16.886
Air Transportation Systems Architecting

# Formation Flight Aerodynamic Performance

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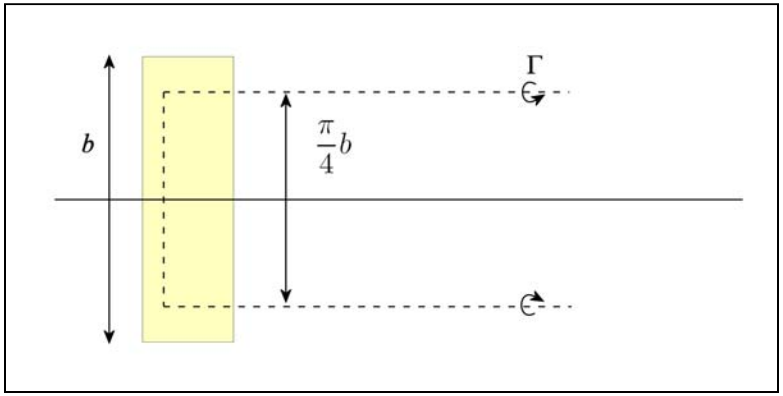
# Outline

- Theoretical Predictions
- Experimental Results
- Comments

# Models and Parameters

Theoretical Results

- Horseshoe vortex model:




$$\Gamma = \frac{L}{\rho V_\infty b} = \frac{1}{2} V_\infty c C_L$$

Speed — Lift Coefficient — Chord

- Multhopp and Blake:

$$C_{Di} = f(C_{Lj}, X_j, Y_j, Z_j, j=1, N)$$

Lift Coefficient — Position

# Performance Benefits

*Theoretical Results*

In the maximum range condition ($C_{Di} = 0.5\ C_D$)

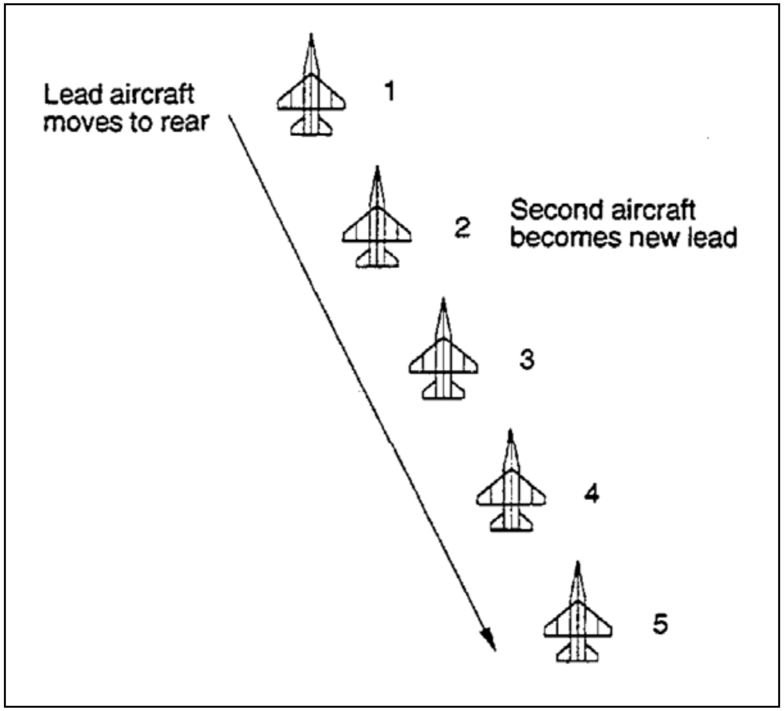
| Model | Quantity | Total Flight Power Reduction |
|---|---|---|
| Wings | 2 | 10% |
| | 3 | 13-14% |
| | ∞ | 26% |
| Airplanes | 2 | ~10% |

| Constraint | Gain in range (factor) |
|---|---|
| Maximum formation range | $\sqrt{n}$ |
| Maximum range for one aircraft | $\frac{2n}{n+1} < 2$ |
| Simulation for 3 aircraft with rotation | 11.5% |

# Shape of the formation

*Theoretical Results*

- Streamwise spacing does not influence the total flight power reduction
- The distribution of the power reduction on the wings depends strongly on the shape of the formation
- Optimum lift distribution:
  - **Elliptical distribution** of aircraft weight across the formation (heaviest in the center)
  - It can be simulated by a **rotating echelon formation**
  - Advantage: safer



# Number of aircraft

Theoretical Results

- Numerical simulations using the rotating echelon formation show that as more aircraft are added, relative range increases up to a maximum of about 1.8 $R_{single}$
- Beyond **5 or 6 aircraft**, the additional payoff is rapidly diminished.

# Importance of accuracy



About 50% of the maximum achievable benefit is lost if the lateral position cannot be maintained to better than 0.1 span.

# Performance benefits

Experimental Results

Wind tunnel measurements and flight tests

- Observation of 10-20% drag reduction for the trail aircraft
- No improvements for lead aircraft
- Sometimes, discrepancy with predictions for the amplitude of the reduction or the optimum position
- Near the optimum position, the increase in lift can allow the trail aircraft to fly at a lower angle of attack, thereby achieving an overall decrease in drag

# Relative position

*Experimental Results*

- Dependence on altitude and speed that did not appear in the models
- Dependence on downstream spacing
- Shape of the vortex is different

# Trailing Vortices



- The wake of an aircraft is composed of:
  - Concentrated vortices from flaps and the wing tip
  - an unstable vortex sheet along the trailing edge
  - Disturbances coming from protruding parts and jets
- It merges into a pair of concentrated vortices
- The **position and decay** of these vortices is very dependent on the **environment**:
  - Ambient wind
  - Atmospheric turbulences
  - Stratification
  - Heat flux (convection)

# Comments



- Problems of the models:
  - wings / aircraft
  - Only valid in ideal conditions
- Some other things to consider:
  - The optimum lift distribution of each wing deviates significantly from an elliptic distribution
  - Use of adaptive lifting surfaces may enable future aircraft to take full advantage of formation flight benefits by enabling them to adapt their wing geometry.

# Questions?