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Experimental Assessment of the Aerodynamics of a Slotted Wavy Blade

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Abstract

Many techniques have been incorporated into the design of turbine blades in an attempt to improve their performance. An open subsonic wind tunnel with a test section of (30.5 ×30.5×60 cm) was employed to conduct the test. The work experiment investigated two modified models (slotted and hybrid slotted and wavy) then compared them to the normal blade model. A slotted blade NACA 0012 airfoil model with a slot width of 1.5 mm at 60% of the chord was employed in the current study. All blades exhibited stall between 10º to 12º angles of attack at various wind speeds (10,15,20, and 20 m/s). The normal blade showed an earlier stall at angle of attack at 10º. Additionally, the increase in wind speeds showed that the modified models did not exhibit better stall delay than the normal one. However, they observed better performance than the normal model.

Keywords: Slotted blade; Wavy blade; NACA0012 Airfoil; Drag and Lift Forces.

الخلاصة: تم دمج العديد من التقنيات في تصميم شفرات التوربينات في محاولة لتحسين أدائها. تم استخدام نفق رياح مفتوح دون سرعة الصوت بمقطع اختبار (30.5×30.5×60 سم) لإجراء الاختبار. تم في تجربة العمل فحص نموذجين معدلين (مشقوق وهجين مشقوق ومموج) ومن ثم مقارنتهما مع نموذج الشفرة العادية. تم استخدام نموذج الجنيح ذو الشفرة المشقوقة NACA 0012 بعرض فتحة يبلغ 1.5 مم عند 60٪ من الوتر في الدراسة الحالية. أظهرت جميع الشفرات توقفًا بين 10 إلى 12 درجة من زوايا الهجوم عند سرعات رياح مختلفة (10،15،20، و20 م/ث). أظهرت الشفرة العادية توقفًا سابقًا عند زاوية الهجوم عند 10 درجات. بالإضافة إلى ذلك، أظهرت الزيادة في سرعة الرياح أن النماذج المعدلة لم تظهر تأخيرًا أفضل من النموذج العادي. ومع ذلك، فقد لاحظوا أداء أفضل من النموذج العادي.

1. INTRODUCTION

Within the ever-evolving field of aerospace engineering, the advancement of flight technology is a monument to humanity's unwavering pursuit of creativity and advancement. From the Wright brothers at Kitty Hawk, ground-breaking days to the state of the art developments in contemporary aeronautics, the history of flight development has been a fascinating tale of creativity, tenacity, and scientific prowess[1]. The development of flying technology has been a complex process that has involved many different fields, including avionics, materials science, propulsion systems, and aerodynamics. Overcoming innumerable obstacles, engineers and innovators have persistently pushed the limits of what was previously thought to be impossible. There have been many different reasons throughout history for wanting to fly, from transportation and exploration to trade and defines. Every major advancement in flight has not only deepened the understanding of the planet but also transformed society as a whole, bridging geographical gaps, promoting global collaboration, and encouraging future generations of dreamers to take to the sky [2]The fundamental laws of physics, particularly those of aerodynamics, form the foundation for the laws that regulate flight. Among these guidelines are: Bernoulli's principles, lift and drag, Newton's laws of motion, stability, and control, and center of gravity, and Balance. According to ideas and experimental evidence in fluid dynamics, drag and lift forces are produced when a body moves through fluid or when fluid moves around a body.

Two significant aerodynamic forces that affect things moving through a fluid, such as water or air, are lift and drag. Where drag force is a force that prevents an object from moving through a fluid. It results from the object's interaction with the fluid molecules. Pressure drag and friction drag are forms of the drag force. The difference in pressure between the front and back of an object, what can cause pressure drag. It usually has to do with the object's shape.

The shear tension between the fluid and the object's surface is what causes friction drag. The object's surface roughness has an impact on it. Drag force is dependent on the object's size, shape, speed, and surface properties, among other things.

Reducing the object's speed, normaling its surface, or simplifying its design can all help to lessen drag force. Lift force is a force that can affect upright on an object's direction of motion through a fluid. The pressure differential between the upper and bottom surfaces causes the lift force [3].

Many studies were conducted investigations that primarily examined a slot design. In addition, plenty of studies have incorporated a wavy technique in the blades and wings design. The slot is a straight channel that joins the air foil's low-pressure side on the upper surface with the high-pressure side at the lower surface. Ramzi and Abd Errahmane (2013) [4] conducted a study to investigate the possibility of passive control with slotted blades under stall conditions. The optimal layout was determined by analysing the slot location, slope, and width through a thorough 2D numerical study. The 3D aerodynamic performances of the cascade were examined based on the ideal slot, and the impact of slotted blading on end wall flow management was looked into. The NACA 65(18)10, was numerically and experimentally were used. In a two-dimensional arrangement, the effects of the slot's placement, width, and slope were examined one after the other. The slot, which was situated roughly 50% before the separation point, showed the threshold value.

Asli, Mashhadi Gholamali, and Mesgarpour Tousi (2015) [5] examined the leading-edge bumps of whale flippers as a novel passive stall management technique on a thick airfoil S809. The validation was conducted using an experimental data. The airfoil was numerically modeled using the CFD approach at a Reynolds number of 10^6. As a result, computational findings for an altered airfoil featuring a sinusoidally wavy leading edge were showcased. However, the findings showed that the lift coefficient somewhat reduced at low angles of attack before the stall region. Beyhaghi and Amano (2017) [6] studied the leading edge of NACA 4412 airfoils and two-segment slots was suggested so that some of the entering air can pass through them and out the bottom of the airfoil. These kinds of slots could lead to a high lift and more local pressure. The slots' length, width, input angle, and exit angle were adjusted to determine the best possible arrangements. The investigation focused on the aerodynamics at many angles of attack (AoAs) and the Reynolds number of 1.6×10^6. Ignoring the drag cost, the best design case under consideration showed an enhancement up to 8% for the lift coefficient.

Beyhaghi and Amano (2018) [7] examined the aerodynamic performance using a span-wise rectangular slot that inserted close to the leading edge. The slot turned slightly and emerges from the pressure side of the cambered airfoil, having begun at the leading edge. By using the NACA 4412 as a reference airfoil profile, the effects of many shapes of slots at Reynolds number of 1.6×10^6 and on the lift and drag coefficients at various angles of attack (AoAs) started from 0^o to 16^o, were examined. The impact of the vertical location, inlet angle, and slot width (thickness) were examined. A notable 30% lift coefficient enhancement was noted for one of the better examples studied, with no drag penalty. Seeni (2019) [8] presented a numerical discussion of slotted propeller blade designs concerning static structural analysis and aerodynamic performance. The 10 × 7-inch small-scale propeller blade was numerically studied by adding slots to its length then the slot angle effect on the power coefficient. For the majority of slot angles, there was an improvement ranging from 0.2 to2.7% in thrust power of the propeller.

Mohamed and Rajendran (2021) [9] conducted a work to present a thorough analysis of the design of slotted propellers using a variety of airfoils with distinct characteristics, including low, high, symmetric, and asymmetrical lift and low drag. The computational fluid dynamics CFD was used in investigate propeller performance prediction for small-scale propellers. The thrust coefficient, power coefficient, efficiency, and thrust-to-power ratio performance of the slotted blade designs are provided. The performance of the slotted propeller blade was examined for a variety of airfoil types. The shape of the slot was fixed shape as a square and located at 62.5% of the chord length. Results indicated that the design of a slotted propeller at high Reynolds number could yield the most benefits from the use of slots reached in power to 69.13%.

There were numerous researches conducted to look into and measure any potential hydrodynamic benefits of a wavy leading edge. It is now more important than ever to improve the aerodynamics of any windy shape. However, achieving this goal is difficult and necessitates reconsidering how to change these shapes.

Yoon et al. (2011) [10] examined the impact of the wavy leading edge on hydrodynamic at a Reynolds number of 10^6 . At a fixed wavelength of 0.2C and wavy amplitude of 0.025C, five distinct waviness ratios of 0.2, 0.4, 0.6, 0.8, and 1.0 were taken into consideration. The lift coefficient CL varied similarly with the angle of attack (AOA) for the normal wing and Rw = 0.2, leading to the same stall angle (20°) at which the maximum lift is observed. The stall at AOA = 12° occurred at the earliest possible time in the case of Rw = 0.6. The stall angle of AOA = 16° was the same for Rw = 1.0, 0.8, and 0.4. CL for Rw = 0.4, 0.6, 0.8, and 1.0 recovered and grew larger in the post-stall region compared to those of the normal wing and Rw = 0.2. The leading-edge faced a comparatively low pressure, and that could lead to wavy troughs where the limiting streamlines form in a spiral pattern. Rostamzadeh et al. (2014) [11] experimentally and numerically investigated the influence of tubercles on the flow over wings based on the NACA 0021 profile. The generation of streamwise vortices, whose growth was accompanied by flow separation in delta-shaped regions close to the trailing edge. Tests used wind tunnel pressure measurement showed that the existence of vortices reduces full-span wing performance before stalling, but improved performance afterward. Lastly, post-stall primary and secondary vortices were found, which result in an improved momentum transfer effect that lessens flow separation and raised lift generation. Chang, Dally and Cheng (2014) [12][13] studied the sinusoidal leading edge in order to explore the hydrodynamic performance of a three-dimensional airfoil with tubercles on the leading edge and to enhance the hydrodynamic performance of airfoils. Using a model created by the ICEM program and split by structural grid, some parameters, including amplitudes and tubercle counts, were examined using the FLUENT software. The results showed that tubercle airfoils might postpone the stall angle, increased lift, and increased the drag ratio coefficient under certain situations. Al-Bakri and Aljuhashy (2021) [14] examined the aerodynamic of a wavy blade experimentally and numerically. The findings referred to importance of the of existence of the wave shape in front of the blade in enhancing the lift to drag force ratio in fluctuating wind conditions. Ji (2012) [15] declared that the existence of an internal slot could significantly upgraded for angles of attack.

In the current research, the two techniques; wavy leading-edge and slot were combined in seeking combined benefits of delay stall then increasing gain lift force at a high angle of attack.

2. DESCRIPTION NORMAL, WAVY, AND SLOTTED AIRFOIL

A common symmetric airfoil in many aerodynamic applications, such as wind turbine blades, rotor blades, and airplane wings, is the NACA 0012, as shown in Figure 1. The airfoil profile is among the numerous ones created by the National Advisory Committee for Aeronautics (NACA) in the early 1900s. The number 0012 denotes certain geometric properties of the airfoil [3].

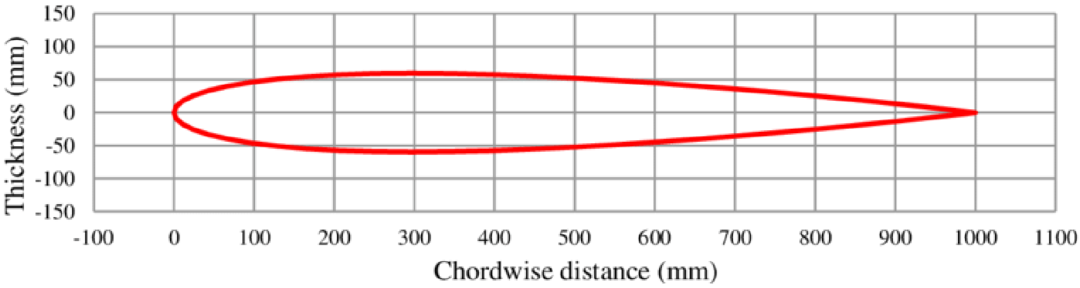


Fig. 1 Geometry of NACA0012 Airfoil.

The basic NACA0012 geometry is altered to add slots or apertures strategically placed across the air foil's surface to form a slotted NACA0012 airfoil. NACA0012 Profile The cornerstone is the fundamental NACA0012 profile. It is a symmetric airfoil with a maximum thickness of 12% of the chord length and zero camber.

The NACA0012 airfoil model (slotted NACA0012) feature designs has a slot located at 60% from the leading edge.

The term (slotted wavy NACA0012) describes an airfoil that has been modified to include wave-like patterns throughout its surface in addition to a slot located at 60% from the leading edge. These waves are usually injected to alter the airfoil's aerodynamic performance. They can vary in amplitude, wavelength, and frequency, as illustrated in Figure 2.

The objective of the research is to modify the wing shape to alter the flow pattern and overcome flow separation at high angles of attack.

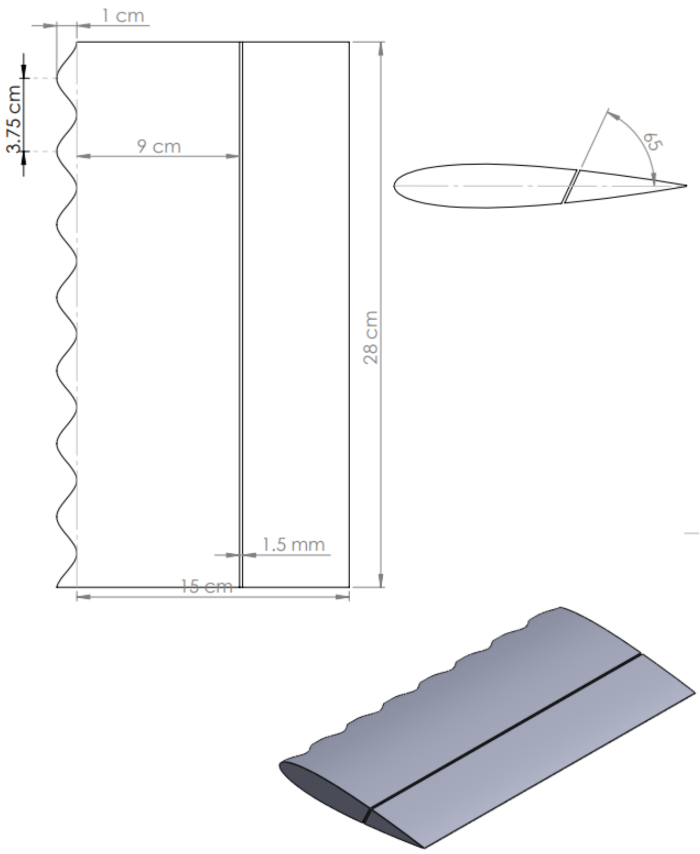


Fig. 2 Configuration of third model.

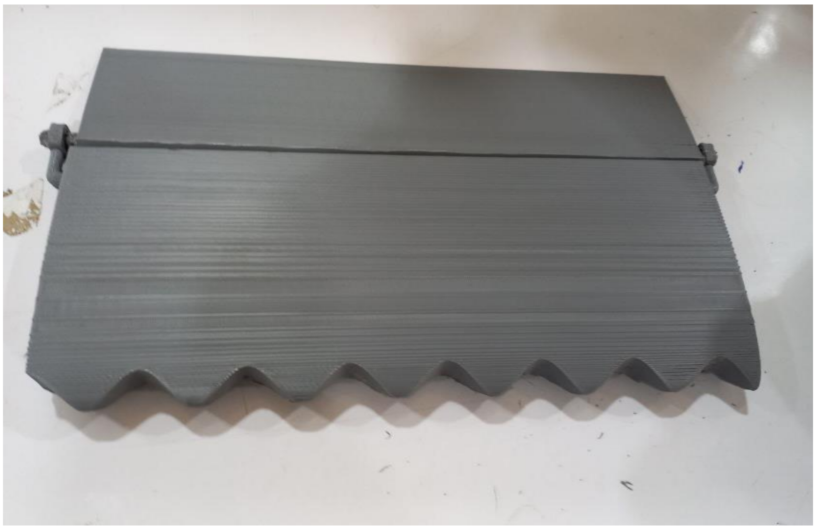
3. EXPERIMENTAL SETUP OF BLADE MODELS

The model contains a cross-sectional for the wing made by using a (CNC) machine to manufacture a mold from Acrylic, as shown in Figure 3a. The mold consists of two other symmetrical parts as the same shape for the first model. The normal model is made with dimensions (28 cm width, 15 cm length, and 17 cm height). While the second model is made as a slot with the same previous dimensions with a hole at 65% from the chord with a width of 1.5 mm, as illustrated in Figure 3b.

The third model is manufactured with a slot and wavy at the leading edge of the wing with a height of 1 cm from the projection. The width from one top to another was 3.75 cm, as shown in Figure 4. Lift and drag forces are measured on models mounted in the AF1300 Subsonic Wind tunnel by Lift and Drag Balance (AF1300z), as seen in Figure 3c. The force generated by the model in a direction that is perpendicular to the upstream path indicates lift force, and the force generated in a direction that is parallel to the upstream path indicates drag force. The force exerted on the model is measured by a strain-gauged load cell with a digital display that has an electronic readout.

(a)

(b)



(c)

Fig.3 Description of first original model (a), second model with a slot (b), and the third model (c).

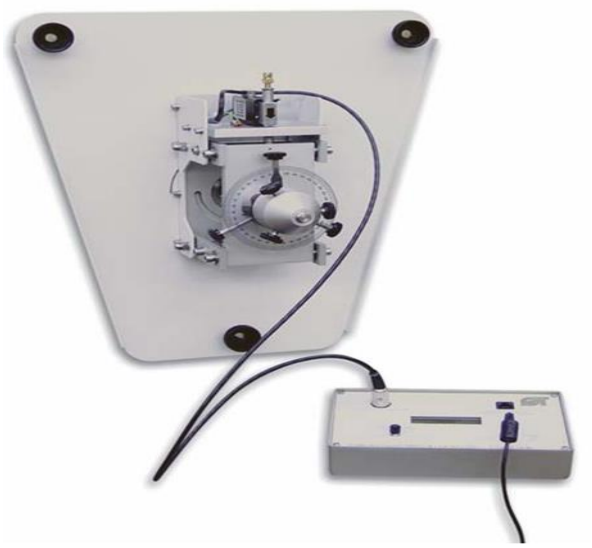


Fig.5 Lift and drag device balance.

The experiments were performed in an open-circuit suction subsonic wind tunnel that delivered by Al-Furat Al-Awsat Technical University. The general arrangement of the wind tunnel is seen in Figure 6.

The stage at which air enters the tunnel is designated by a diffuser. The diffuser is constructed in an aerodynamically rightful manner, and it imparts a linear acceleration to the air passing through it. The air sucked by a variable-speed axial fan via grids, then a diffuser, and finally reaches a test section. The test section, which has dimensions of 305 mm by 305 mm and 600 mm in length, is designed to study protypes. The grille helps prevent the fan from being damaged by stray items. Then the flow departure from the fan, is routed via a silencer device before being released back into the atmosphere.

The rate at which the axial fan rotates is regulated by a control and instrumentation unit that is located in an indicated enclosure (and the air velocity in the test section). Manometers and electrical outlets are also included.

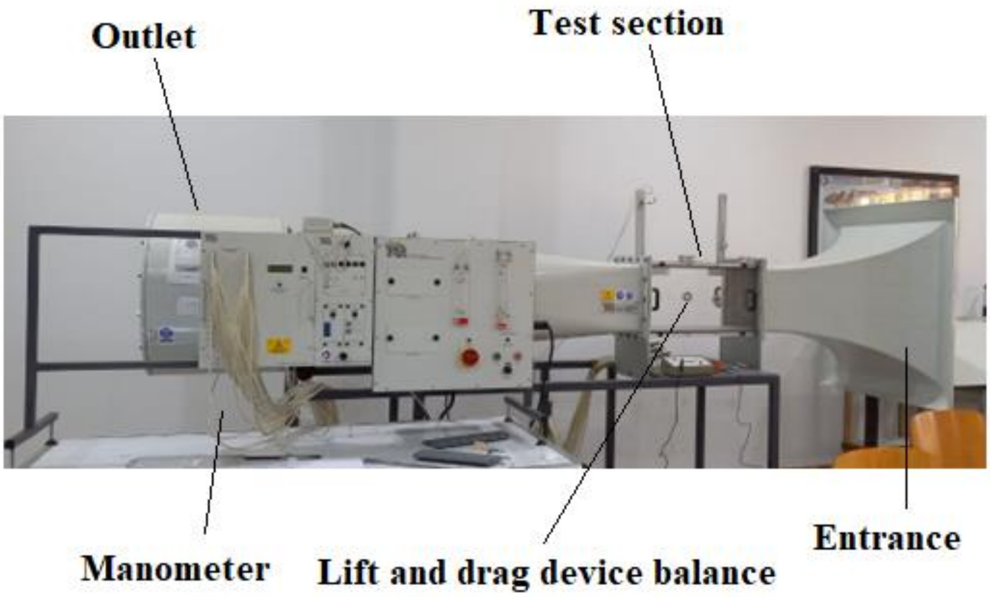


Fig. 6 The open loop wind tunnel.

3.1 THE EXPERIMENT PROCEDURES AND METHDOLOGY

The main processes in the current experiment can be summarized in the following points:

1. Switch on the electric regulator on the control and instrumentation frame.
2. Check to see if the Pitot-static probe is aligned properly.
3. Use the equations below to determine the level of the manometer (h) that is fixed on the pitot static tube in the test section:

$$U_\infty = \sqrt{\frac{2\rho_{water} g h}{\rho_{air}}} \quad (1)$$

4. A wind tunnel is switched on and sets the wind tunnel test section's air speed to the proper value.
5. An airfoil model can be installed in the wind tunnel for testing. The airfoil is installed tightly across the test section. There are mechanical facilities can provide the desired model angle of attack. The model angle of attack is setting by a fixed protractor on the wall of the test.
6. Tested models are rotated to a different angle of attack, and so (stages 1, 2, 3, 4 and 5) were repeated for each case at a given speed and different angles of attack. The experimental ranges for the variables that were measured:
   Free stream velocity ≈ 10,15, 20 and 25 m/s.
   Angle of attack = 0, 2, 4, 6, 8, 10, 12,14,16,18 and 20 degrees.
7. To measure the lift and drag force, the Lift and Drag Balance unit must be firstly installed, in which the model is set and (stages 1, 2, 3 and 4) were repeated for each case at a given speed and different angles of attack measure the lift force with speeds at different angles of attack.
8. The Lift and Drag Balance unit can be adjusted to measure horizontal force, which represents drag force to measure in the same way as lift force is measured.

4. RESULTS AND DISCUSSION

Figure 7 shows the effect of slot and slotted wavy blade on the lift coefficient at a speed of 10 m/s and a Reynolds number of 1.04×10^5. The results indicate that slotted wavy modification to the blade could not influence highly the lift coefficient; however, the slot model shows significant improvement at angles of attack between 10 and 12 degrees. The normal blade could perform better than the wavy blades at low attack angle [5][16]. The CL of the normal blade is up to 1.3. Whereas, CL for the slot and hybrid models are lower than 1.3.

When the wind speed is increased to 15 m/s, as illustrated in Figure 8, the modified models exhibit a same behavior. However, the slotted and wavy model showed an earlier stall than the normal model. This could be due to the existence of modifications at high velocity had negative effect on the flow above the blade surface.

At a speed of 20 m/s and higher, as shown in Figure 9, there is a perfect match through all curves. The slotted wavy and models records values higher than the normal model. Similar to [17], the slotted and wavy model provides high lift forces at low angles of attack, as shown in Figure 10. The limitation of the size of the models might have a reversal influence on the delay of the stall at high wind speeds.

At wind speed 25 m/s, as shown in Figure 11, the CL/CD ratio was comparatively studied at all angles of attack. The ratio stays close to steady performance with variations after 40. At an AOA of 6 degrees, the peak is seen, and the greatest CL/CD ratio is around 70. When the angle is greater than this, the ratio begins to decline but remains larger than the normal model. The slot and wavy curve showed a smaller peak than the slot curve but still improves the CL/CD ratio when compared to the normal blade. Moreover, the maximum ratio is reached, with a value of 40 and then the ratio drastically drops.

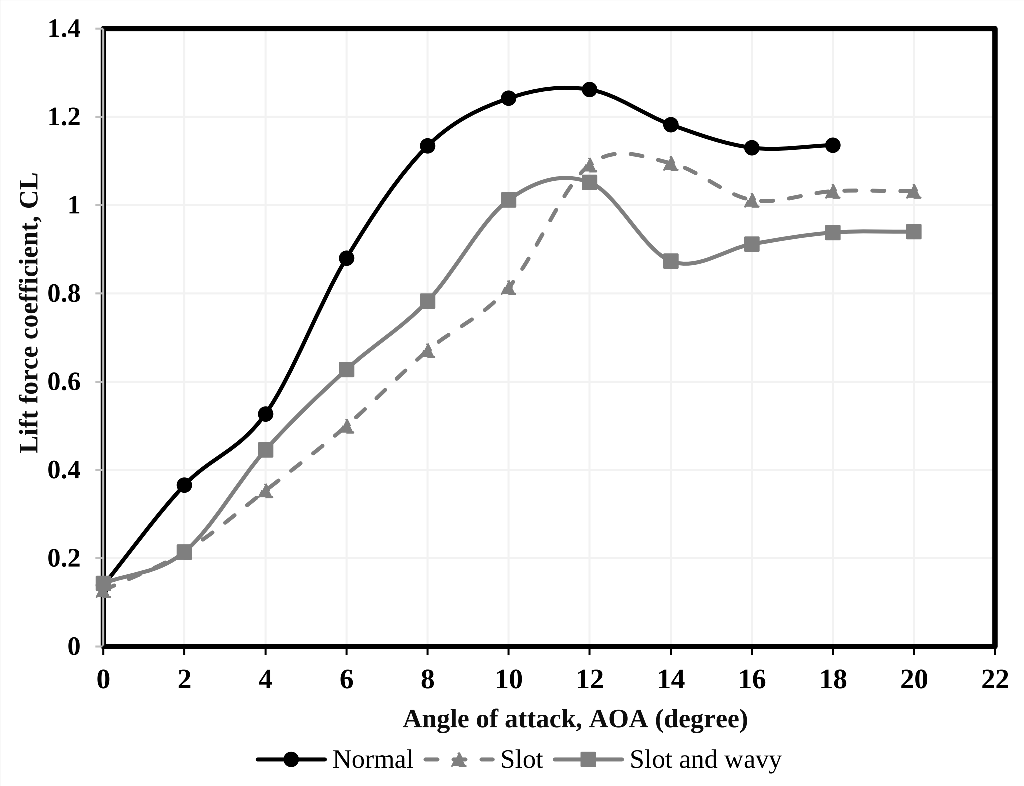


Fig. 7 Lift coefficient at various angles of attack at velocity 10 m/sec.

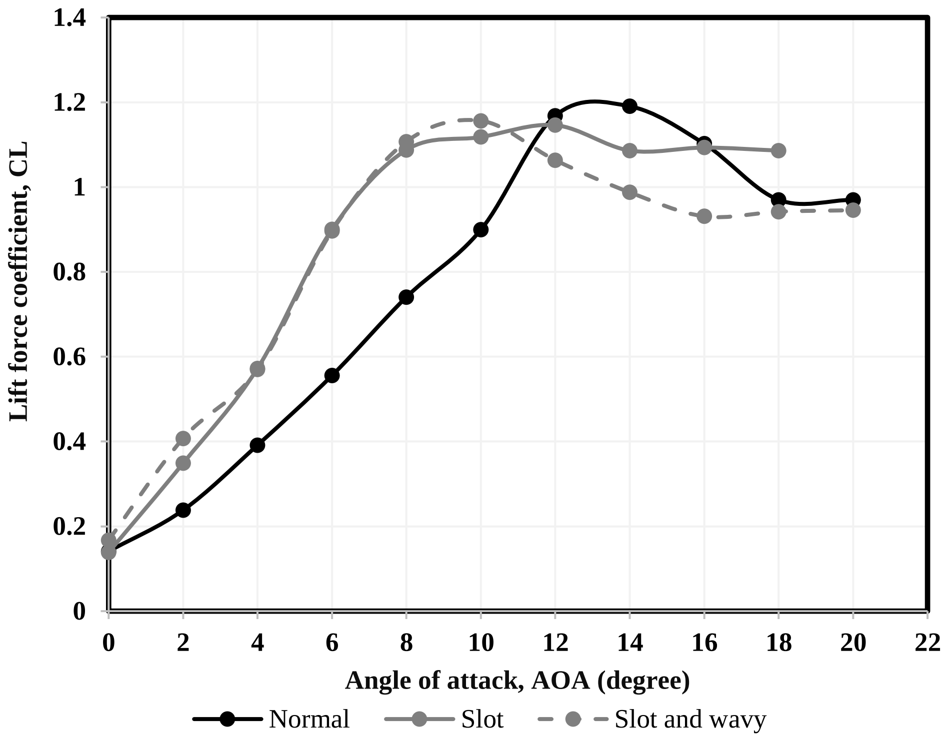


Fig. 8 Lift coefficient at various angles of attack at velocity 15 m/sec.

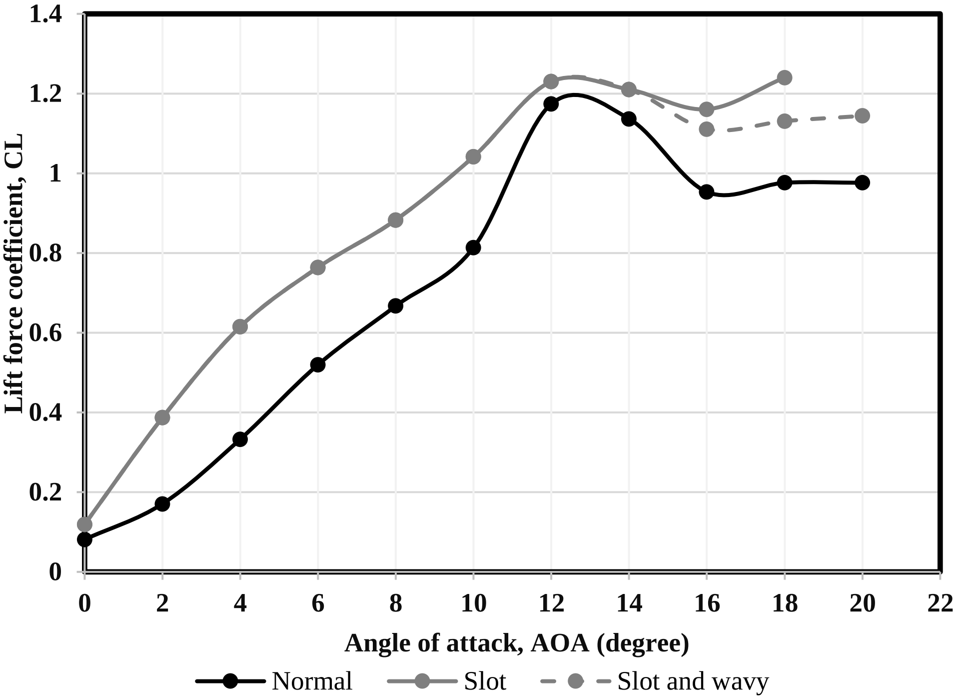


Fig. 9 Lift coefficient at various angles of attack at velocity 20 m/sec.

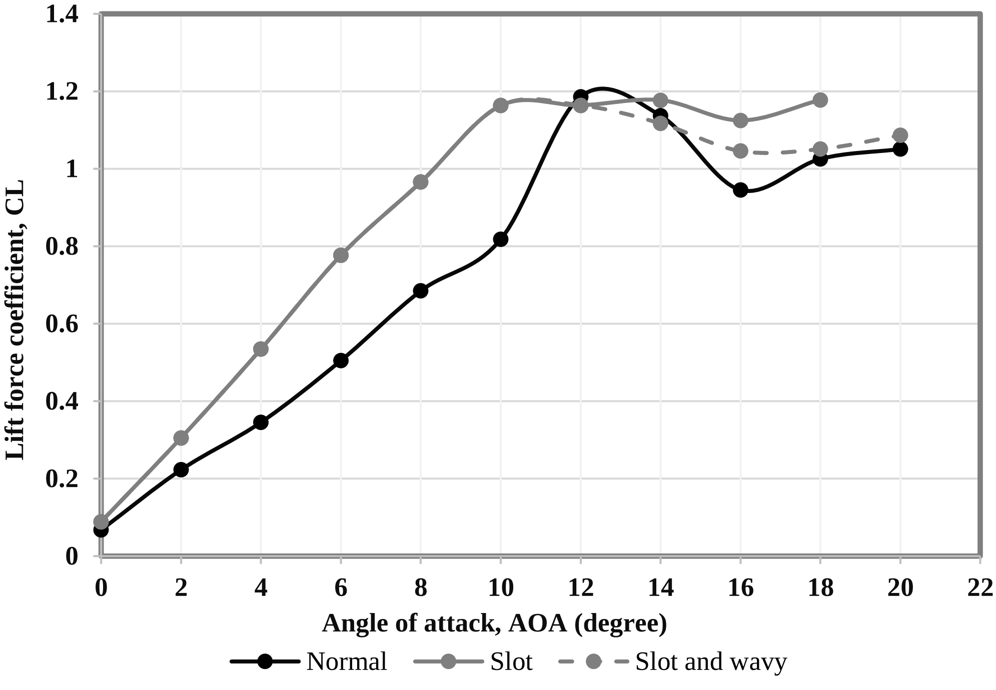


Fig. 10 Lift coefficient at various angles of attack at velocity 25 m/sec.

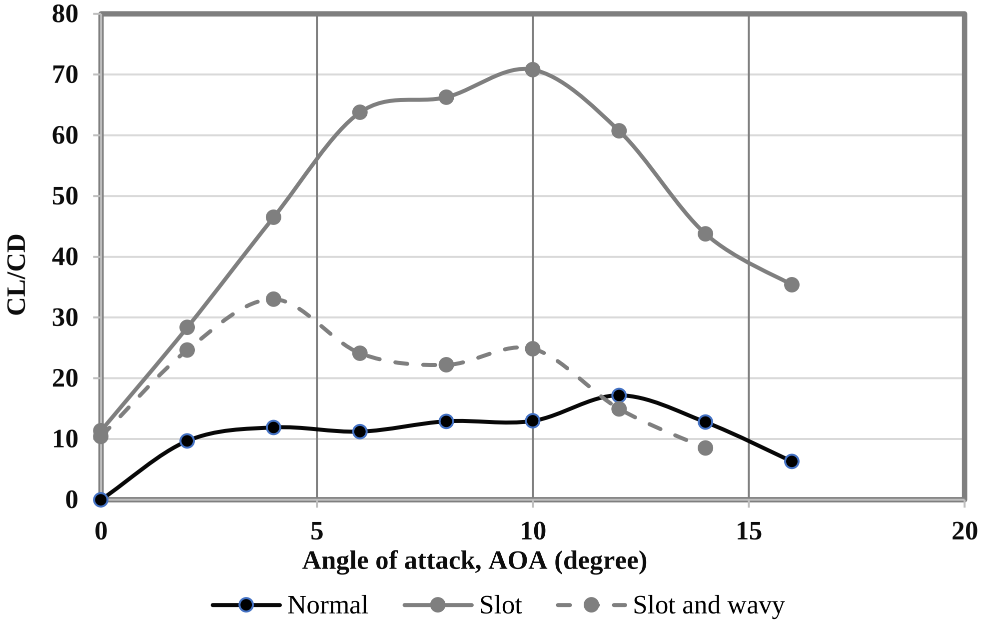


Fig.11 Lift-to-drag ratio at various angles of attack at a velocity of 25 m/sec.

5. CONCLUSIONS

The main objective of this work is to investigate methods that could increase the lift coefficient in blades of wind turbines, aircraft, and helicopters by overcoming flow separation at various angles of attack. The study focused on the NACA 0012 airfoil model with angles of attack ranging from 0 to 20 degrees at various speeds.

The impact of the internal slot (slotted) in the wing, along with the combined effect of slots with leading-edge waves, was studied. The experimental work showed that the hybrid model may not always cause the delayed stall. The normal model compared with the hybrid model blade declared an excellent at 10 m/s.

It is evident that the slotted and wavy leading-edge blades displayed a stall delay from 12^{o} to 10^{o} when the wind speed was increased. All in all, the modified models could perform stall delay at low relatively Reynolds numbers.

The CL/CD ratio curves declared that the slotted blade can performed better than other models.

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