Lecture 8 – Dynamic Stall Model

Previously we studied the physics of the unsteady flows around an aerofoil during a dynamic stall cycle. We saw that there are four main stages during a cycle namely

1. Delay of flow separation
2. Vortex shedding
3. Full stall
4. Flow reattachment

Obviously the most important effect of the dynamic stall phenomenon is the large fluctuation of aerodynamic lift and moment, which are what we will attempt to study now.

The aerodynamic forces that occur during a dynamic stall cycle can be calculated using a mathematical tool which is called a dynamic stall model. It is simply a series of equations which try to simulate the aerodynamic forces according to the motion of the aerofoil.

In this course, we will limit our attention to two dimensional problems only, i.e. only flows around an aerofoil will be considered. An aerofoil usually has two degree-of-freedom in pitch (rotation) and plunge (vertical translation). This means the aerofoil motion can be described by

$$\alpha(t), \dot{\alpha}(t), \dot{h}(t) \text{ and } \ddot{h}(t)$$

Dynamic Stall Model

A dynamic stall model is a mathematical tool which should be able to predict the aerodynamic loads (lift, moment, drag, normal force, chord force) of an aerofoil with known motion, i.e. $\alpha(t)$ and $h(t)$ are defined.

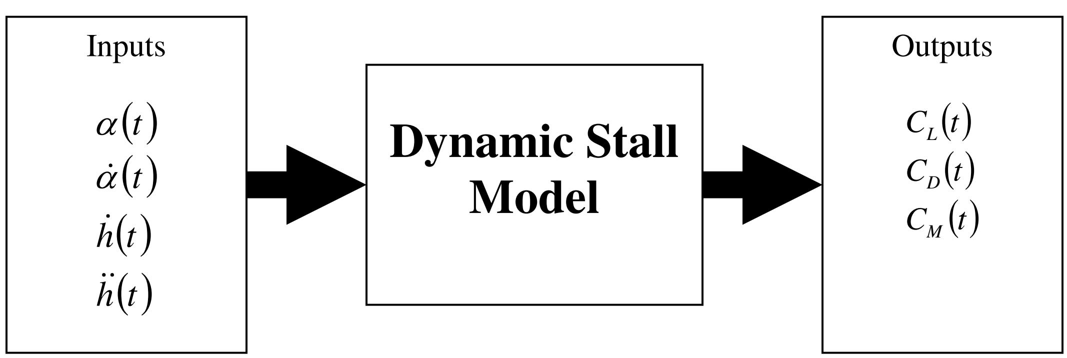

Figure 1

The model normally consists of three parts

1. Static aerodynamic model

2. Unsteady flow model, or delay of flow separation model
3. Vortex shedding model

Static Aerodynamic Model

The static aerodynamic model is the simplest part and is also the most important. One can think of it as the foundation of the complete model, whereas the unsteady and vortex parts are the additional effects.

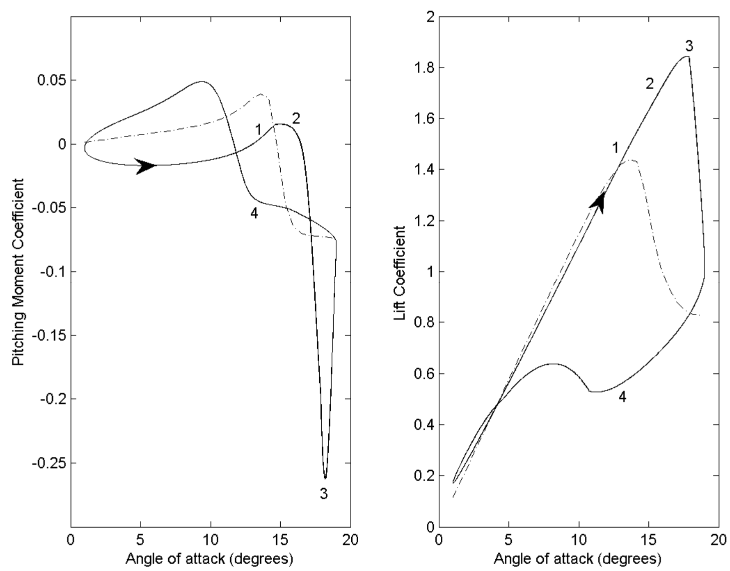

Figure 2 Comparison of static and dynamic aerodynamic moments and lift forces

The static aerodynamic loads are different for each aerofoil and can be regarded as its own properties. Traditionally, these static plots are obtained from experimental data at various Reynold's numbers and Mach numbers. The main features of static plots are

1. Linear region – This is normally the small angle of attack region where the lift and moment vary linearly with respect to changes in the angle of attack.
2. Static stall angle – This is the angle of attack where the maximum static lift is achieved. It also marks the point of full separation over the aerofoil upper surface should the angle of attack increases further.

Several methods are available to compute the static aerodynamic loads. For an ideal flow (inviscid and incompressible), we can determine the analytical solution from theory. However, for a real flow (viscous effects are present and fluid is compressible) which is governed by the Navier-Stokes equations, a more complex numerical method is required.

Here, we will use the Kirchhoff's theory to determine the static aerodynamic loads.

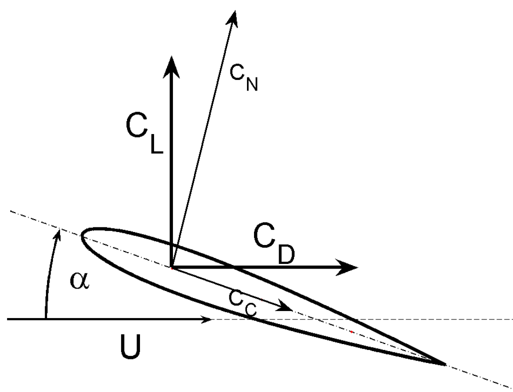

Figure 3 – Normal-chordwise directions and the traditional lift-drag directions

Before we begin, it is worth studying the following terms

- Normal force (C_N), and
- Chord force (C_C)

Dynamic stall is a phenomenon usually associated with helicopter blade aerodynamics. In this special field of fluid mechanics, they often work with normal-chordwise directions rather than the more traditional lift-drag directions.

The lift and drag can be easily calculated by resolving the normal and chord forces, i.e.

$$C_L = C_N \cos\alpha - C_C \sin\alpha$$
$$C_D = C_N \sin\alpha + C_C \cos\alpha$$

Kirchhoff's Theory

This method is based on the assumption that the flow separation over the upper surface of the aerofoil begins at the trailing edge and moves gradually forward as the angle of attack increases. It also assumes that the aerodynamic loads depend on the position of the separation point.

Let us define a new variable called, *f*, which represents the trailing edge separation point over the upper aerofoil surface. The variable *f* is measure as a fraction of the chord length, i.e. *f=0* at the leading edge and *f=1* at the trailing edge. A photograph in figure 3 shows an example of trailing edge flow separation.

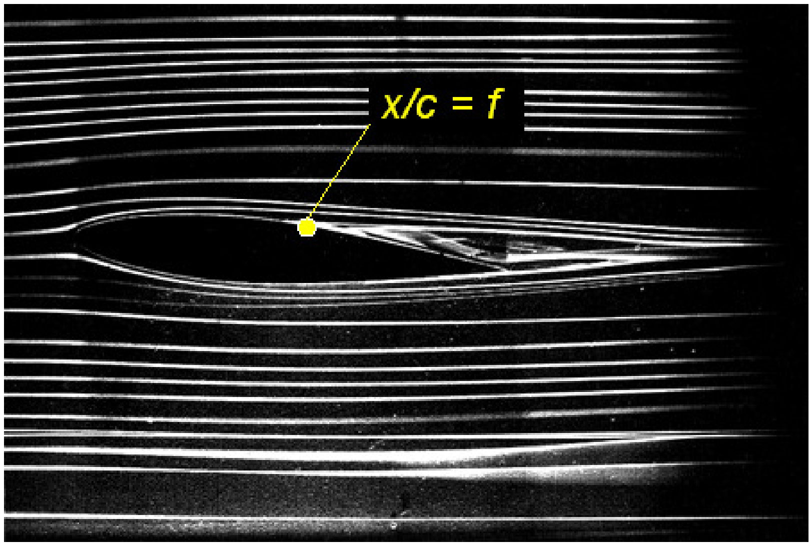

Figure 3 – Example of trailing edge separation

The trailing edge separation point is given by

$$f(\alpha,\alpha_1)=\begin{cases}1-0.3e^{\left(\frac{|\alpha|-\alpha_1}{S_1}\right)} & \text{if } 0\le|\alpha|\le\alpha_1 \\ 0.04+0.66e^{\left(\frac{\alpha_1-|\alpha|}{S_2}\right)} & \text{if } \alpha_1<|\alpha|\end{cases}$$

The normal force, chord force and pitching moment are given by

$$C_{N\text{ static}}=C_{N\alpha}\alpha\left(\frac{1+\sqrt{f}}{2}\right)^2$$

$$C_{C\text{ static}}=(0.97)\,C_{N\alpha}\alpha^2\sqrt{f}$$

$$C_{M\text{ static}}=\left[K_0+K_1(1-f)+K_2\sin\left(\pi f^2\right)\right]C_{N\text{ static}}$$

The parameters are functions of the Mach number and are given in table 1.

Mach	0.30	0.40	0.50	0.60	0.70	0.75	0.80
$C_{N\alpha}$	6.1879	6.589	7.0187	7.7063	9.0527	10.2273	12.7483
α_1	0.2662	0.2182	0.1833	0.1484	0.0977	0.0611	0.0122
S_1	0.0524	0.0567	0.0611	0.0698	0.0785	0.0611	0.0122
S_2	0.0401	0.0279	0.0209	0.0122	0.0087	0.014	0.0031
K_0	0.0025	0.006	0.02	0.038	0.03	0.001	-0.01
K_1	-0.135	-0.135	-0.125	-0.12	-0.09	-0.13	0.02
K_2	0.04	0.05	0.04	0.04	0.15	-0.02	-0.01

Table 1 – NACA0012 aerofoil parameters as functions of the Mach number

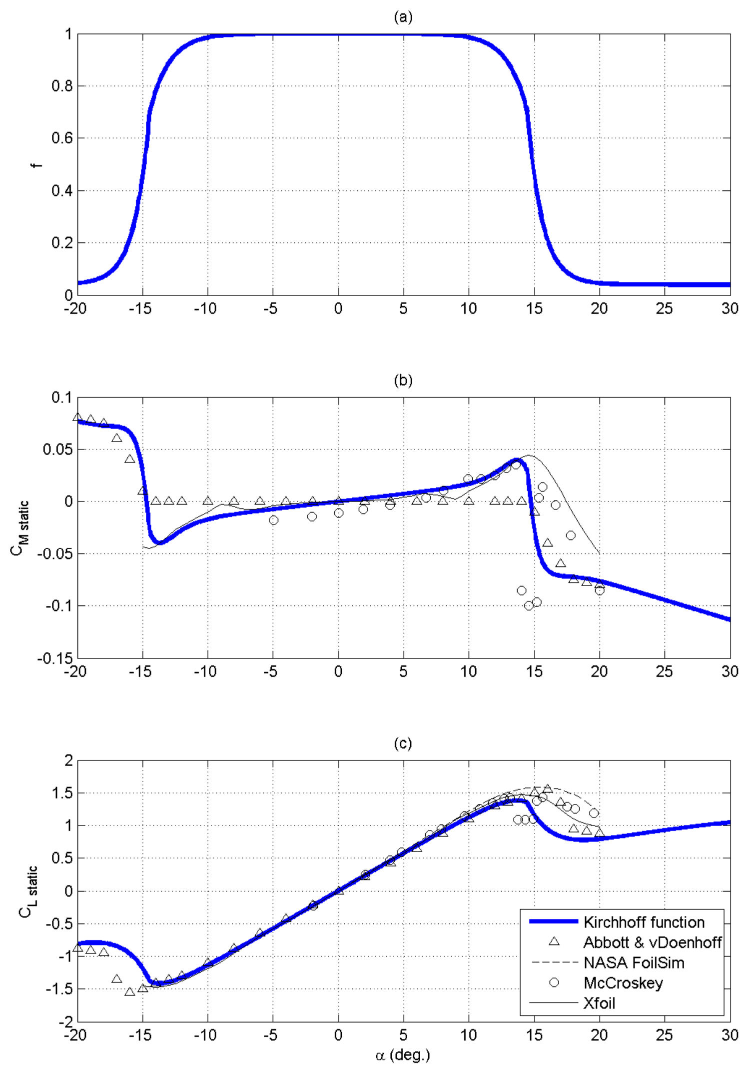

Figure 4 Comparison of static aerodynamic loads computed with various methods