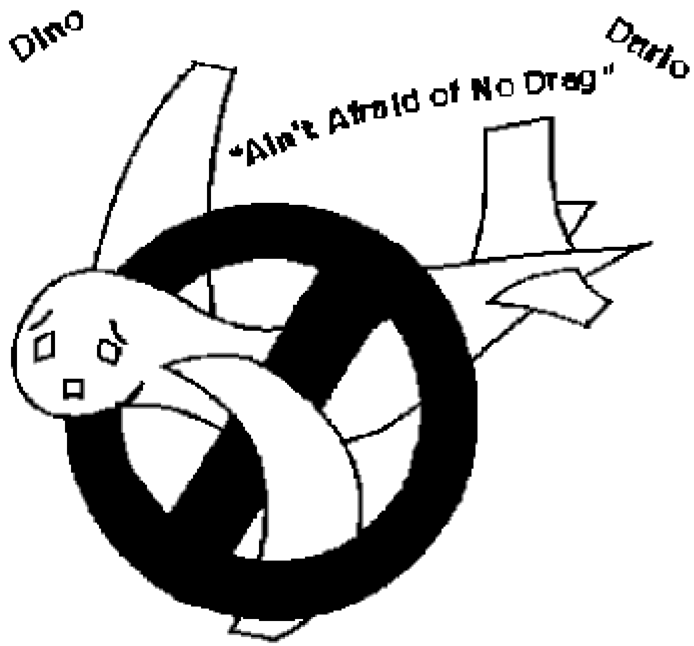
Drag Computation (1)



DRAGBUSTERS

PRESENTS

Why drag so concerned

- Its effects on aircraft performances
  - On the Concorde, one count drag increase (ΔC_D = .0001) requires two passengers, out of the 90 ~ 100 passenger capacity, be taken off the North Atlantic run.
  - A drag decrease is equated to the decrease in aircraft weight required to carry a specified payload for the required distance.
    - One advanced fighter study found the drag sensitivity in supersonic cruise was 90 lb/ct and 48 lb/ct for subsonic and transonic cruise.

Why drag so concerned

- For one executive business jet the range sensitivity is 17 miles/drag count.
- Advanced supersonic transports now being studied have range sensitivities of about 100 miles/drag count.

- Conclusion
  - A minor changes in drag can be critical !

Why drag so concerned

- Its effects on the company
  - The economic viability and future survival of an aircraft manufacturer depends on minimizing aerodynamic drag while maintaining good handling qualities to ensure flight safety and ride comfort.
  - A company was willing to invest $750,000 for each count of drag reduction.
  - Examples:
    - Boeing 767, 777
    - Airbus A340

Why drag so concerned

- The designing for low drag and the ability to estimate drag is at the heart of aerodynamic design
  - Initial drag estimates can dictate the selection of a specific configuration concept in comparison with other concepts early in the design phase.
  - The drag projections have a huge effect on the projected configuration size and cost, and thus on the decision to proceed with the design.

Issues on Drag

- Drag cannot yet be predicted accurately with high confidence levels (especially for unusual configuration concepts) without extensive testing.
- No one is exactly sure what the ultimate possible drag level really is that can be achieved for a practical configuration.
  – To this extent, aerodynamic designers are the dreamers of the engineering profession.

The efforts on drag estimation and reduction

- Conferences
  - Aerodynamic Drag, AGARD CP-124, 1973.
  - Aircraft Drag Prediction, AGARD-R-723, 1985.
  - Drag Reduction Techniques, AGARD-R-787
  - AIAA CFD Drag Prediction workshop, 2001
- AIAA progress series book
  - *Thrust and Drag: Its Prediction and Verification*, AIAA, New York, 1985.

Objective of this chapter

- To introduce the key concepts required to use computational aerodynamics to evaluate drag.

Outline

- *Nomenclature and Concepts*
- *Farfield Drag Analysis*
- *Induced Drag*
- Zero Lift Drag Friction and Form Drag Estimation
- Supersonic Wave Drag
- Trim Drag
- Current Issues for Drag Calculation Using CA

Some Different Ways to View Drag - Nomenclature and Concepts

- Simple Integration
  - Approach
    - Consider the distribution of forces over the surface.
      - pressure force
      - shear stress force due to the presence of viscosity
    - An integration over the surface results in an estimate of the drag.
    - This approach is known as a nearfield drag calculation.

- Simple Integration
  - Disadvantages
    - This integration requires extreme precision
      - remember that program PANEL did not predict exactly zero drag
    - The results are difficult to interpret for aerodynamic analysis
      - Exactly where is the drag coming from?
      - Why does it exist, and how do you reduce it?

- Fluid Mechanics:
  - This viewpoint emphasizes the drag resulting from various fluid mechanics phenomena.
  - This approach is important in conceiving a means to reduce drag.
  - Providing a means of computing drag contributions in a systematic manner.
    - friction drag
    - form drag
    - induced drag
    - wave drag
  - The term can be confusing !

The Terms on Drag

- Friction Drag
  - Skin friction drag which depends mostly upon the wetted area.
- Form Drag (Pressure Drag)
  - Viscous separation drag which depends upon the location of the separation point on the body.
- Profile Drag (Parasite Drag)
  - Skin friction drag + Form drag
- Induced Drag
  - Drag forces that are a strong function of lift
- Wave Drag
  - The drag caused by the information of shocks at supersonic and high subsonic speeds.

- Aerodynamics:
  - This approach combines the fluid mechanics viewpoint with more practical considerations.
  - Thinking in terms of contributions from a variety of aircraft features.
  - The basic contributions from each component must be included.
    - individual component contributions to drag
    - base drag
    - inlet drag with spillage
    - boattail drag
    - camber drag
    - trim drag
    - thrust-drag bookkeeping
    - aeroelastic effects on drag

- Performance:
  - To calculate the performance of an airplane it is natural to define drag as the sum of the *drag at zero lift* and *the drag due to lift*.

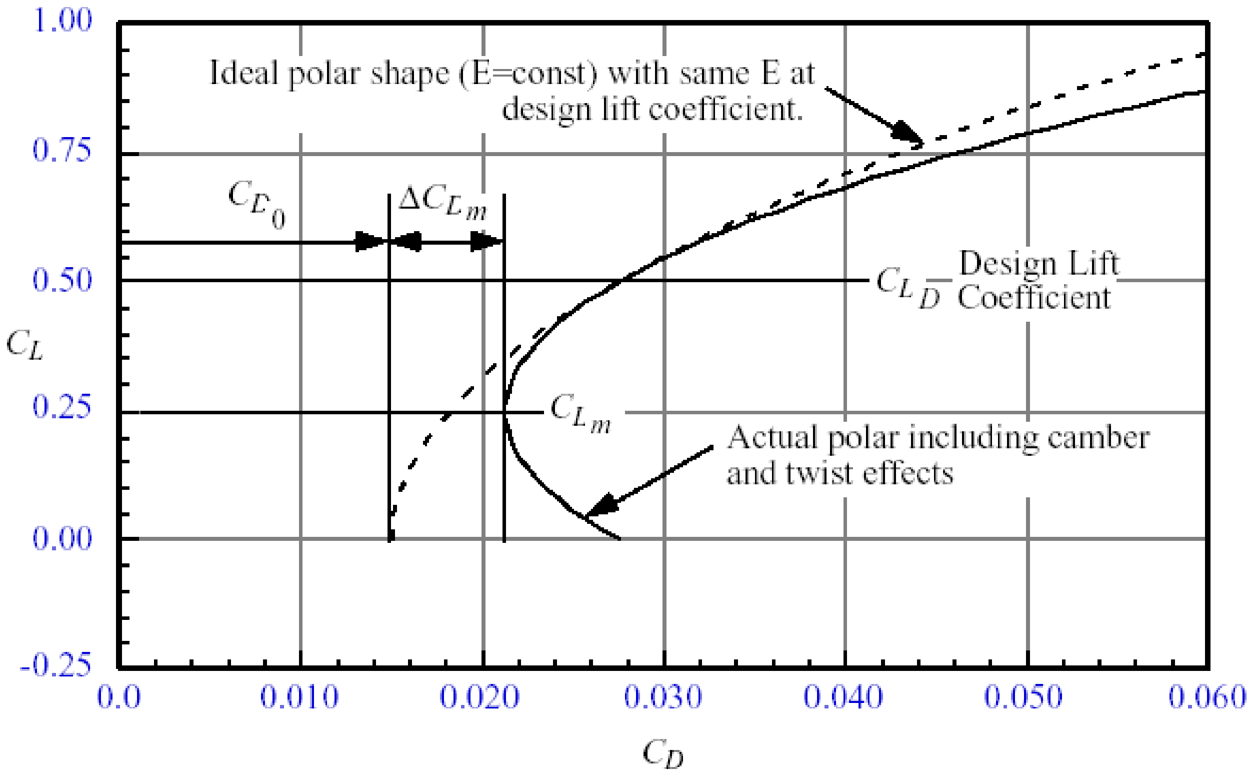
$$C_D = C_{D_0} + \frac{C_L^2}{\pi ARE}$$

Each term is a function of Mach number, Reynolds number (or altitude), and the particular geometric configuration (flap deflection, wing sweep, *etc*.).

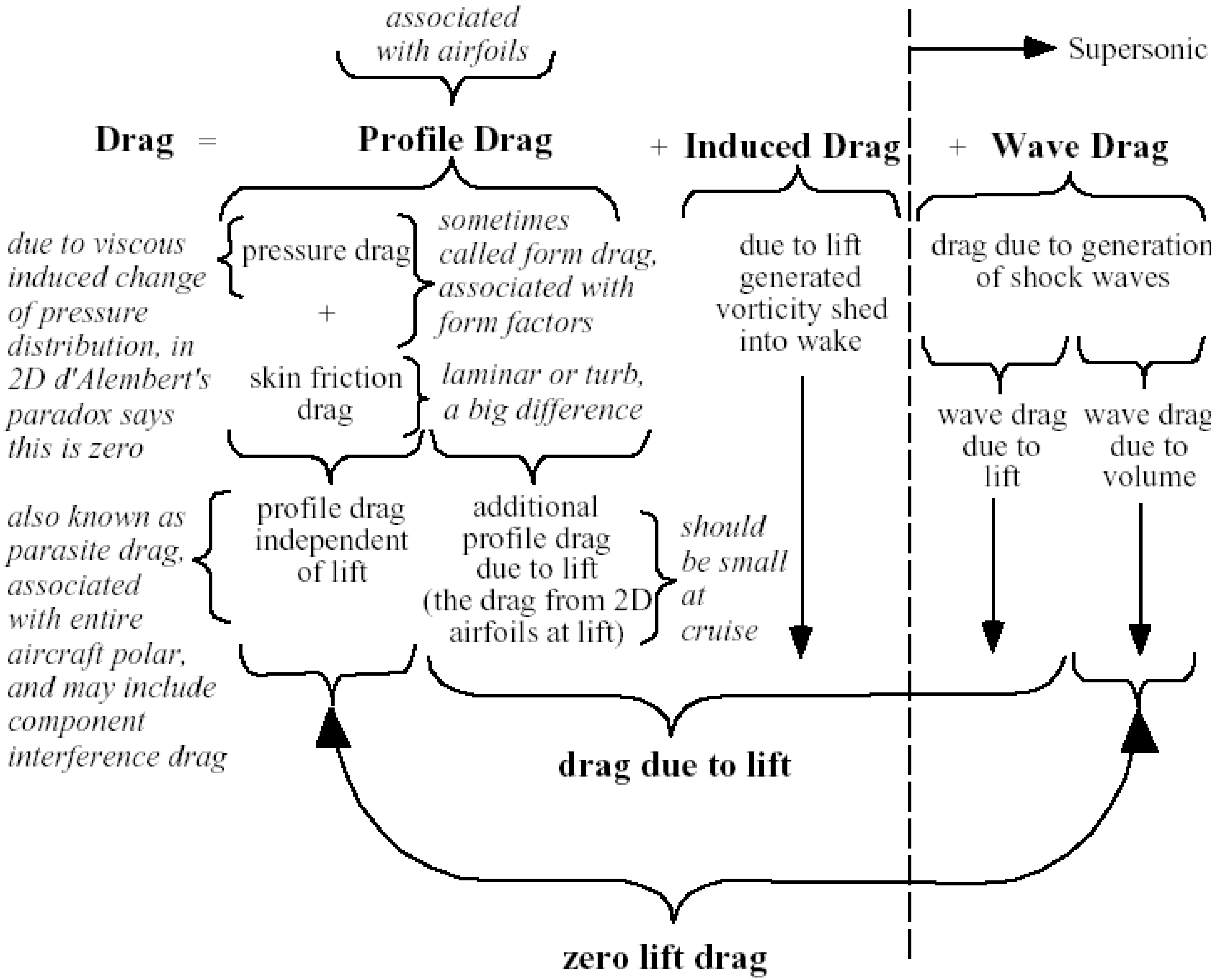
The value of the Oswald efficiency factor, *E,* is defined as a function of the lift coefficient and Mach number

- Performance:
  - To take into account the effect of wing camber and twist, drag polar become asymmetrical about the C_L = 0 axis.

$$C_D = C_{D_0} + \Delta C_{D_m} + K(C_L - C_{L_m})^2$$



A categorization of drag



Drag Term Again

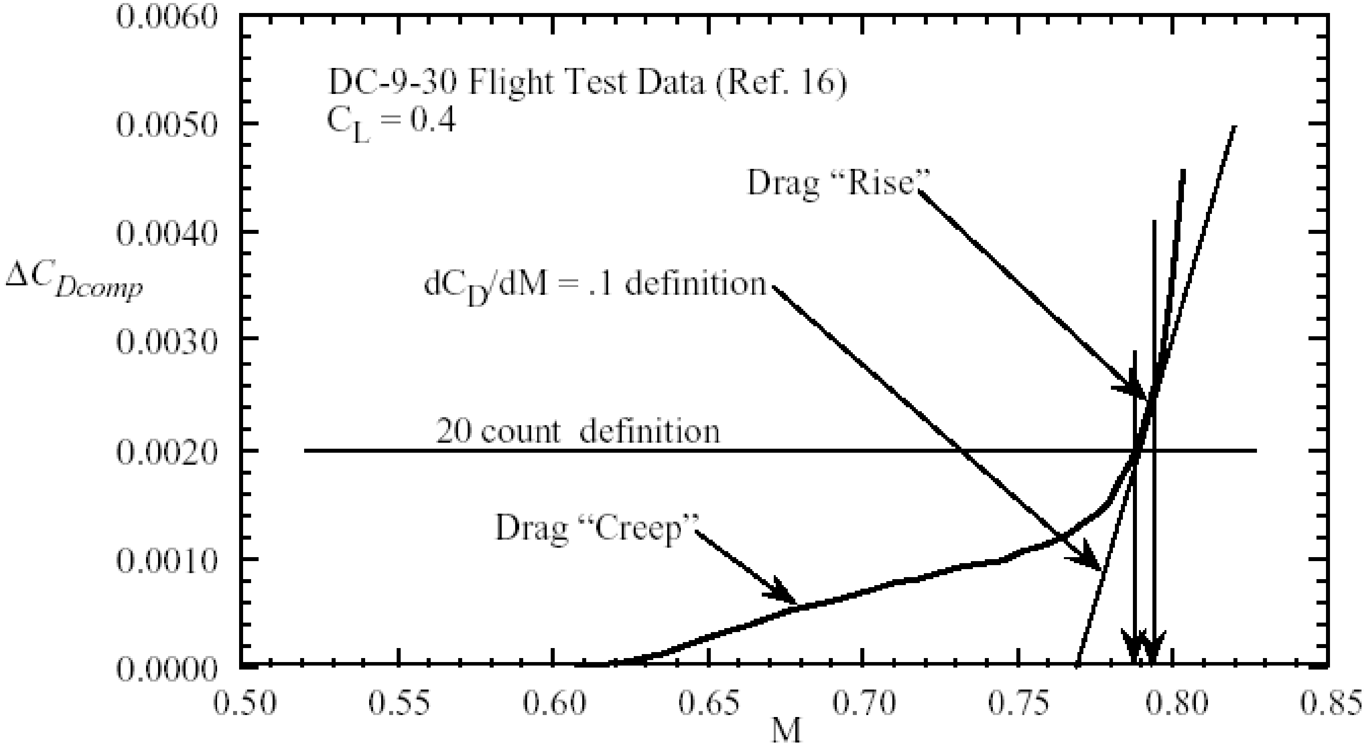
- Pressure drag / Form drag
- Skin friction drag
- Wave drag
- Parasite drag
- Profile drag
  - Independent of lift
  - Additional profile drag due to lift (should be small)
- Drag due to lift
  - Due to lift generated vorticity shed into wake
  - Additional profile drag due to lift
  - Wave drag due to lift
- Zero lift drag
  - Profile drag independent of lift
  - Wave drag due to volume

- A fluid mechanics refinement: transonic wave drag
  - Transonic flow
    - The wave drag arises at subsonic speeds when the flow accelerates locally to supersonic speeds, and then returns to subsonic speed through a shock wave.
  - Drag divergence Mach number, M_{DD}
    - The Mach number at which the rapid drag increase occurs
  - At drag divergence the additional transonic drag is divided between the *explicit shock drag* and *the shock induced additional profile drag*.

- A fluid mechanics refinement: *transonic wave drag*
  - Definitions of the drag rise Mach number

$$\left.\frac{dC_D}{dM}\right|_{C_L=conts.} = 0.1 \qquad or \qquad \Delta C_D = 0.0020$$

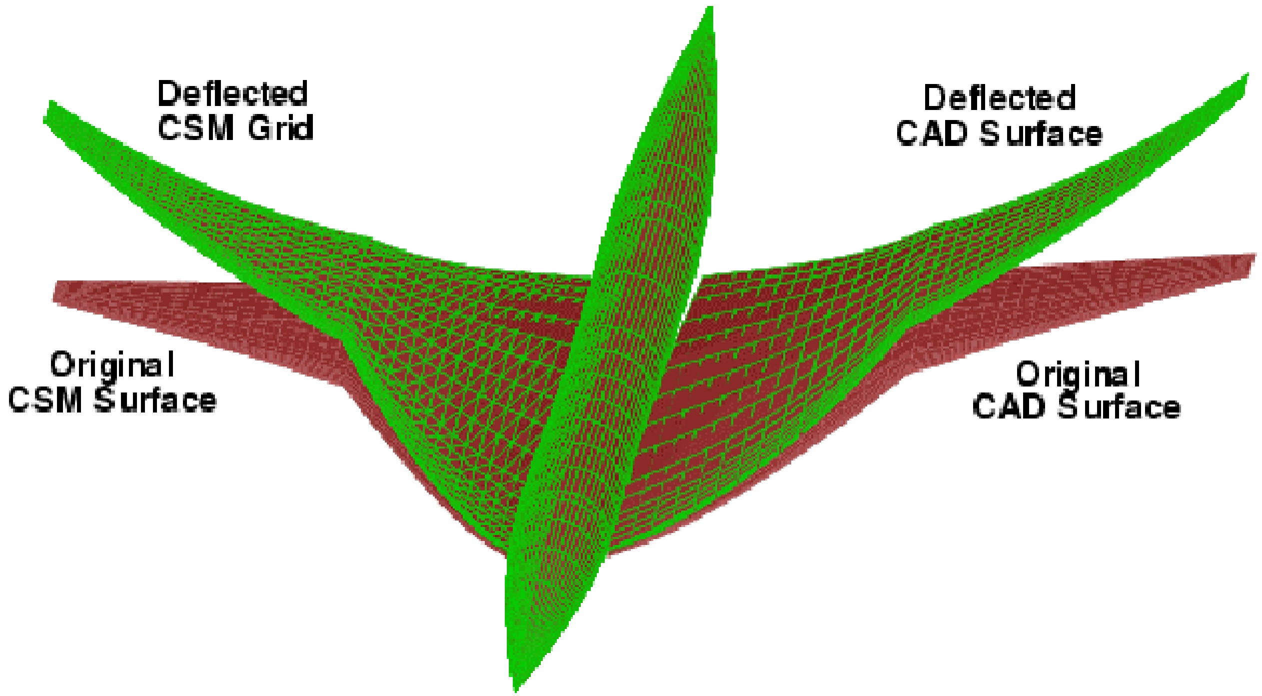
Details of wave drag increases at transonic speeds



- An aerodynamics/flight mechanics refinement: *trim drag*
  - The requirement of steady flight can lead to control surface deflections that increase the drag.
  - The cases of significant drag:
    - The shift in the aerodynamic center location with Mach number for supersonic aircraft
    - The use of airfoils with large values of the zero lift pitching moment about their aerodynamic center
    - The configurations with variable wing sweep

- A practical aspect of aero-propulsion integration: *thrust-drag bookkeeping*
  - The drag of the airframe is affected by the operation of the propulsion system
    - a spillage drag
    - the boattail drag over the external portion of the nozzle
  - Approach
    - thrust-drag bookkeeping.

- Aerodynamic-structural interaction: ***aeroelastic effects on drag***



aerodynamic loads → structure → deformation → change of drag

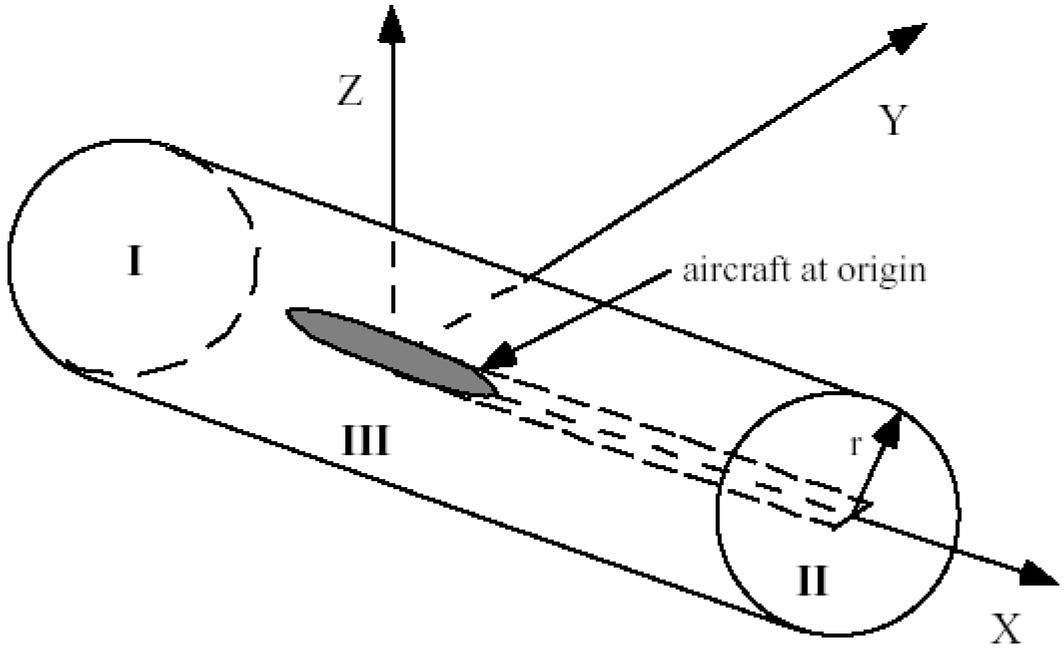
Farfield Drag Analysis

- Approach
  - Estimate the drag on a body by considering the overall momentum balance on a control volume surface well away from the body.
- Advantage
  - Less sensitive to the detailed calculations of surface pressure and integration of the pressures over the surface to obtain the drag.

- Derivation (1)

$$\mathbf{F} = -\oiint_S (p - p_\infty) d\mathbf{S} - \oiint_S \rho \mathbf{q} \left[(\mathbf{V}_\infty + \mathbf{q}) \cdot d\mathbf{S} \right]$$

where q is the disturbance velocity vector $\mathbf{V} = \mathbf{V}_\infty + \mathbf{q}$



Control volume for farfield drag evaluation.

- **Derivation (2)**
  - Using linearized flow relations and the small disturbance relations:

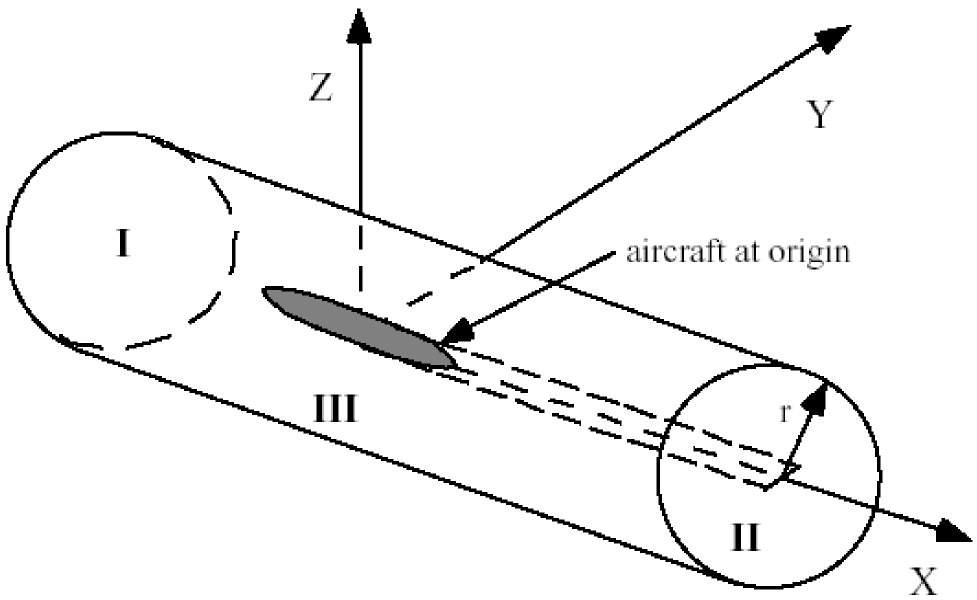
$$\rho \cong \rho_\infty \left(1 - M_\infty \frac{u}{U_\infty} \right)$$

$$(p - p_\infty) \cong -\left[U_\infty u + \tfrac{1}{2}\left(u^2 + v^2 + w^2 \right) \right] + \tfrac{1}{2} \rho_\infty M_\infty^2 u^2$$

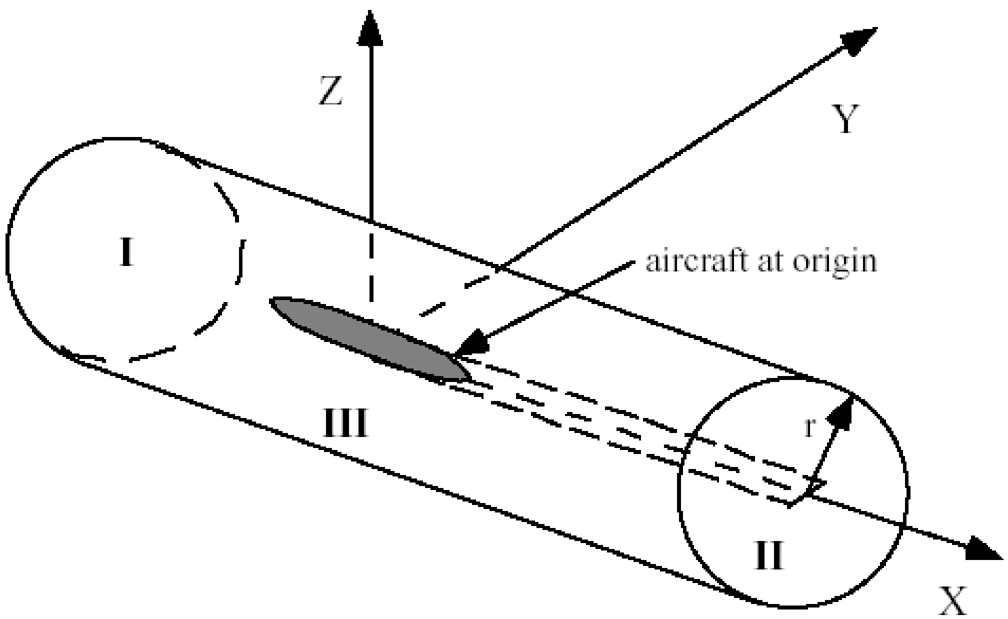
- Derivation (3)
  - The equation became:

$$D = \frac{1}{2}\rho_\infty \iint_{I+II} \left[\left(M_\infty^2 - 1\right)u^2 + v^2 + w^2\right] dy\,dz - \rho_\infty \iint_{III} u v_r r\,d\theta\,dx$$

Where v_r is the radial component



- Derivation (4)
  - The integral over I is zero as x $\rightarrow -\infty$.
  - The integral over II as x $\rightarrow \infty$, corresponds to the so-called Trefftz Plane.
  - The integral over III is the wave drag integral, which is zero for subsonic flow, and when any embedded shock waves do not reach III.

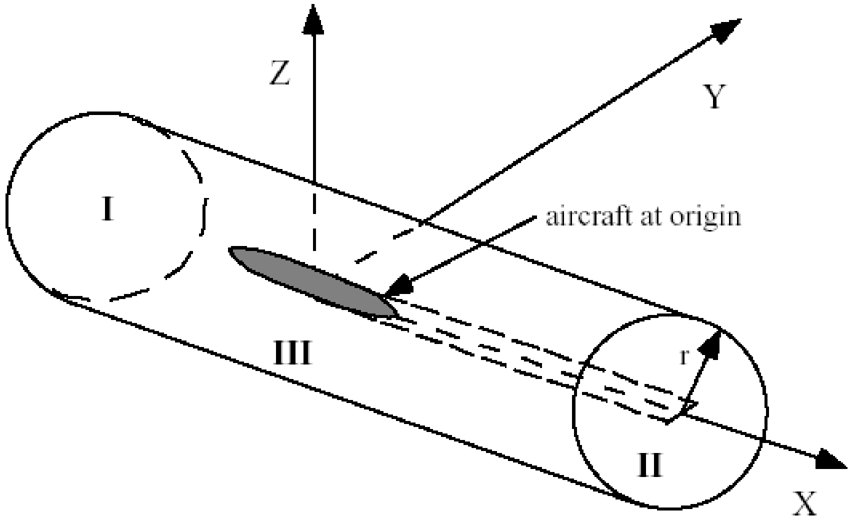


Drag Categorization
& Farfield Drag Analysis

Drag = friction drag + induced drag + wave drag + form drag

$$D = \frac{1}{2}\rho_\infty \iint_{II} [(M_\infty^2 - 1)u^2 + v^2 + w^2]dydz - \rho_\infty \iint_{III} uv_r r d\theta dx$$

Farfield Drag Analysis



- Consider the integral over II
  - The induced drag integral

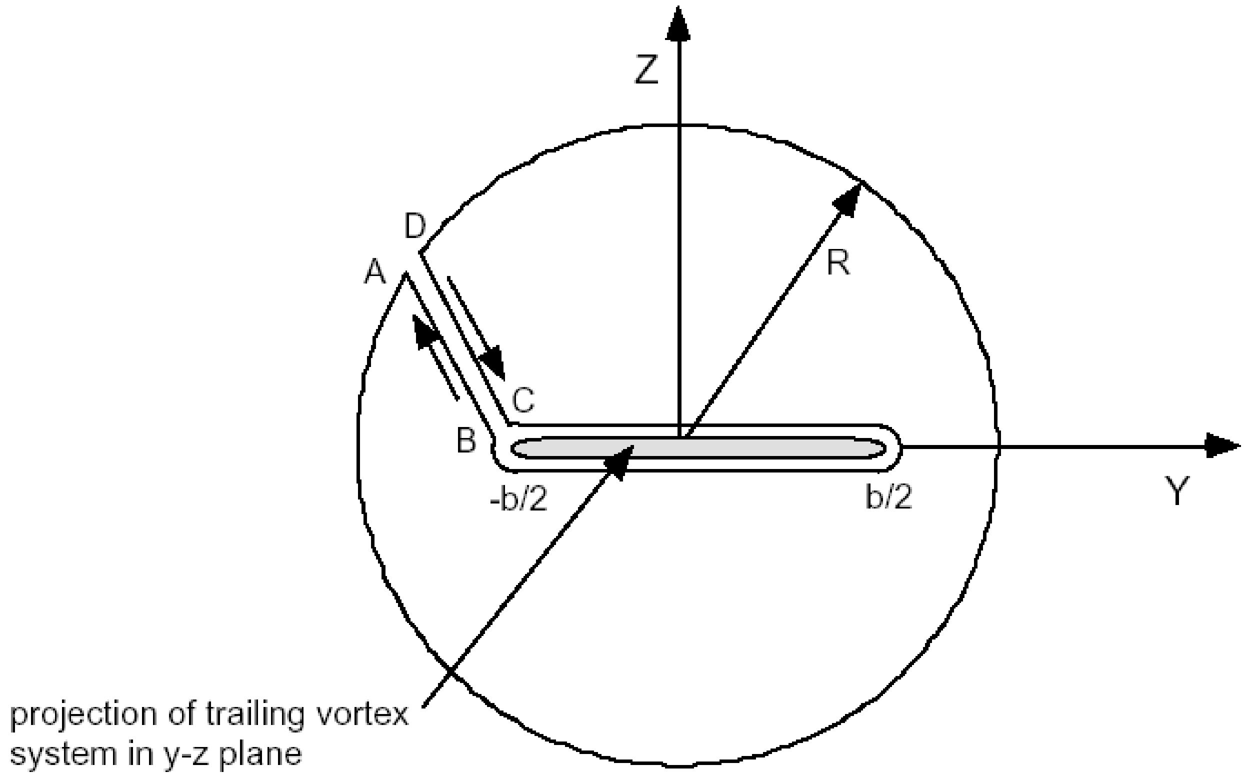
$$D_i = \tfrac{1}{2}\rho_\infty \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} [(M_\infty^2 - 1)u^2 + v^2 + w^2]\,dydz$$

Far downstream, u → 0

$$D_i = \tfrac{1}{2}\rho_\infty \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} [v^2 + w^2]\,dydz$$

Using Green's theorem $\iint_{II} (v^2 + w^2)\,dS = -\oint_c \phi \frac{\partial \phi}{\partial n} dc$

$$D_i = -\tfrac{1}{2}\rho_\infty \oint_c \phi \frac{\partial \phi}{\partial n} dc$$



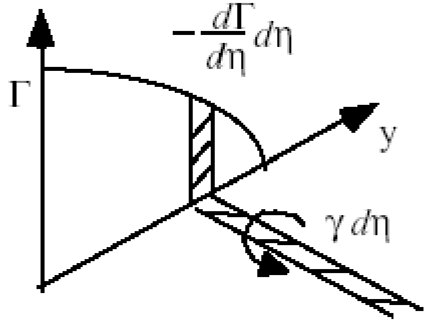
- In this *Trefftz plane*, the integral vanishes around the outside contour as $R \to \infty$ and the integrals along *AB* and *CD* cancel.
- The only contribution comes from the slit containing the trace of vorticity shed from the wing.
- The value of ϕ is equal and opposite above and below the vortex sheet,and

$$\frac{\partial \phi}{\partial n} = w$$

$$D_i = -\tfrac{1}{2}\rho_\infty \int_{-b/2}^{b/2} (\Delta\phi)_{x=\infty} w_\infty dy$$

Relation between ϕ and circulation

$$\Delta\phi_{x=\infty} = \Gamma(y)$$



Using lifting line theory

$$w_{x=\infty}(y) = \frac{1}{2\pi}\int_{-b/2}^{b/2} \frac{\gamma(\eta)}{y-\eta} d\eta$$

$$\gamma(\eta) = -d\Gamma / dy$$

Relation between the trailing vorticity strength and the change in circulation

$$D_i = -\frac{\rho_\infty}{4\pi}\int_{-b/2}^{b/2}\int_{-b/2}^{b/2} \frac{d\Gamma(y_1)}{dy}\frac{d\Gamma(y_2)}{dy}\ln|y_1 - y_2| dy_1 dy_2$$

$$D_i = -\frac{\rho_\infty}{4\pi} \int_{-b/2}^{b/2} \int_{-b/2}^{b/2} \frac{d\Gamma(y_1)}{dy} \frac{d\Gamma(y_2)}{dy} \ln|y_1 - y_2| dy_1 dy_2$$

– **Comments on this equation**

- This result shows that the induced drag is a function of the Γ distribution (spanload) alone.
  - – The spanload distribution is responsible for the induced drag.
- Because of the double integral we can get the total drag, but we have lost the ability to get detailed distributions of the induced drag on the body.
  - – This is the price we pay to use the farfield analysis.

Summary

- The importance of drag in aircraft design
- Nomenclature and Concepts
  - Don’t be confused by the all those terms !
- Far-field Drag Analysis Formulation
- The Integral over Surface II: Induced Drag