# Lecture 7 - Unsteady Flows and Dynamic Stall

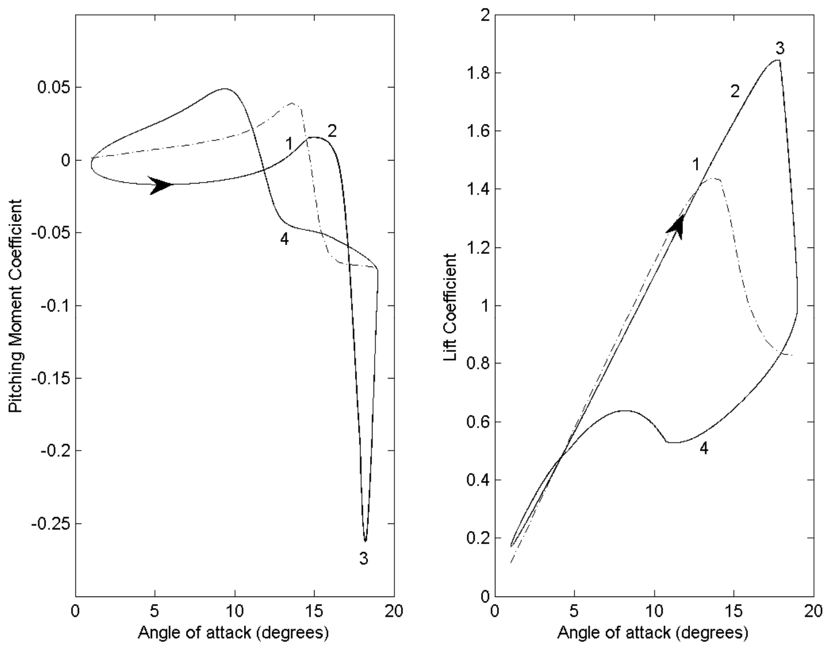



*Figure 1 Comparison of static and dynamic aerodynamic moments and lift forces*

Everyone should be familiar with the dashed lines in the figure above, where they represent the ______________________________________________________ and ______________________ curves of a typical aerofoil for a range of angles of attack. In the static lift curve figure, the two main parts are 1. the region of _______________ changes in lift with respect to angle of attack and 2. the _________________________ ____________________ of attack.

The solid lines in the figures represent the ______________________________ moment and lift curves for the dynamic angle of attack described by $\alpha = 10 + 8\sin(\varpi t)$. It is quite clear that the corresponding values of ____________________________ lift and moment are different from the static counterparts.

Note when we say dynamic angle of attack or dynamic lift, it refers to the value which is a ____________________________________________.

The reason we are interested in the dynamic aerodynamic loads (lift and moment) is because in ____________________________________________, the solutions of the system normally involve aerofoil oscillations in pitch, i.e. flutter. Hence, its effective angle of attack is almost always a ___________________________ as time increases.

The differences between the static and dynamic aerodynamic loads can be explained with ___________________ main phenomena.

***1.*** **__________________________________________________**

In the flow over a typical aerofoil, when the angle of attack increases from zero (but still lower than the static stall angle), flow separation will occur over the upper surface near the trailing edge, and the separation will propagate upstream as the angle of attack increases. The flow separation is a result of severe ____________________ ______________________________________ which occurs over the upper surface.

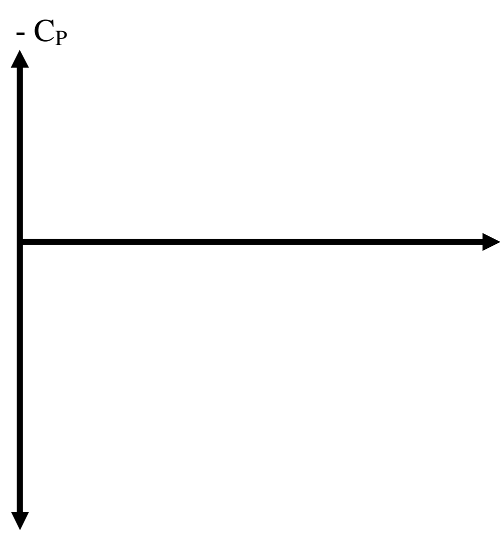
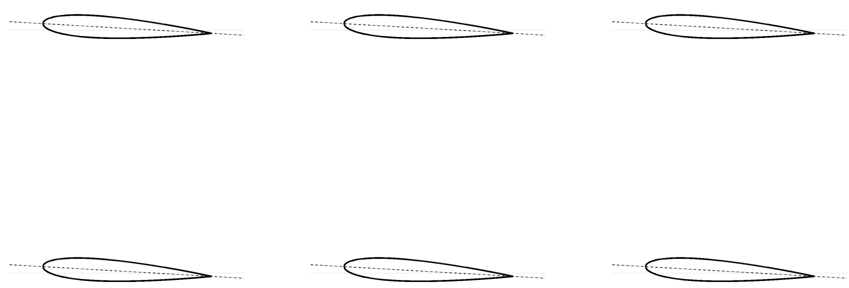



*Figure 2 – Pressure distribution over the surfaces of a typical aerofoil*

Now let us consider the streamlines over the aerofoil at $\alpha = 5^\circ$, $\alpha = 8^\circ$ and $\alpha = 10^\circ$, in both _________________________ and ________________________ circumstances ($\dot{\alpha} > 0$ in the dynamic case).



*3 deg.* *5 deg.* *8 deg.*

*Figure 3 – Streamlines over the aerofoil in static and dynamic conditions*

The ____________________ in streamline arrangements over the aerofoil results in the ___________________________________________________________ and, ultimately, ______________________________________________. It also accounts for the lower value of lift at the same angle of attack (during nose up motion) than that under static conditions.

**2.** _____________________________________________________

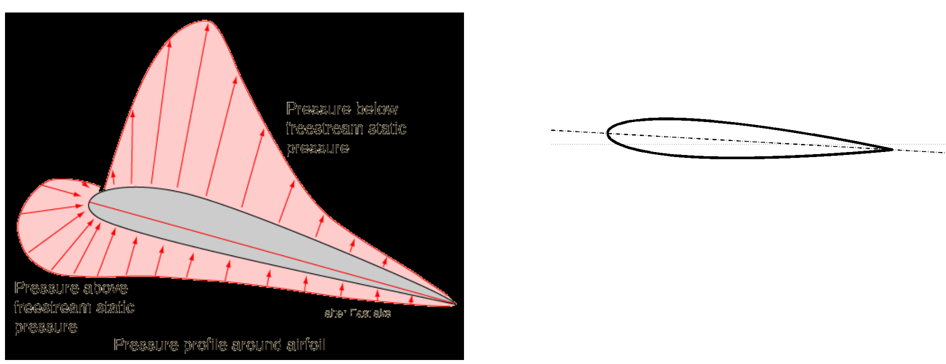



*Figure 4 – Induced velocity due to aerofoil rotation*

Let us consider the induced velocity around an aerofoil during a pitch-up motion as shown in figure 4. The extra ________________________ near the leading edge helps to further reduce the leading edge pressure and pressure gradients.

This will contribute to the delay of flow separation over the leading edge of the aerofoil.

***3.*** ___________________________________________

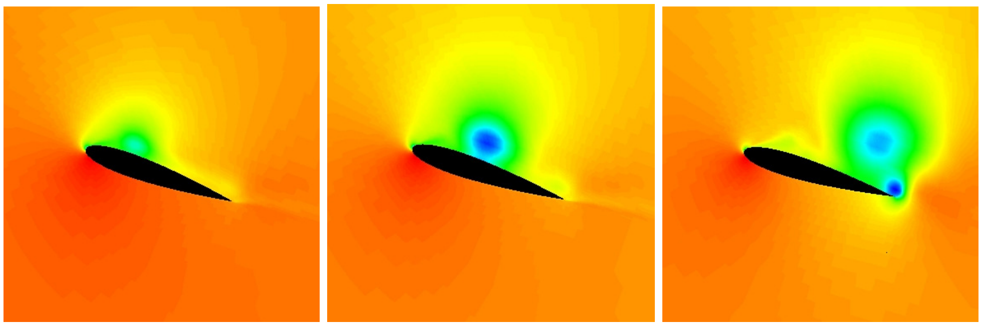


*Figure 5 – Formation of leading edge vortex and its movement over the aerofoil*

During a __________________ motion at an angle of attack significantly ________________ than the ________________________________________, the leading edge pressure is finally high enough to cause a flow separation (at the leading edge). This releases the high pressure that has been building up on the lower surface near the leading edge in the form of a ___________________________ over the upper surface of the aerofoil.

The vortex generates a large amount of ____________________ while it is being convected over the aerofoil.

Note: *Aerofoil lift is created by a positive net circulation around itself. The presence of a vortex helps increase the amount of positive circulation, hence, generates extra amount of lift force.*

Now, with explanations of these contributions we can revisit the moment and lift curves in figure 1 and analyse them in details. Notice that there are numbers 1-4 in both lift and moment curves. These numbers indicate the four main events which occur during ____________________________ of angle of attack oscillation, i.e. $\alpha = 10 + 8\sin(\varpi t)$ and $0 \le t \le (2\pi/\varpi)$.

*Stage 1*

At the static stall angle, the effects of flow separation are not yet present in the dynamic lift curve as it continues to increase linearly. Between stages 1 and 2, only delay effects and kinematic induced camber effect are present.

*Stage 2*

The leading edge pressure exceeds the critical value and is released as a leading edge vortex. At this point, the lift still continues to increase but the pitching moment begins to decrease very rapidly. This is because the vortex is being convected downstream, so its centre of pressure changes continuously in the chord-wise direction.

*Stage 3*

The vortex reaches the trailing edge where it marks the maximum value of lift, as once the vortex has travelled past the aerofoil, the vortex lift is suddenly removed and the lift decreases rapidly. It also marks the minimum value of pitching moment. Between stages 3 and 4, the aerofoil enters full stall regime.

*Stage 4*

When the angle of attack is low enough, flow starts to reattach again.

The term unsteady flow refers to the condition where the streamlines over the aerofoil are constantly changing. By definition, unsteady flow is the fluid flow whose ________________________________ with respect to ________________.

The term dynamic stall refers to the ________________________________ that occur when the range ________________________________________________________ ________________________, i.e. delays of separation, leading edge vortex shedding.

Dynamic stall is not a very common aerodynamic phenomenon and is only observed in a number of engineering applications.

*Figure 6 – Engineering applications where dynamic stall phenomenon is present*