Spacecraft and Aircraft Dynamics

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Lecture 8: Roll Control and Review

In this Lecture we will cover:

Roll Stability

- Contributions to Rolling Moment
- Aileron Control

Review

- A Short Review of Static Stability Equations
- A Summary of Coefficients

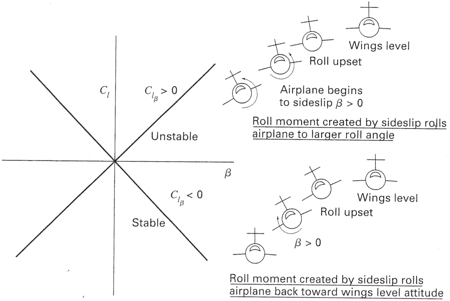
We cannot discuss rolling motion without pitch and yaw. Why?

To define the EOM, $I\ddot{\phi} = C_l(\phi)$, we want

$$C_l = C_{l0} + C_{l\phi}\phi$$

However, if $\beta = 0$ and $\alpha = 0$, then the velocity vector $\vec{V}$ does not change with ϕ. If we only count aerodynamic forces, then this means

$$C_{l\phi} = 0$$



This means ANY ϕ is a neutrally stable equilibrium.

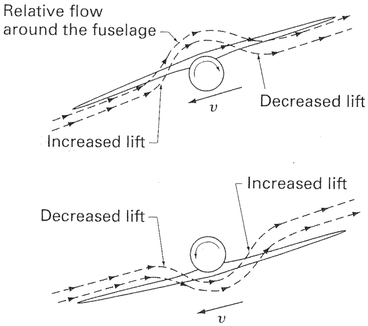
To be useful, we bend our definition of static stability even further.

Consider the rolling angle coupled with motion in the y-direction. For a positive ϕ, the Lift vector becomes

$$\vec{F} = \begin{bmatrix} 0 \\ L\sin\phi \\ -L\cos\phi \end{bmatrix} \cong \begin{bmatrix} 0 \\ L\phi \\ -L \end{bmatrix}$$

In a pseudo-static world, suppose that V_y is proportional to $L\phi$. Specifically, let

$$V_y \cong K\phi$$



This creates a proportional relationship between roll angle and sideslip, angle

$$\beta \cong \frac{V_y}{V} \qquad \text{hence} \qquad \beta \cong \frac{K}{V}\phi$$

The horizontal motion creates aerodynamic roll moments proportional to ϕ.

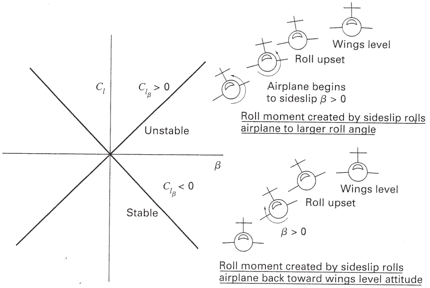
$$C_l = \frac{dC_l}{d\phi}\phi = \frac{dC_l}{d\beta}\frac{d\beta}{d\phi}\phi = C_{l\beta}\frac{K}{V}\phi$$

We write the equations of motion for ϕ.

$$I\ddot{\phi} = QScC_l = \frac{QScK}{V}C_{l\beta}\phi$$

Since Q, S, c, K and V are all positive:
The aircraft is

- Axial **Stable** if $C_{l\beta} < 0$
- Axial **Unstable** is $C_{l\beta} > 0$



A horizontal velocity, V_y creates two primary sources of rolling moment:

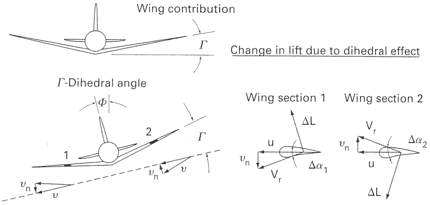


Figure: Wing Dihedral: Positive Roll, Front View

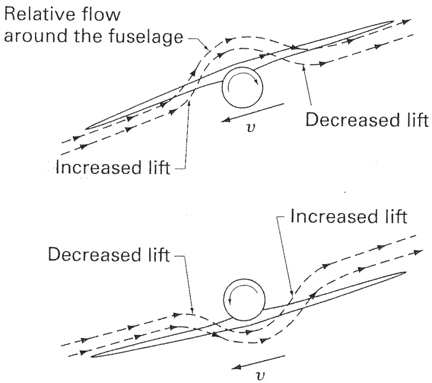


Figure: Fuselage Interaction: Positive Roll, Front View

The wing acts as a lifting surface with $Q = \frac{1}{2}\rho V_y^2$ and $\alpha = -\phi$. Consider top-mounted wings

- A negative roll creates a positive V_y
- The fuselage blocks the free-stream V_y, reducing the velocity at the downstream wing.
- This reduces the dynamic pressure on the bottom of the downstream wing, Q_d, reducing the lift as $L_d = C_{L\alpha}\phi Q_d S$.
- A moment differential between the wings is created

$$C_l = C_{L\alpha} l_{ac} S (Q_d - Q_u)\phi$$

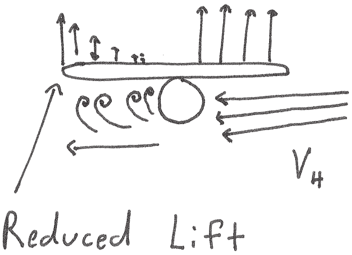


Figure: Fuselage Interaction: Negative Roll, Front View

Mounting wings on the bottom will create the **Opposite** effect!

- A negative roll creates a positive V_y
- With respect to V_y, upstream wing has positive AOA, Γ; downstream wing has negative AOS, $-\Gamma$.
- This creates positive lift differential on upstream wing and negative lift downstream.
- A positive moment differential between the wings is created.

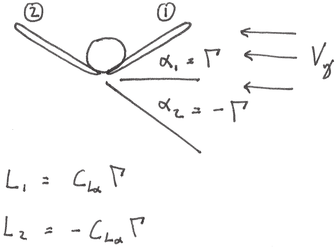


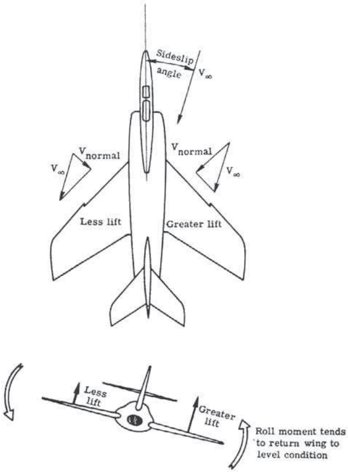
Figure: Wing Dihedral: Negative Roll, Front View

$$C_{l0} = 2C_{L\alpha} l_{ac} SQ\Gamma$$

Wing sweep creates roll stability

- A positive roll creates a positive β.
- A Positive β means a negative Yaw (ψ).
- A negative ψ creates a larger $V_\perp$ on the right wing.
- A larger $V_\perp$ means more lift.
- The right wing rotates up, reducing ϕ

A result of coupling between y, ψ, and ϕ



The same **Force** as for directional stability, different moment arm

- A positive roll creates a positive β.
- Sideslip creates pressure on tail surface.
- Pressure on tail creates positive Rotation.

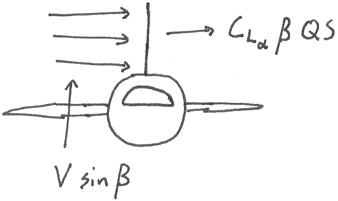


Figure: Roll Stability

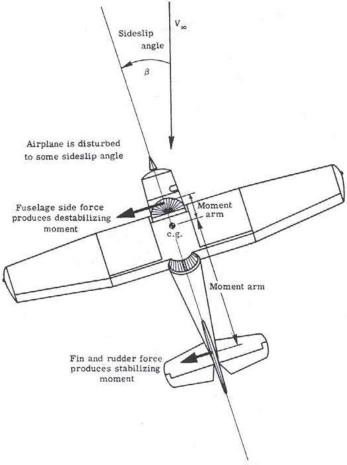
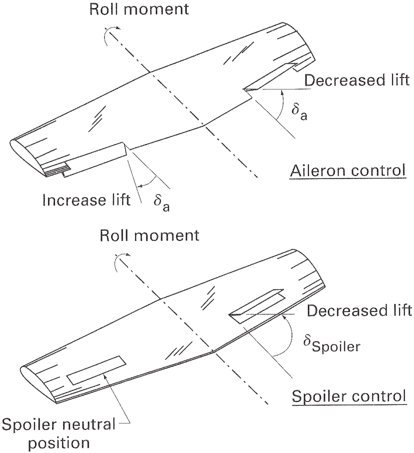


Figure: Directional Stability

Ailerons are control surfaces attached to the wings. They are similar to elevators, but move in opposite directions.

A δ_a is defined as

- A downwards deflection on the left.
- An upwards deflection on the right.

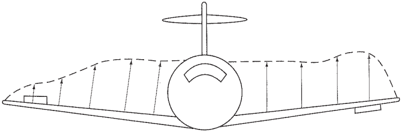


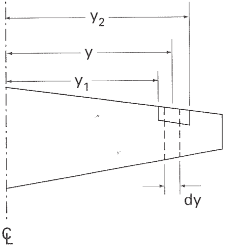
The change in lift on the right wing is

$$\Delta C_{L\alpha} = -\tau_a C_{L\alpha} \delta_a$$

The change in lift on the left wing is positive. The overall moment contribution is described as

$$C_l = C_{l\beta}\beta + C_{l\delta_a}\delta_a$$





$$C_{l\delta_a} = 2\frac{C_{L\alpha}\tau}{Sb}\int_{y_1}^{y_2} cydy \cong 2C_{L\alpha}\tau\frac{y_c}{b}$$

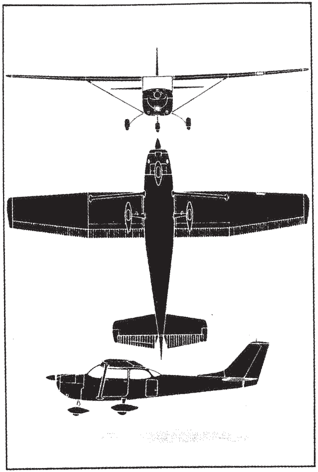
Directional Stability

Example: Cessna Skyhawk

Cessna Model 172 Skyhawk USA

Type: light sports aircraft

Accommodation: two pilots, two passengers



Dimensions:

Length: 26 ft 11 in (8.2 m)
Wingspan: 35 ft 10 in (10.9 m)
Height: 8 ft 9 in (2.7 m)

Weights:

Empty: 1433 lb (650 kg)
Max T/O: 2400 lb (1089 kg)
Payload: 120 lb (54 kg)

Performance:

Max speed: 141 mph (228 kmh)
Range: 875 nm (1620 km)
Power plant: one Avco Lycoming O-320-D2J piston engine
Thrust: 160 hp (119 kW)

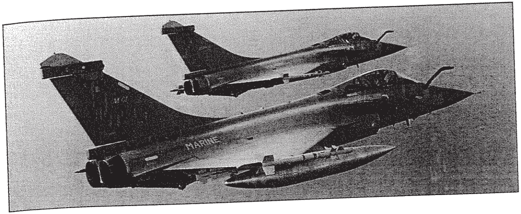
Variants:

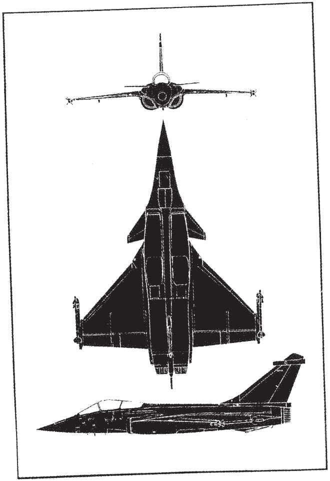
T-41 Mescalero; floatplane; FR 172K armed version

Notes: One of the most popular light aircraft ever, some 35 545 examples have been built, including the Reims F172 built in France.

Dassault Rafale France

Type: multi-purpose fighter **Accommodation:** one pilot





Dimensions:

Length: 50 ft 2 in (15.30 m)
Wingspan: 35 ft 9 in (10.9 m)
Height: 17 ft 6 in (5.34 m)

Weights:

Empty: 19 973 lb (9060 kg); 21 319 lb (9800 kg) Rafale M
Max T/O: 47 399 lb (21 500 kg)

Performance:

Max Speed: Mach 2
Range: 2000 nm (3706 km) air-to-air; 1180 nm (2186 km) ground attack
Powerplant: two SNECMA M88-2 augmented turbofans
Thrust: 21 900 lb (97.4 kN) - 32 800 lb (145.8 kN) with afterburner

Armament:

one 30 mm DEFA 791B cannon; Maximum of 14 hardpoints; 13 228 lb (6000 kg) warload; ASMP stand-off nuclear weapon; Mica AAMs; Apache stand-off weapon dispenser; Exocet ASMs; bombs

Variants:

Rafale A proof of concept demonstrator; Rafale B two-seat operational trainer; Rafale C for French Air Force; Rafale M carrier borne fighter

Notes: 250 planned for French Air Force and 86 for French Navy. In an attempt to replace the ageing F-8 Crusader as soon as possible, the first naval aircraft will lack the full avionics suite to bring them into service earlier.

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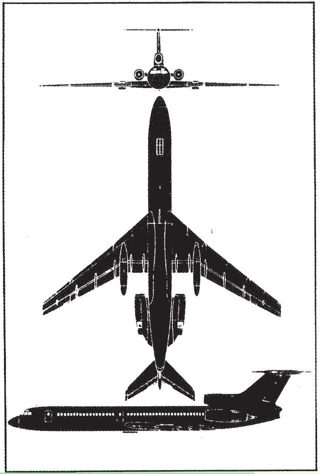
Tupolev Tu-154 Careless Russia

Type: medium-haul airliner **Accommodation:** two pilots; flight engineer; optional navigator; 167 passengers



Dimensions:
Length: 157 ft 1 in (47.9 m)
Wingspan: 123 ft 2 in (37.5 m)
Height: 37 ft 4 in (11.4 m)

Weights:
Empty: 95 900 lb (43 500 kg)
Max T/O: 198 416 lb (90 000 kg)
Payload: 44 090 lb (20 000 kg)

Performance:
Cruising speed: Mach 0.9
Range: 2850 nm (5280 km)
Power plant: three Kuznetsov NK-8-2 turbofans
Thrust: 62 850 lb (279.9 kN)

Variants:
154A, 154B developed versions; 154C cargo; 154M reduced size and redesigned tailplane

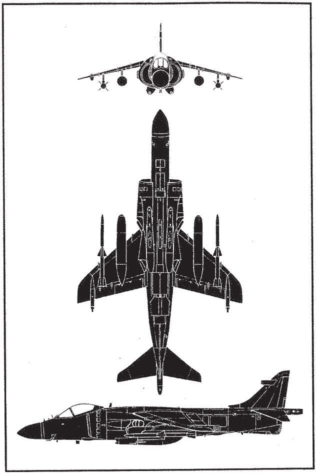
Notes: First flown in 1968, the Tu-154 was designed to cover the medium stages of Aeroflot's internal routes. To carry out these duties it can operate from low-grade airfields including packed earth and gravel.

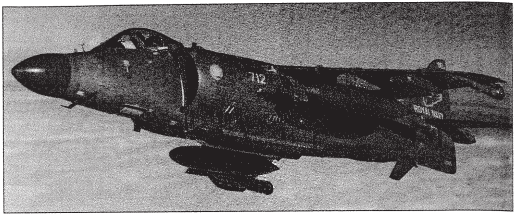
Directional Stability

Example: Harrier

BAe Sea Harrier F/A Mk 2 UK

Type: carrier borne multi-role fighter **Accommodation:** one pilot





Dimensions:
Length: 46 ft 6 in (14.17 m)
Wingspan: 25 ft 3 in (7.70 m)
Height: 12 ft 2 in (3.71 m)

Weights:
Empty: 14 052 lb (6374 kg)
Max T/O: 26 200 lb (11 880 kg)

Performance:
Max Speed: Mach 1.25; 736 mph (1185 km/h) low level
Range: 800 nm (1500 km)
Powerplant: one Rolls-Royce Pegasus Mk106 vectored Thrust turbofan
Thrust: 21 500lb (95.6kN)

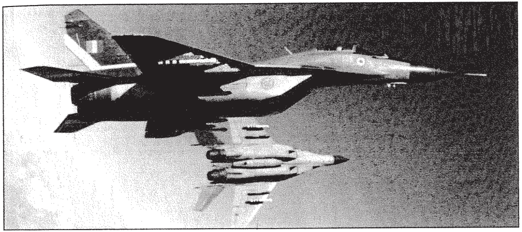
Armament:
two 30 mm ADEN cannon pods; five hardpoints; 8000 lb (3630 kg) warload - 5000 lb (2270 kg) with vertical take off; AMRAAM/AIM-7M Sidewinder AAMs; Sea Eagle SSMs; WE117 nuclear bomb; bombs; rockets

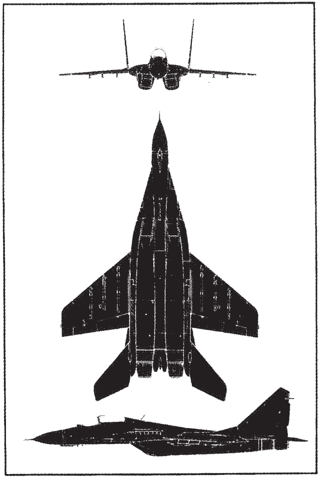
Notes: Essentially a stretched Sea Harrier FRS Mk 1 with new radar and avionics, plus the ability to carry the AIM-120 AMRAAM (the first European fighter so equipped), the F/A Mk 2 has now virtually replaced its predecessor in squadron service in the Royal Navy's Fleet Air Arm.

Example: Mig 29

Mikoyan MiG-29 Fulcrum Russia

Type: multi-role fighter **Accommodation:** one pilot





Dimensions:
Length: 48 ft 9 in (14.87 m)
Wingspan: 37 ft 3 in (11.36 m)
Height: 15 ft 6 in (4.73 m)

Weights:
Empty: 24 030 lb (10 900 kg)
Max T/O: 40 785 lb (18 500 kg)

Performance:
Max Speed: Mach 2.3
Range: 1133 nm (2100 km)
Powerplant: two Klimov/Sarkisov RD-33 turbofans
Thrust: 22 220 lb (98.8 kN)

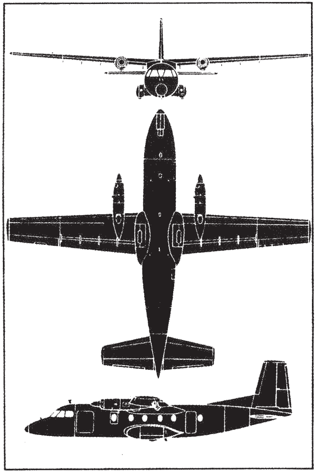
Armament:
one 30 mm GSh-301 cannon; seven hardpoints; R-77, R-60MK, R-27R1, AAMs; weapons dispensers; bombs; rockets

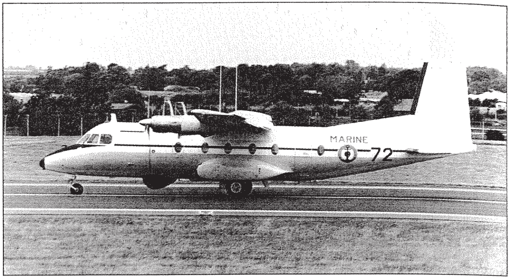
Variants:
MiG-29UB trainer; MiG-29K carrier borne fighter

Notes: The 'Fulcrum-C' and MiG-29S have a larger curved spine housing an active jammer and fuel. MiG-29M with FBW controls, sharp LERX, new spine, broad-chord tailplanes and PGM capability. The MiG-29K did extensive trials aboard the aircraft carrier Kuznetsov.

Aerospatiale N 262 Frégate France

Type: light military transport **Accommodation:** two pilots; 29 troops; 18 paratroops





Dimensions:
Length: 63ft 2in (19.2m)
Wingspan: 71ft 8in (21.9m)
Height: 20ft 4in (6.2m)

Weights:
Empty: 6175lb (13 613kg)
Max T/O: 23 370lb (10 600kg)

Payload: 6834lb (3100kg)

Performance:
Max Speed: 260mph (418km/h)
Range: 1295nm (1490km); 565nm (650km) with Max payload

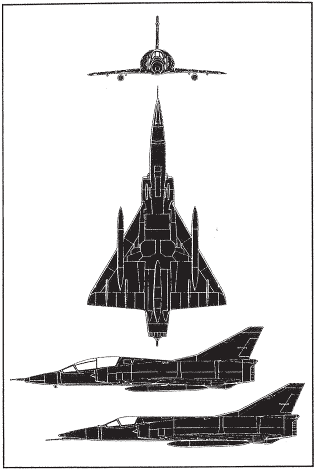
Powerplant: two Turbomeca Bastan VIIA turboprops
Thrust: 2260ehp (1685.2KW)

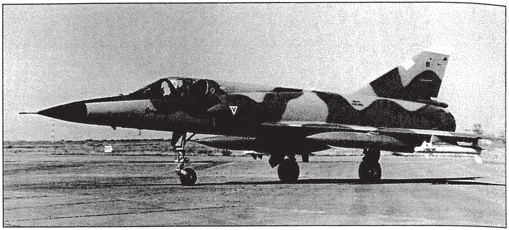
Variants:
short-haul civil commuter

Notes: The French Air Force still operates the Frégate in a utility transport and training role, the civil version is rare.

Dassault Mirage 50 France

Type: multi-role fighter **Accommodation:** one pilot





Dimensions:
Length: 51 ft (15.56 m)
Wingspan: 26 ft 11 in (8.22 m)
Height: 14 ft 9 in (4.5 m)

Weights:
Empty: 15 765 lb (7150 kg)
Max T/O: 30 200 lb (13 700 kg)

Performance:
Max Speed: Mach 2.2
Range: 1330 nm (2410 km); 740 nm (1370 km) low level
Powerplant: one SNECMA Atar 9K-50 turbojet
Thrust: 15 873 lb (70.6 kN) with afterburner

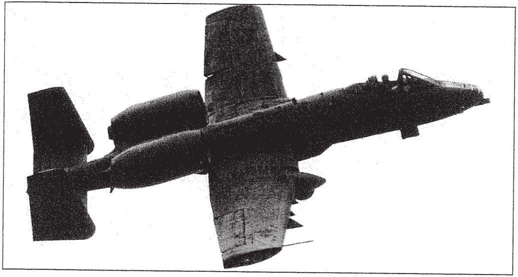
Armament:
two 30 mm DEFA cannon; seven hardpoints; Matra R.530, Magic, AIM-9 Sidewinder AAMs; Exocet, AS.30 ASM; bombs; rockets

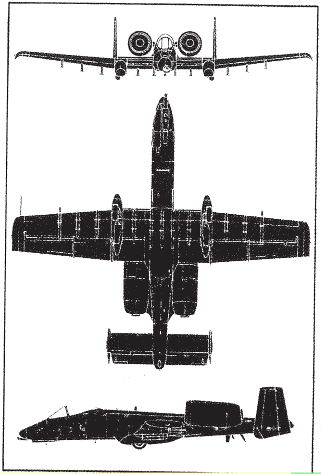
Variants:
operational trainer; Pantera (IAI upgrade of Chilean Mirage 50)

Notes: Re-engined Mirage 5 with additional fuel and a higher payload, Mirage 50s can be equipped with Agave radar and Exocet missile. Both Dassault and IAI are offering upgrades, the latter product featuring a Kfir-style nose plug, whilst the former boasts a Mirage F1-type IFR probe.

Fairchild A-10A Thunderbolt USA

Type: close support aircraft **Accommodation:** one pilot





Dimensions:
Length: 53 ft 4 in (16.26 m)
Wingspan: 57 ft 6 in (17.53 m)
Height: 14 ft 8 in (4.47 m)

Weights:
Empty: 23 370 lb (10 710 kg)
Max T/O: 47 400 lb (21 500 kg)

Performance:
Max Speed: 449 mph (722 kmh)
Range: 1080 nm (2000 km)
Powerplant: two General Electric TF34-GE-100 high bypass ratio turbofans
Thrust: 18 130 lb (80.6 kN)

Armament:
one 30 mm GAU-8/A seven-barrelled cannon; 11 hardpoints; 16 000 lb (7257 kg) warload; AGM-65A Maverick; wide range of bombs

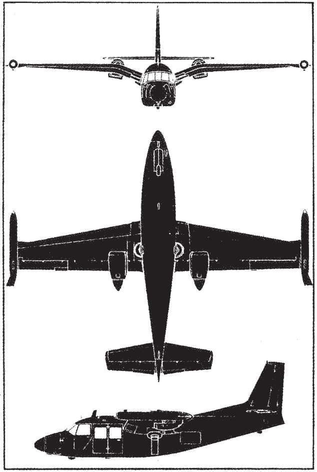
Variants:
OA-10A Fast FAC aircraft

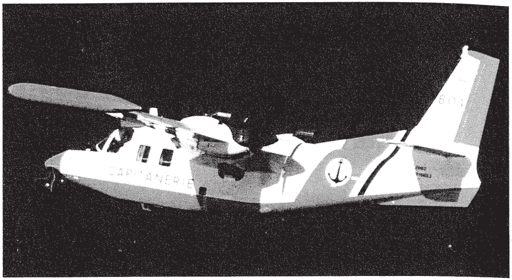
Notes: The pilot is protected by a titanium `bathtub' capable of withstanding 23 mm gun fire.

Example: P.166

Piaggio P.166-DL3SEM Italy

Type: offshore patrol aircraft **Accommodation:** two pilots plus mission crew





Dimensions:
Length: 39ft (11.8m)
Wingspan: 48ft 2in (14.6m)
Height: 16ft 5in (5m)

Weights:
Empty: 5926lb (2688kg)
Max T/O: 9480lb (4300kg)

Performance:
Max Speed: 248mph (400km/h)
Range: 1150nm (2130km)
Powerplant: two Lycoming LTP 101-700 turboprops
Thrust: 1200shp (895kW)

Armament:
no fitted armament

Variants:
special patrol/observation and transport versions offered

Notes: Used by the Italian Custom Service, Navy, Air Force and Ministry of Merchant Marine.

Roll Instability with Inertia

Falling Leaf Mode

If we truly couple the dynamics of horizontal motion with roll moment, we get

$$\begin{bmatrix}\ddot{y}\\ \ddot{\phi}\end{bmatrix} = K \begin{bmatrix}y\\ \phi\end{bmatrix}$$

When an eigenvalue of K has positive real part, we get motion akin to the "falling leaf" mode, which was unstable in the F/A-18.

This mode will **NOT** be present in static stability dynamics

Falling Leaf Mode

Example: Elevator-Induced

Falling Leaf Mode

Example: F/A-18 Cockpit Camera

Conclusion

We need 6DOF

The dynamics of aircraft are described by 6 degrees of freedom:

Rotational Coordinates

- Roll
- Pitch
- Yaw

Translational Coordinates

- Nose
- Right
- Down

Because body-fixed coordinates are defined in terms of rotation angles, equations for rotational and translational motion cannot be decoupled for aircraft.

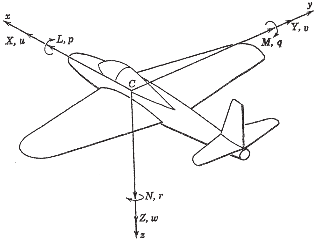
Conclusion

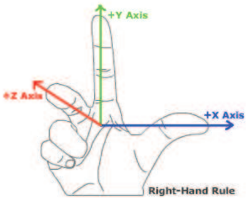
In this Lecture, you learned:

Roll Stability

- Contributions to Roll Stability or instability.
  - Roll Contributions result from coupling with ψ.
  - Not really static Stability.
- Control Surfaces.
- A design example.
- Motivation for 6DOF analysis.

- The origin is the center of mass.
- The x-axis points toward the front of the aircraft.
- The z-axis points down.
- The y-axis is perpendicular to the $x-z$ plane.
- Use the "right-hand rule" to define y





Moment Equation:

$$C_m = C_{m0} + C_{m\alpha}\alpha + C_{m\delta_e}$$

Expressions for $C_{m\alpha}$ and $C_{m\delta}$

$$C_{M0,wf} + \eta V_H C_{L\alpha,t}(\varepsilon_0 + i_{wf} - i_t)$$

$$C_{m\alpha} = C_{L\alpha,wf}\left(\frac{X_{CG}}{\bar{c}} - \frac{X_{AC,wf}}{\bar{c}}\right) - \eta V_H C_{L\alpha,t}\left(1 - \frac{d\varepsilon}{d\alpha}\right)$$

$$C_{m\delta_e} = -\eta V_H C_{L\alpha,t}\tau$$

- Stable if $C_{m\alpha} < 0$
- $\alpha_{eq} = -\frac{C_{m0}}{C_{m\alpha}}$
- Neutral point when $C_{m\alpha} = 0$

Review: Static Stability

Directional Stability

$$C_n = C_{n\beta}\beta + C_{n\delta_r}\delta_r$$

where

$$C_{n\delta_r} = -\eta_v V_v C_{L\alpha,v}\tau,$$

- Stable if $C_{n\beta} > 0$
- Use plots/data to find $C_{n\beta}$

$$C_l = C_{l\beta}\beta + C_{l\delta_a}\delta_a$$

where

$$C_{l\delta_a} \cong 2C_{L\alpha}\tau\frac{y_c}{b}$$

- Stable if $C_{l\beta} < 0$
- Use plots/data to find $C_{l\beta}$