 0015 ذو 300 ملم طول الوتر مع 20 ملم قطر مقدمة الجناح. الاجهزة تتألف من 1.2 ملم قطر الفتحة الخارجية على سطح الجناح مع 15 ملم قطر الغشاء المتحرك المسؤول عن توليد النفث المصطنع وبالتالي زيادة السرعة في الطبقة المتاخمة الضعيفة المعرضة للانفصال وجعلها متكاملة بإضافة زخم متغير تبعا للتردد المسلط والفولتية وموقع الاجهزة والذي بدوره يندمج مع هذه الطبقة ويعمل على تحسينها وتأخير الانفصال.

الكلمات الدالة: سيطرة انفصال الجريان، محركات النفث الاصطناعي مقطع مطيار.