Università di Roma Tor Vergata

DYNAMIC STALL IN PITCHING AIRFOILS:

AERODYNAMIC DAMPING AND COMPRESSIBILITY EFFECTS

University Tutor:

Prof. Roberto Verzicco

Degree Candidate:

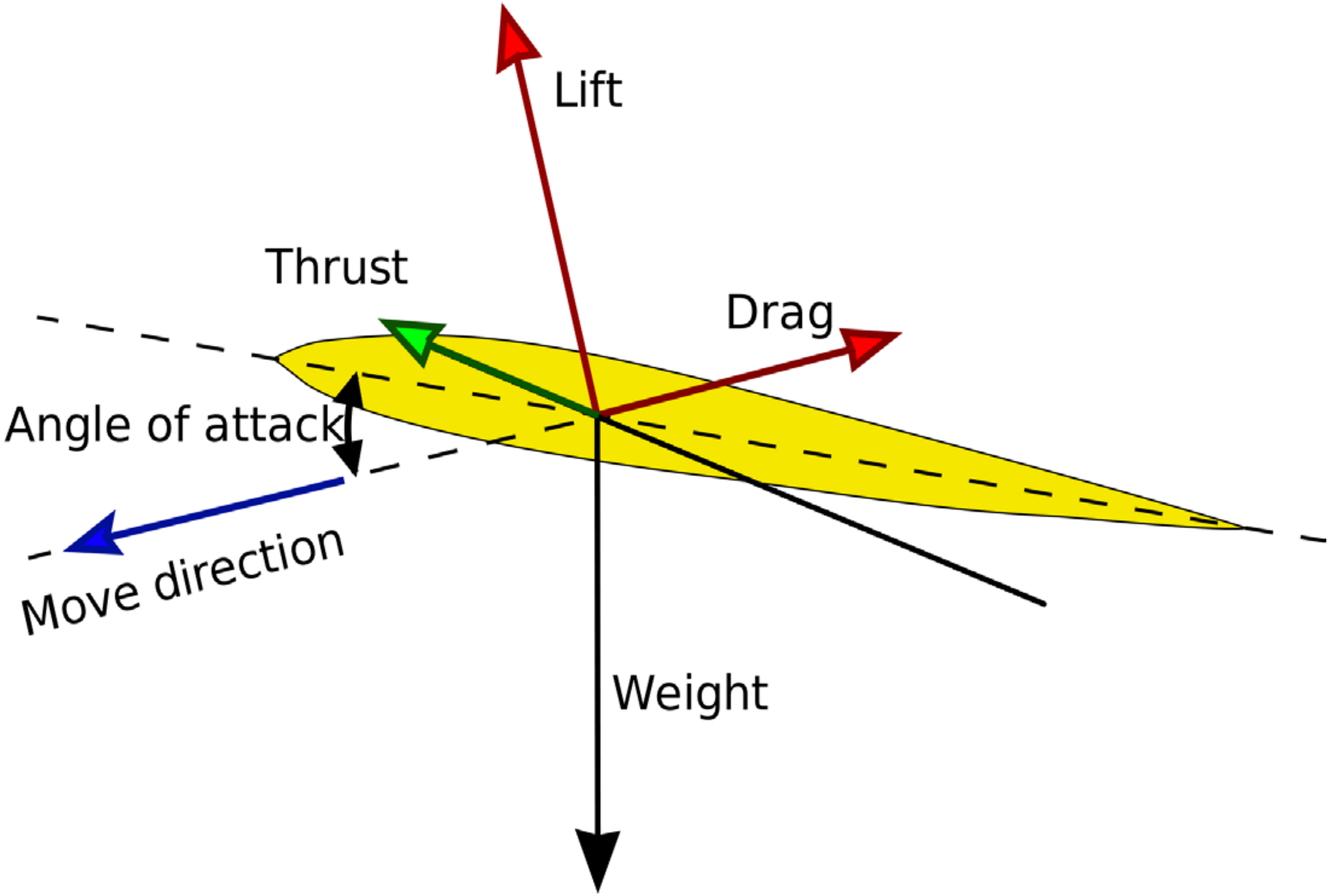
Alice Proietti

Dynamic stall occurs in an airfoil during rapid, transient motion in which the angle of incidence surpasses the static stall limit.

When this situation takes place, dynamic stall vorteces and great variations in the aerodynamic load can be observed.

Both surface roughness and local compressibility effects affect the dynamic stall process.

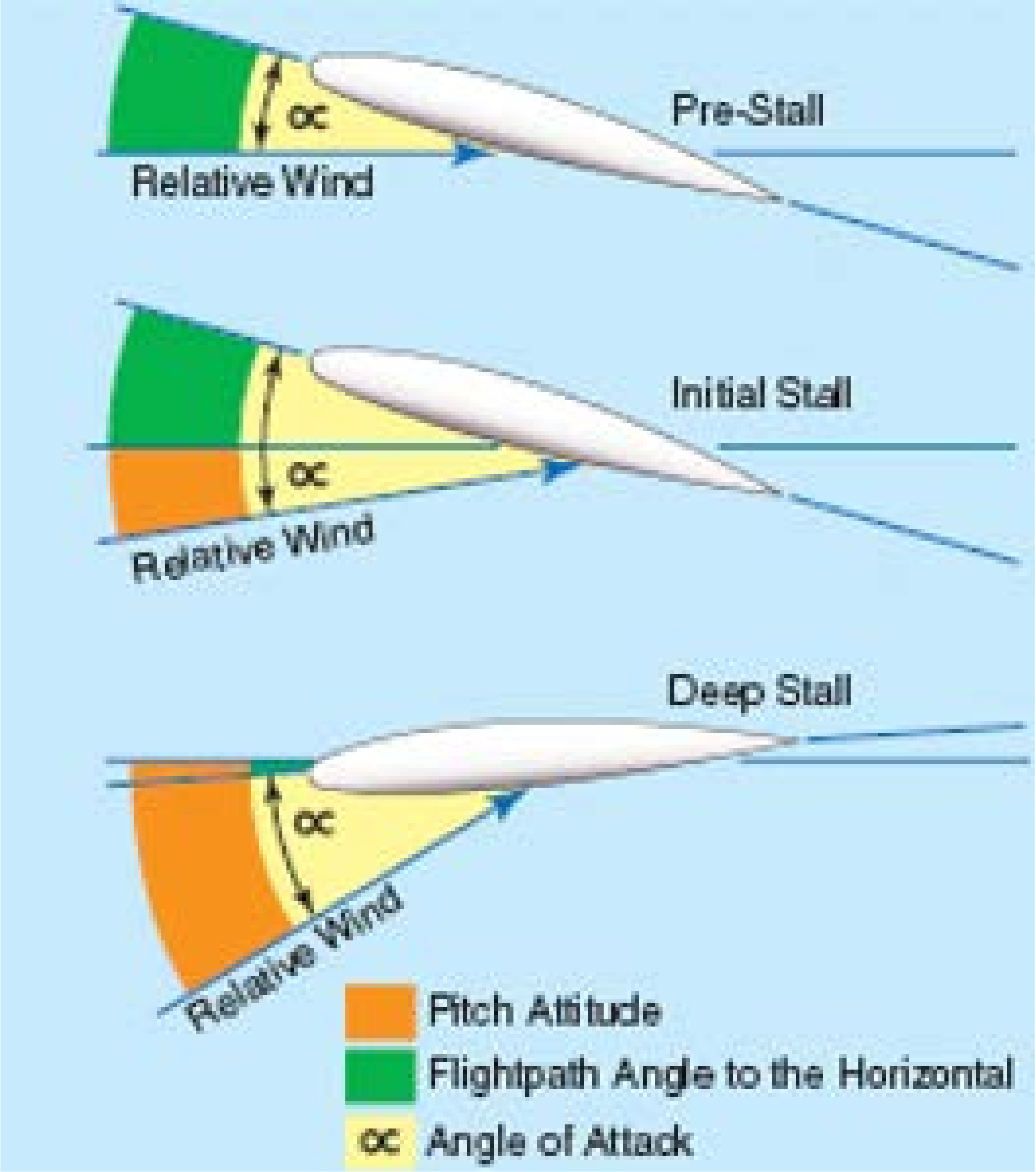
Under some particular conditions, dynamic stall can result in negative aerodynamic damping that leads to structural vibrations and, consequently, to mechanical failures.



BACKGROUND

Dynamic stall can be divided into four categories:

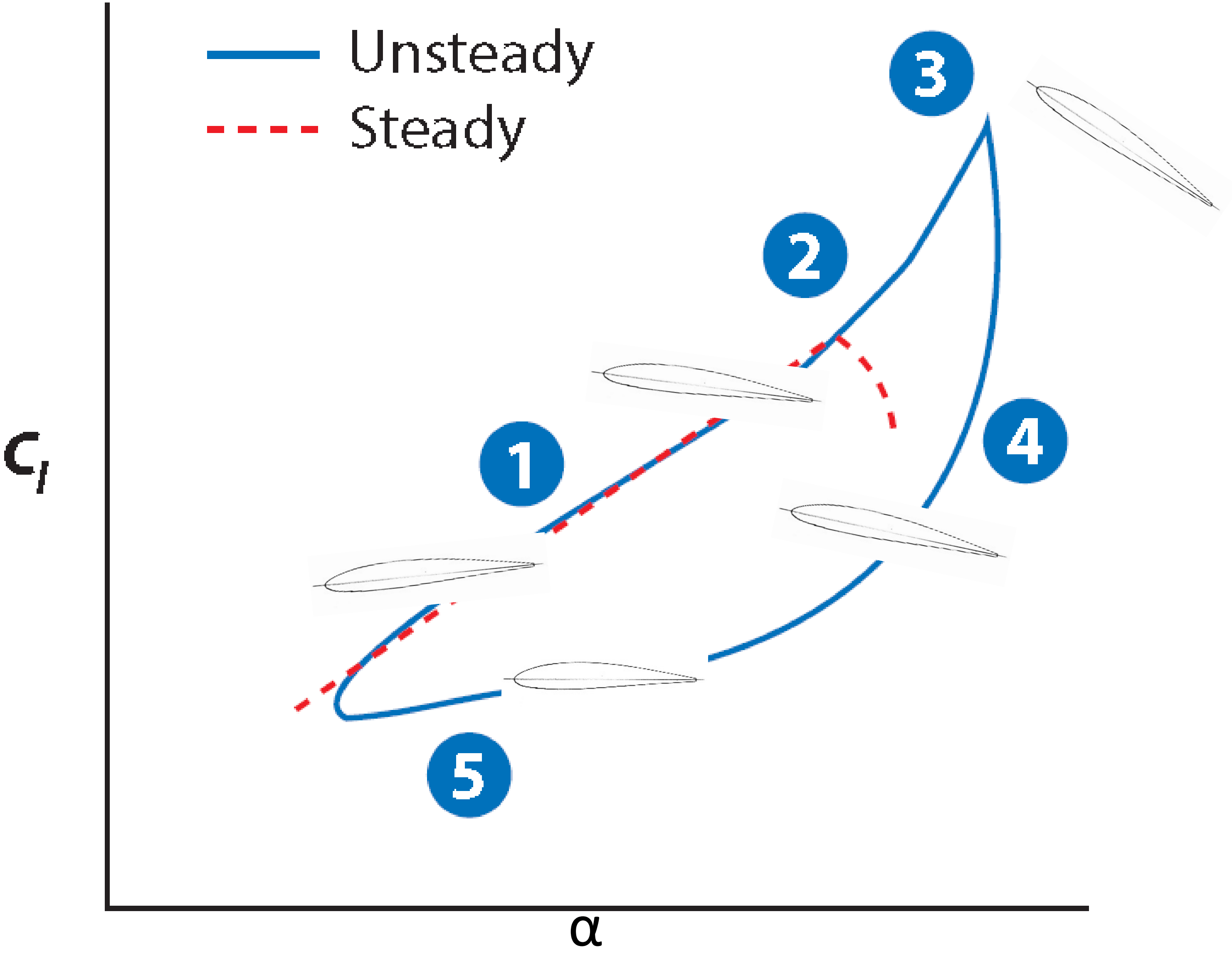
- no stall
- stall onset
- light stall
- deep stall



Dynamic stall process can be explained by a number of a stages.

- **STAGE 1:** the boundary layer on the suction surface of the airfoil is attached, and the lift force increases linearly with the pitch angle. This continues to the point at which the pitch angle reaches αss.

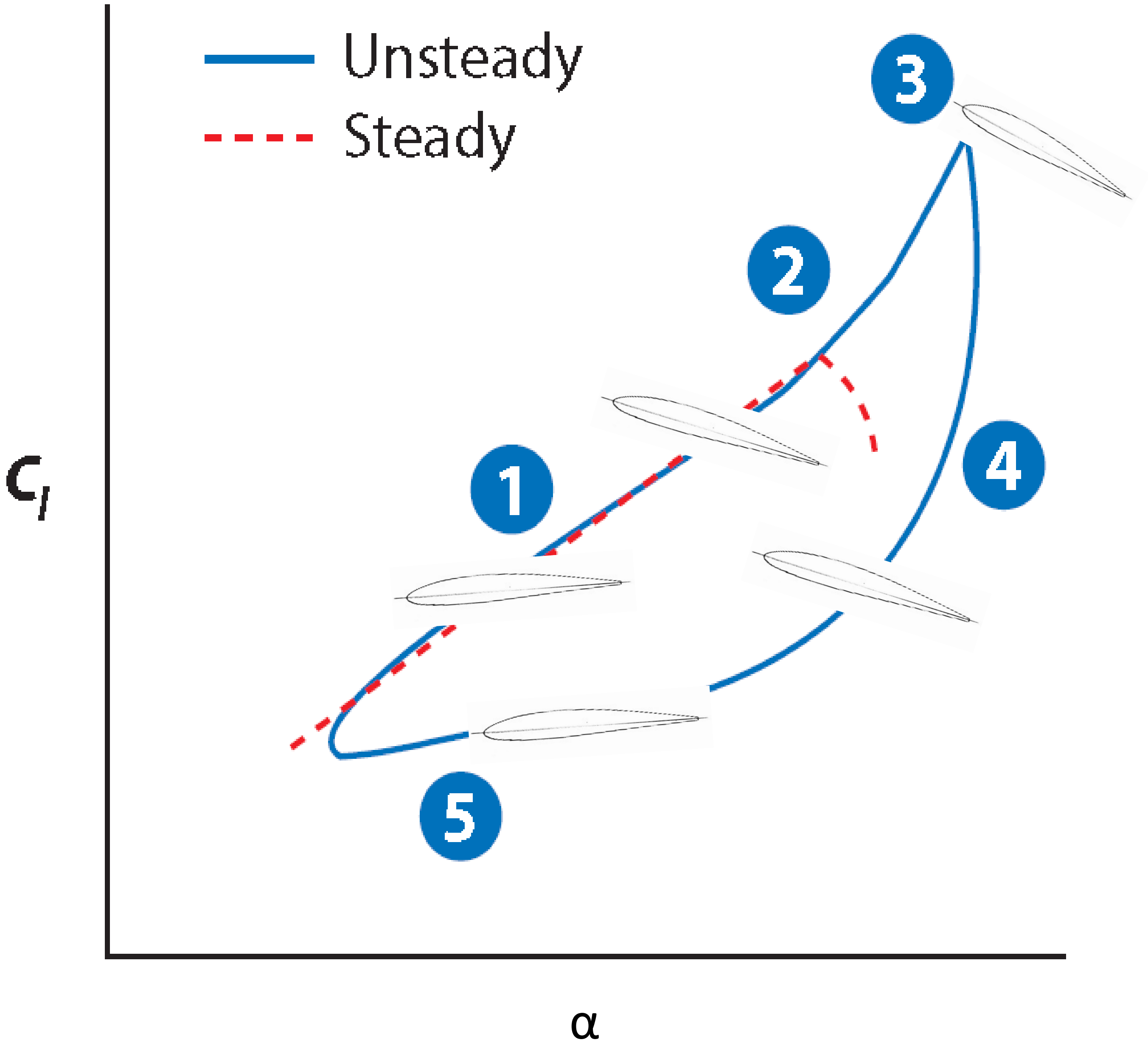
- **STAGE 2:** generation and ejection of vorticity from the boundary layer into the inviscid outer flow. The growth of the dynamic stall vortex increases the aerodynamic loading as well.



- **STAGE 3:** The fully formed dynamic stall vortex convects over the suction side. This motion of the low-pressure vortex core shifts the airfoil center of pressure toward the trailing edge, resulting in an acute nose-down pitch moment.

- **STAGE 4:** The low-pressure core of the dynamic stall vortex also augments the aerodynamic suction on the airfoil, increasing the lift. The added lift drops when the dynamic stall vortex convects off the airfoil and the flow is fully separated.

- **STAGE 5:** The pitch-down motion of the airfoil causes the flow to begin to reattach. As the process goes on, the load is redistributed toward the leading edge, which restores the positive pitch moment.



Compressibility affects dynamic stall in many ways:

- stall delay
- aerodynamic damping
- shock-induced stall
- stall vortex strength

STALL FLUTTER

Stall flutter is a single-degree-of-freedom aeroelastic motion that results from negative system damping.

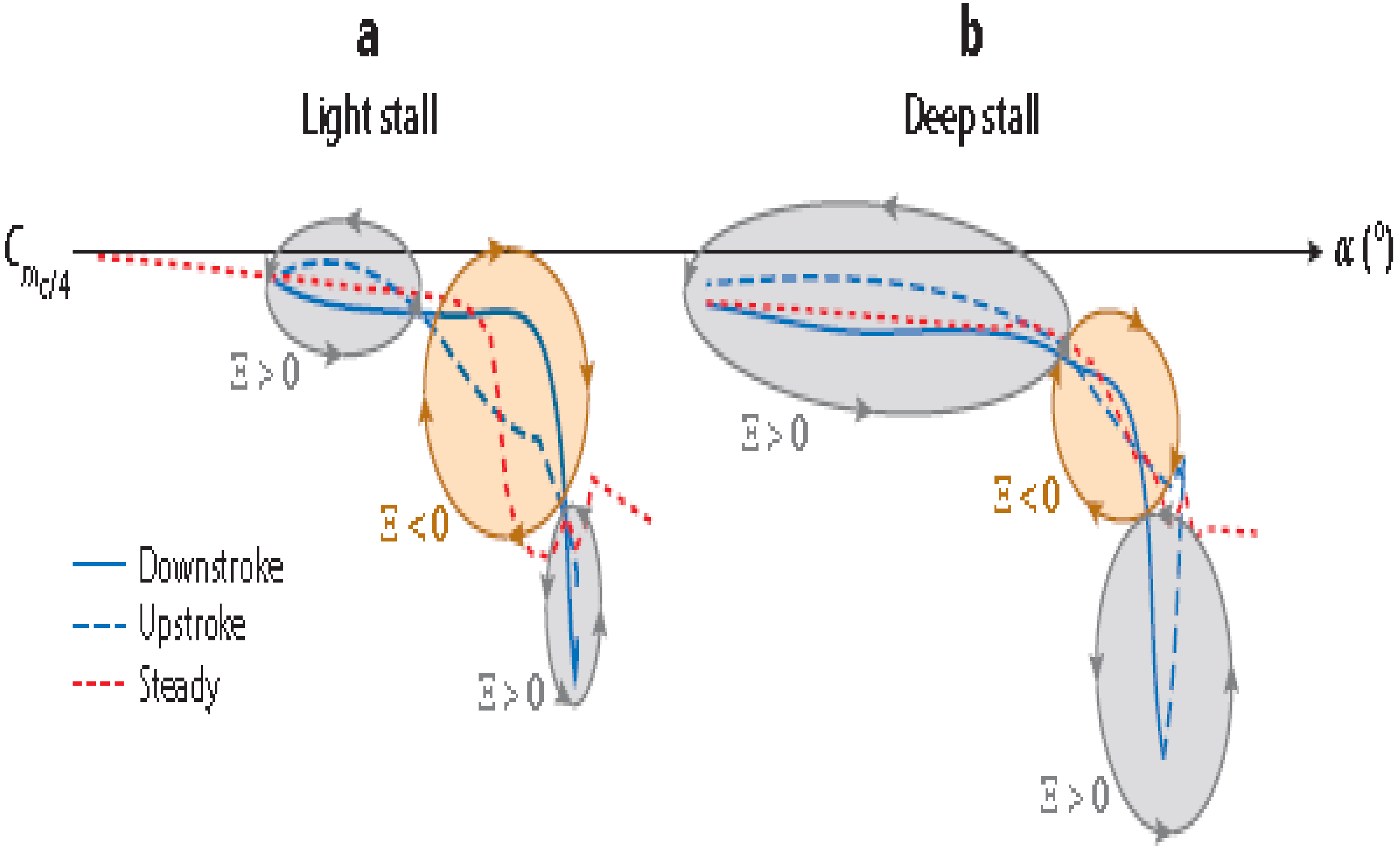
For a single-degree-of-freedom structure subject to harmonic forcing in a uniform airstream:

$$\Xi_{\text{cycle}} = -C_W/(\pi\alpha_1^2) = -\frac{1}{\pi\alpha_1^2}\oint C_{m_{c/4}}\,d\alpha$$

If I consider pure pitch oscillation Ξ_{cycle} reduces to:

$$\Xi_{\text{cycle}} = \pi k/2$$

- LIGHT STALL
- DEEP STALL



DEEP STALL IS MORE AERODYNAMICALLY STABLE THAN LIGHT STALL

The aerodynamic damping coefficient can also be written as

$$\Xi(t) = \xi / q c^2 = -\frac{A_{C_m}(t)}{\alpha_1} \sin \psi(t)$$

$$A_{C_m}(t) = \sqrt{C_m^2 + \tilde{C}_m^2}$$

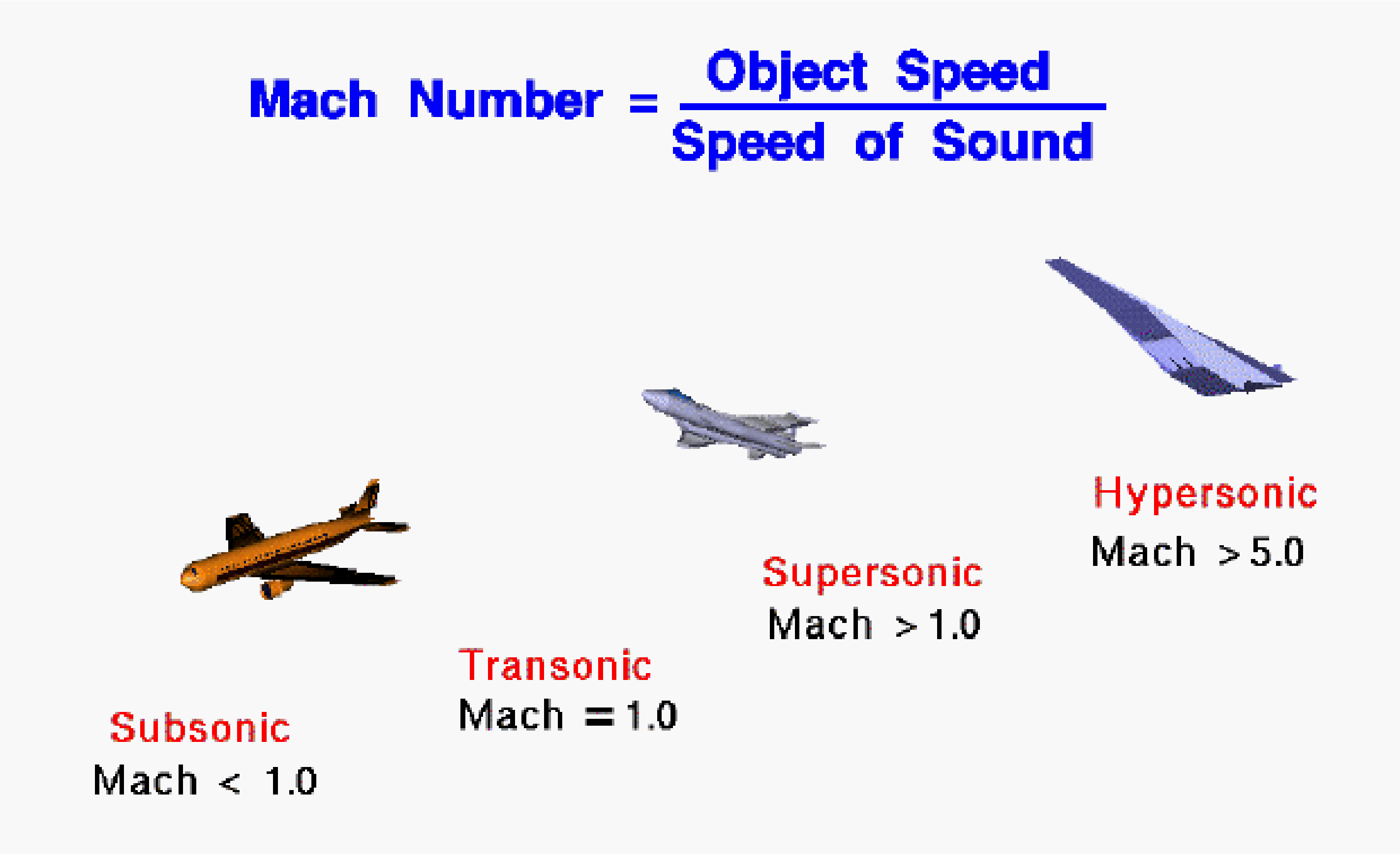
$\psi(t) < 0$ phase lag → positive damping

$\psi(t) > 0$ phase lead → negative damping

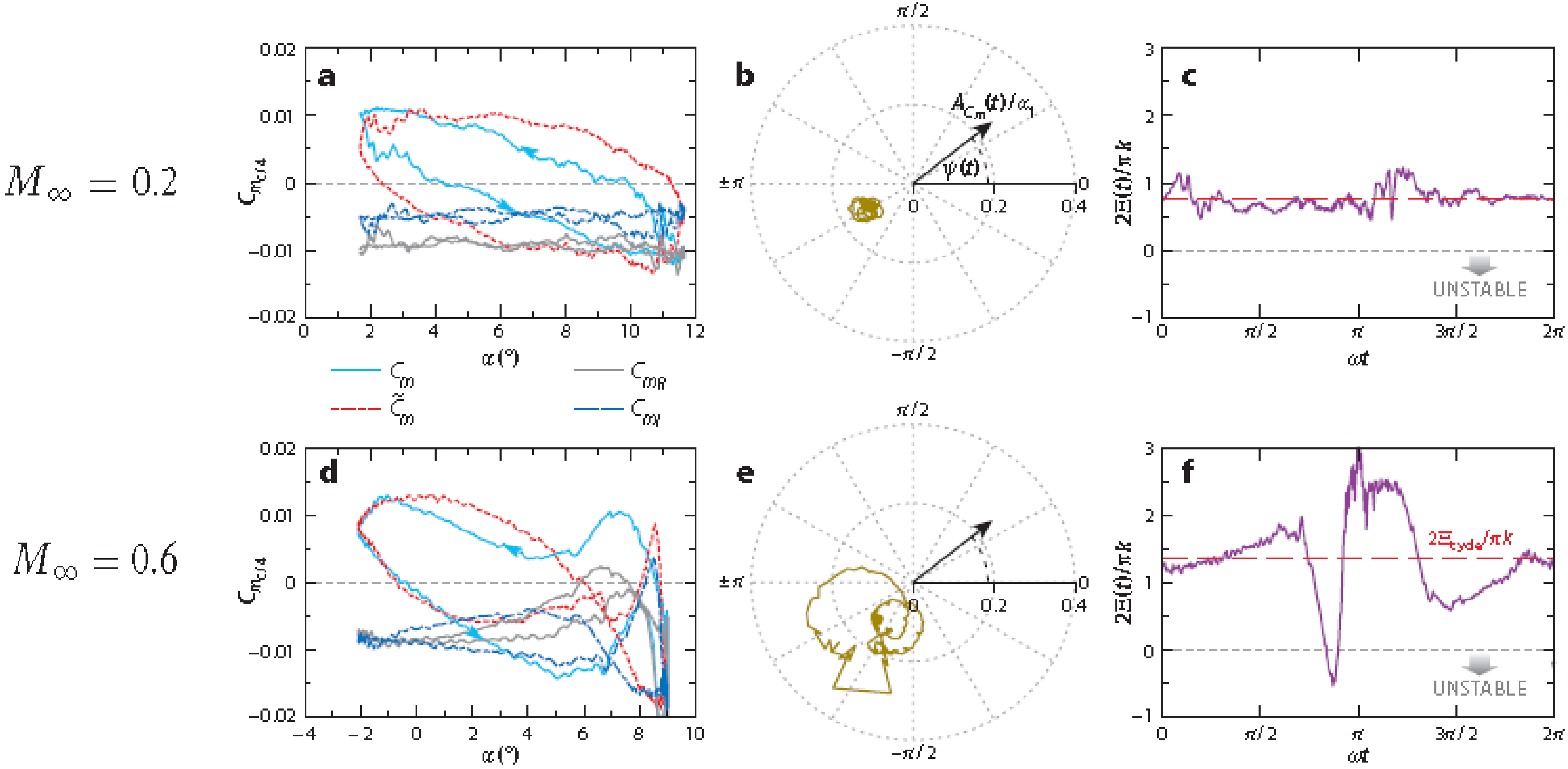
ATTACHED FLOW

The cycle-integrated damping, Ξ_{cycle} , for attached flow increases with increasing Mach number.

When shocks form, the cycle-integrated damping rapidly increases.



$$\text{Mach Number} = \frac{\text{Object Speed}}{\text{Speed of Sound}}$$


$M_\infty = 0.2$
$M_\infty = 0.6$
a
b
c
d
e
f
$C_{m_{c/4}}$
0.02
0.01
0
−0.01
−0.02
α (°)
0
2
4
6
8
10
12
−4
−2
C_m
$\tilde{C}_m$
C_{mR}
C_{mI}
$\pi/2$
$-\pi/2$
$\pm\pi$
0
0.2
0.4
$A_{C_m}(t)/\alpha_1$
$\psi(t)$
$2\Xi(t)/\pi k$
3
2
1
0
−1
ωt
$\pi/2$
π
$3\pi/2$
2π
UNSTABLE
$2\Xi_{cycle}/\pi k$

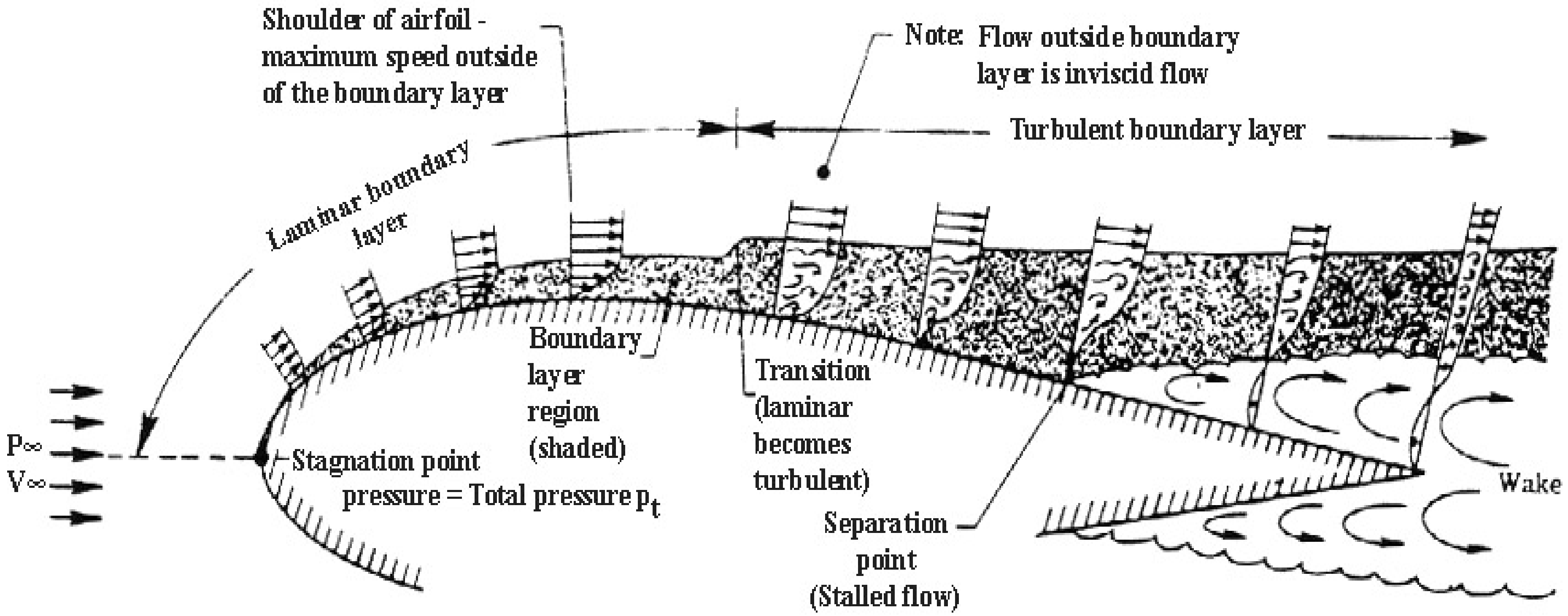
LEADING-EDGE TURBULENT TRIP EFFECTS

The pitch-up motion of the leading edge results in an acceleration of the boundary layer flow, which delays separation.

The flow acceleration near the leading edge should make the boundary layer more stable to disturbances and therefore suppress turbulent transition.

THE NATURE OF THE BOUNDARY LAYER SEPARATION STRONGLY INFLUENCES DYNAMIC STALL, EXPECIALLY IN THE LIGTH-STALL REGIME

The minimum intracycle damping coefficients for the distributed roughness trips at $M_\infty = 0.2$ support the cycle-averaged view, with a significant reduction in the negative damping peak that is associated to the dynamic stall vortex formation. The edge roughness trip was found to be much less effective. However, at $M_\infty = 0.6$, at which the dynamic stall vortex forms downstream of the shock, the distributed roughness trips result in significantly larger negative damping.

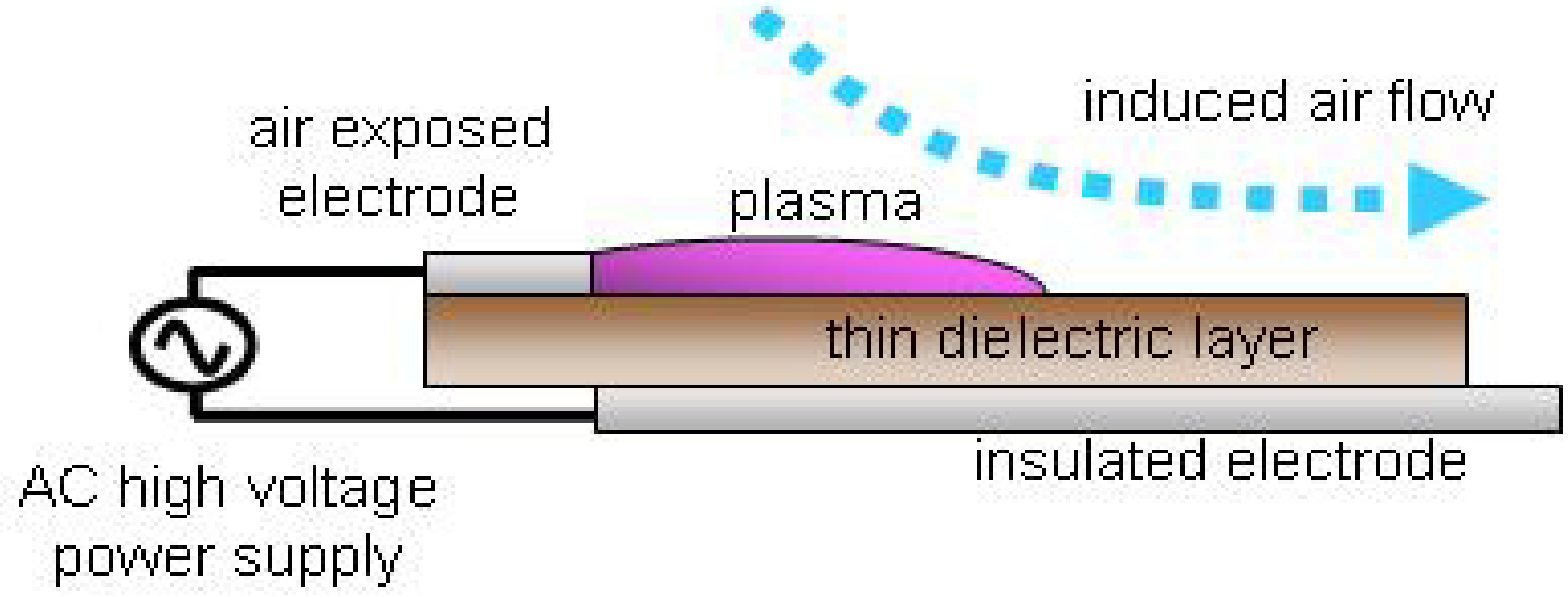


DYNAMIC STALL CONTROL

PLASMA ACTUATORS

It has to be located at the very leading edge.

The actuator is oriented so that when activated, it would produce a 2-D body force that accelerate the boundary layer flow in the direction from the leading edge toward the suction surface of the airfoil.



CONCLUSIONS

- Dynamic stall may result in limit-cycle growth of vibration amplitudes and eventual structural failure.
- The phase relation between the airfoil pitching motion and the aerodynamic pitch moment determines the sign of the aerodynamic damping.
- The dynamic stall process is highly sensitive to surface roughness. Compressibility effects weaken the dynamic stall vortex strength.
- At low Mach numbers, turbulent trips weaken the dynamic stall vortex; at higher Mach numbers, the turbulent trips produce large negative damping.
- Plasma actuators can be used to reduce dynamic stall.

THANK YOU FOR YOUR ATTENTION!!!