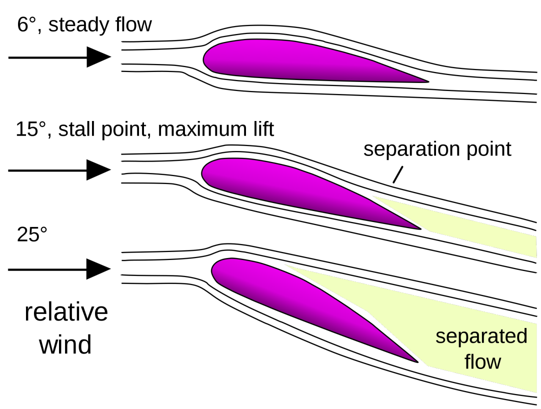
An Introduction to Flow Theory

Even without any quantitative analysis, we can postulate how we expect the lift to vary with the helicopter's blade pitch. If the pitch is $0°$, i.e. the blade is horizontal, we would expect there to be no lift. We would also expect there to be no lift when the blade is at $90°$. To predict what happens in between we must review some flow theory.

Flow regimes

Stall is a condition in aerodynamics that occurs when the angle of attack increases beyond a certain point. Aerofoils are designed to minimise the likelihood of stalling. The reason for stalling is flow separation, a phenomenon which is illustrated in the figure below[1]. Beyond a certain point, the streamlines detach from the surface of the blade due to the adverse pressure gradient along its upper surface, i.e. the fluid can no longer "stick" to the surface as the angle is too large. As the area of separation increases, the lift falls off dramatically.



Since we are using a flat plate in our Lego experiment, we would expect separation to occur rather early. While the streamlines are attached, simple models can be used to calculate the expected lift. However, once there is significant flow separation, the analysis becomes more tricky.

A good tool to help you visualise flow regimes is the smartphone app *Wind Tunnel*, available for Android and iOS. In *smoke* mode, the aerofoil can be rotated and the phenomenon of flow separation is readily apparent.

[1] Figure retrieved from `http://en.wikipedia.org/wiki/File:StallFormation.svg`

Potential flow theory

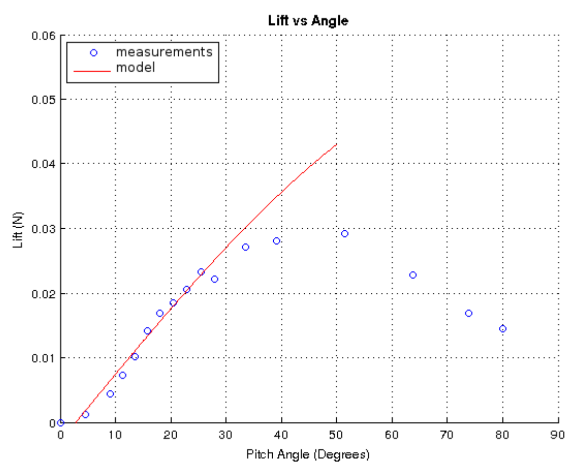
When there is minimal flow separation (i.e. at shallow angles of attack), potential flow theory can be used to predict the lift generated by a flat plate. The theory is covered in detail in Part IIA of the Engineering Tripos, where the following equation is derived for the lift L:

$$L = \pi \rho V^2 c \sin \alpha$$

α is the angle of attack, c is the width of the blade, ρ is the density of the fluid (in our case, air) and V is the speed of the fluid flow over the blade. In practice, our blades will not behave like a perfect flat plate in a steady flow (the Lego parts have holes in them and the flows over the two blades will interact), so there may be some lift even when α is zero. To allow for this, we consider the more general model

$$L = A + B \sin \alpha$$

where A and B are constants. In the graph below, we see the results of fitting this model (red) to data measured on the Lego helicopter (blue). A good fit was obtained with $A = -0.003$ and $B = 0.06$.



It would appear that the flow starts to separate at around $25°$, beyond which the potential flow theory breaks down. There is a nice Wikipedia article about potential flow theory, including its limitations, which you can consult for further information.