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Sinusoidal Delta Wing: Challenges and Opportunities

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Abstract—*In the modern warfare supersonic fighter jets play a vital role. German scientists made a breakthrough at the time of World War II by introducing delta wing which is a delta like wing platform. With time aerospace industry has evolved keeping the basic delta structure same but introducing different flow control methods. This paper is a compilation of the researches done in this sector which describes the flow structures over a delta wing along with the advancements done in this field. Higher lift to drag coefficients, more manoeuvrability and delayed stall angles are such parameters which is essential for supersonic jet planes. In this paper more focus is given to a new wing platform design on which researchers are currently working and results are showing extraordinary scope of achieving high lift to drag ratio and also a delayed stall. This is called Sinusoidal Delta Wing. The leading edge has been made sinusoidal inspired by the flipper movement of the humpback whale. In a delta wing with a normal leading edge two primary vortices are generated which cause the lift. Introducing sinusoidal leading edges multiple vortices thus providing more lift. Review of the experiments and the results are included in this paper thus hope this will help the new researchers to understand the development of delta wing.*

1. INTRODUCTION

Delta wing is a triangular shape wing platform. From the World War 2 German researchers began to find out the exceptional maneuverability facilitated by delta wings. Controllable flight even in exceptional fight situations, e.g. at a high angle of attack at subsonic speed, stall margin, wing design allowing for a high critical Mach number due to the wing sweep and moderate wing thickness distribution facilitated by delta wing .As a result the 5th generation supersonic jets are using different types of delta wings and the transatlantic passenger jet Concord started a new era of supersonic passenger jet. Researchers working day and night to improve its performance. Aerodynamic investigations has been done for understanding the flow field characteristics of generic and complex delta wing. Delta wing having sharp leading edge is the most common, along with this round leading edge, delta wing with center body and also most recently scientists are working on delta wing with sinusoidal leading edge. In this paper we will try to summarize all the research works done on delta wing for a better understanding of the evolution of delta wing. This paper is all about the development of the delta wing platform till now, various experimental and computational studies done by different researchers around the world. This paper is concentrated on sinusoidal delta wing which is a new platform in the delta wing design and it's comparison with the other delta wing designs. Moreover a short review on the flow structure over delta wings is done.

2. FLOW PHYSICS OF DELTA WING WITH SHARP LEADING EDGE

The flow physics of a delta wing with sharp leading edge investigated by researchers [1,2,3,4,5,6,7,8,9,10] reveals that with a highly swept leading-edges the flow separates directly at the apex at low angle of attack. The vortices form close to the surface of the wing [18], and vortex/boundary layer interaction becomes important [19, 20]. The shear layer rolls up and form a pair of primary large-scale vortex over each half of the wing. These two strong vortices greatly influence the flow field of the wing upper side.

Vortex formation along the leading-edge starts from the rear part to the apex. This primary vortex is fully developed when vortices feeding extends over the entire leading-edge. The vortex cross-flow area reveals a rotational core with an embedded sub core, the latter dominated mainly by viscous effects.

The secondary vortices occur due to the interaction of the flow induced by the primary vortex interacting with the boundary layer on the upper wing surface. The strength and position of the primary and secondary vortices is mainly influenced by the free stream velocity, angle of attack, as well as on the sweep angle of the delta wing [12, 13]. The vortex flow under turbulent flow conditions is fairly independent of the Reynolds number for sharp leading edge delta wings whereas under laminar flow conditions the Reynolds number affects the position and strength of the vortices as well as the vortex topology over the wing [14]. At very low Reynolds numbers, vortices exhibit wake like axial velocity profiles even upstream of breakdown [15, 16, 17].

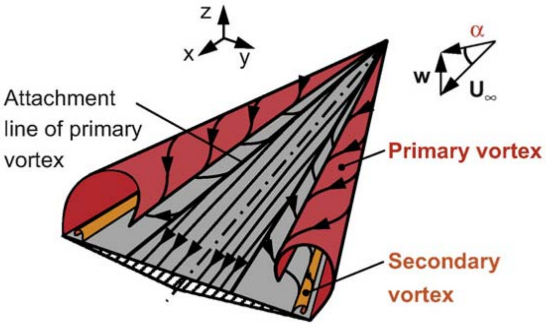

Fig. 1: Delta wing vortex formation [41]

Leading edge vortices in a fully developed, stable stage create additional lift [21] and an increase in maximum angle of attack which significantly improve the maneuver capabilities of high-agility aircraft. Sharp leading-edge configurations are often used in delta wing research work because primary separation is fixed and leading-edge vortex evolution is less sensitive to Reynolds number effects.

3. FLOW PHYSICS OF DELTA WING WITH ROUNDED LEADING EDGE

Flow topology over the delta wing with rounded leading-edge is completely different from the flow around the sharp leading-edge configuration. The flow around delta wing configurations with rounded leading edges is still not entirely understood. The Second International Vortex Flow Experiment—VFE-2 was established focusing on the flow around delta wing configurations with rounded leading edges [23]. The round leading edge generates two primary vortices rotating in the same direction on the upper surface [22] . First generate a inner vortex which is weaker and then a stronger outer vortex. The location, strength, and starting point of the vortex system on the upper wing surface depends on Mach number, Reynolds number, and angle of attack. The same basic flow topology occurs for all flow conditions.

Numerical investigations on VFE-2 65-degree rounded leading edge delta wing was done by Andreas and Heinrich [24]. They used the unstructured DLR TAU-Code a cell-vertex finite volume code using hybrid unstructured meshes. A dual-grid approach was used to get second-order cell-vortex based scheme.

4. DELTA-WING WITH CENTER BODY

Huang [25] investigated the vortex dynamics of military-aircraft-configuration delta-wings of various sweep angles and wing-body configurations. The wing shapes treated included not only 65-deg single-delta and 80/65- degrees double-delta wings with center body positioned behind the wing apex, but also 65-deg delta wing with tail and a tangent ogive fore body. He reported that there was no global effect of the center body on the wing-surface pressure distribution.

The position of vortex breakdown is influenced by the presence of a fuselage-like structure under the lower surface of the delta wing. It moves the position upstream as much as 20% chord for a sharp-edged 65-deg delta wing [26].

Other experiments reveals that adding a center body to the delta wing platform dramatically promoted the onset and chord wise progression of vortex breakdown.[27] Straka and Hemsch used flat-plate delta wing attached to. The fuselage of a pointed tangent-ogive front-body and a 1.5-inch diameter cylindrical aft-body.

Analyzing the flow physic associated with body-induced camber effects for delta wings in [28,29,30] shows that a center body or fuselage of a delta-wing-body configuration has a profound effect on vortex breakdown characteristics.

In [31] Lowson concluded that Reynolds number, strut position, and visualization methods had little effect on vortex breakdown position moreover suggested that the apex shape was the key effect in determining the vortex breakdown position because the vortices shed from the apex formed the center of the vortex core.

Myong in [32] shows that The sharp-edged 65-deg double-delta wing with LEX in the present study maintains a stabilized and well-organized vortex system due to the strong interaction of the wing vortex and the LEX vortex, which subsequently results in the presence of the center body having a minor effect on the flow pattern and the wing-upper-surface pressure distribution.

5. DELTA WING WITH SINUSOIDAL LEADING EDGE

Inspired by Humpback whale's (*Megaptera novaeangliae*), maneuvering agility which is one of the largest baleen whales, is famous for its large pectoral fins researchers started to find out the effects of the sinusoidal leading edge fins on delta wings. Fish and Battle [33] noticed that the special tubercles interspersed among the leading edges of the humpback's pectoral

Fin, which are analogous to large vortex generators used on aircraft, may postpone stall and thus enhance the maneuverability of a humpback whale. Watts and Fish's [34] investigation showed that protuberances on the leading edge may increase lift and reduce drag at certain angle of attack (AOA). Study of a simplified humpback's flipper model with sinusoidal leading edge by Miklosovic [35] showed that the stall angle of attack was postponed by approximately 40% with lift enhancement and drag reduction.

Fig. 2: Pectorial fin of Humpback Whale

Johari et al. [35] investigated the aerodynamic performances of NACA634-021 airfoils with different SLE. Their results demonstrated that with proper amplitude and wavelength, SLE could enhance the lift coefficient in the post-stall region by 50% with little drag penalty. They also pointed out that rather than the wavelength, the leading edge amplitude played a more important role in improving the aerodynamic performance.

Van Nierop et al. [36] developed an aerodynamic lift-line model for showing the effects of the sinusoidal leading of a humpback whale flippers. They found that the lift curve was flattered because of two reasons. First as the trough sections stall at lower angles of at lower angles of attack than the peak section and it is independent of the global flow coupling. Secondly the downwash was larger at the crests of the protuberances than at the troughs, thus leading to a decrease in effective angle of attack and this is the reason behind the delay stall for the flippers.

Hasen et al.[37] done experimental investigation to determine the influence of sinusoidal leading-edge protuberances on the performance of two NACA airfoils with different aerodynamic characteristics. Their experiments reviled that the post stall lift performances of both airfoils were improved. Hydrogen-bubble visualization indicated that stream wise vortices were formed in the troughs between the tubercles, which agreed with the results of Jahari et al.

Guerreiro and Sousa [38] investigated the application of a sinusoidal leading edge to the design of micro air vehicles. Rectangular platforms, and sinusoidal leading edges were studied through a series of wind-tunnel tests and compared with the results of a base line model. It was focused on the effect of Reynolds number and aspect ratio of sinusoidal leading edges was investigated. At *Re* = 140,000 the wing with protuberances caused a reduction in lift coefficient for angles of attack below the baseline model stall angle. For $\alpha \geq \alpha_{stall}$, the results depend strongly on the aspect ratio. For wings with an aspect ratio of 1.5, the sinusoidal models presented a much smoother stall.

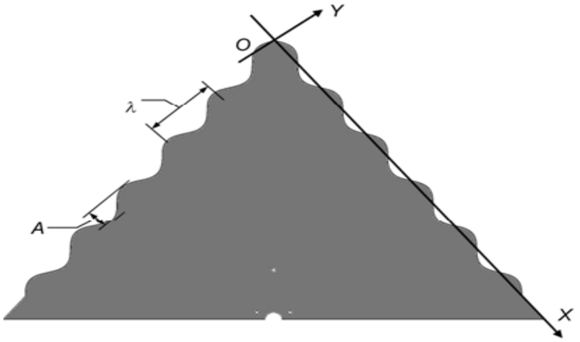

Fig. 3: Sketch of the delta wing model with sinusoidal leading edge [40]

Near surface topology of delta wings with SLE has been investigated by Goruney and Rockwell [39]. Stereoscopic particle image velocimetry technique was applied to determine the effect of the leading-edge geometry on the near-surface flow patterns. It was found that the amplitude of SLE as small as 0.5% of the root chord length can substantially alter the near-surface topology. They predicted that this topological change may enhance lift coefficient around the stall angle. The surface-normal velocity indicate the onset of a pronounced region of flow reattachment close to the plane of symmetry of the wing.

CHEN at el[40] investigated the Effects of sinusoidal leading edge on delta wing performance and mechanism. Flow visualization of 4M model gave a general view of the underlying mechanism of the sinusoidal leading edges. It revealed that flow patterns on the leeward surface of 4M model was quite different from the baseline case: vortices originated from every crest of SLE at small AOA ($\alpha=10^{\circ}$), in distinct contrast to the dual leading edge vortex structure in the baseline case.

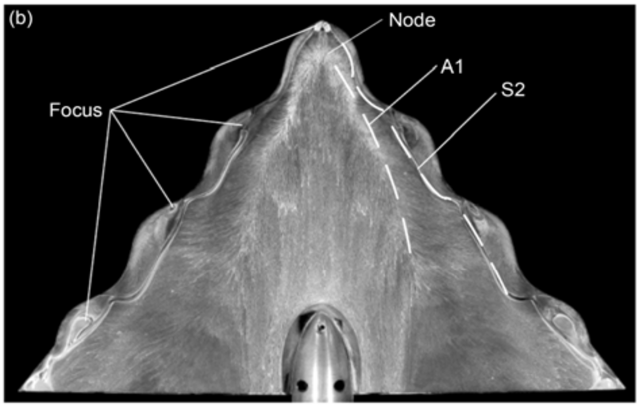

Fig. 4: Oil-flow pattern for the sinusoidal model at $\alpha=10^{\circ}$.[40]

Beyond the stall AOA of the baseline case (α =29º), the leading-edge vortices originating from the first crest of 4M model still persisted around the apex. It was further found that the vortices originated from the crest of the SLE breakdown on the leeward side, which may bring additional turbulent kinetic energy to the flow, resulting in the increase of the separated flow reattachment region on the leeward surface. This phenomenon can be regarded as the reason for the lift coefficient enhancement at large AOA.

They also showed that SLE could delay the stall process and enhance the post-stall lift coefficient for a delta wing with swept angle α=52º. By increasing the amplitude or decreasing the wavelength of SLE, stall AOA for delta wings could be increased. When the amplitude of SLE was small (*A*=2.5%*C*) or moderate (*A*=5%*C*), the stall could be delayed without distinct decrease of *C*Lmax and the lift-to-drag ratio was kept nearly unchanged at the same time. When the amplitude became even large (*A*=12%*C*), *C*Lmax decreased significantly.

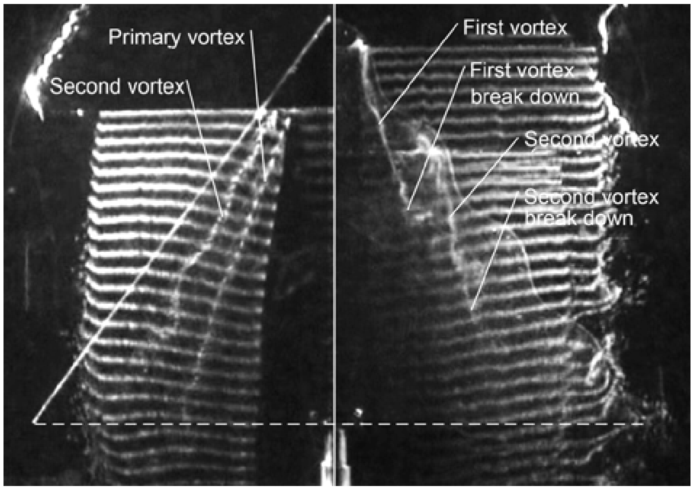

Fig. 5: Hydrogen-bubble visualizations for the baseline and 4M models at α=10º.[40]

Gradual stall behavior could be obtained only when the SLE amplitude was large (*A*=12%*C*) or the SLE wavelength was small (α=31.7 mm). Such characteristics could be used to improve the safety and agility of aircrafts. SLE also brought some additional drag to the delta wing, which made the (*C*L/*C*D)max less than the baseline case for all models with SLE.

In an separate paper CHEH et al.[41] has done the investigation of the vortex structure. Using SPIV method he measured the velocity fields of ten interrogation planes that were perpendicular to the surface of the wing geometry. His experiments clearly showed that the vortex structure with sinusoidal leading edge is totally different from that of the baseline case.

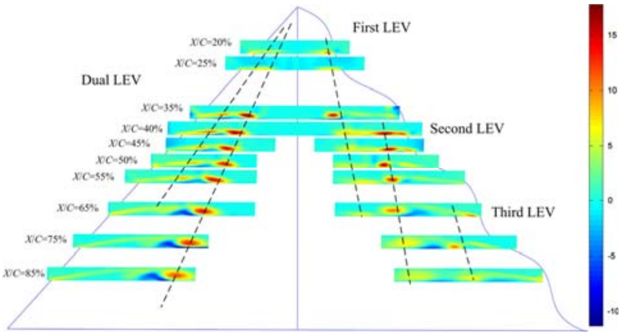

Fig. 6: Vortex structures of baseline and 4M model [41]

LEV stands for leading edge vortex

The leading edge vortices of the wing with sinusoidal leading edge decay faster than the baseline case and it can exist at higher incidence.

6. CONCLUSION

The development of the delta wing models along with the recent advances is discussed in this review paper. The state of art passive flow control technique like sinusoidal leading edge is of new interest. Though various experiments have been conducted in different delta wing models still there is a large scope of research for make such model a success and start commercial use. Clear concept of the flow physics of such design should be understood. The right combination of the wavelength and amplitude of the sine curve can provide highest lift to drag ratio, small angle of attack and delay stall.

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