# Review of Kinematics and Dynamics

Modeling and Simulation Outline

I. **Review of Kinematics, Dynamics, and 6-DOF Equations of Motion**
   A. **Reference Frames / Notation**
   B. **Useful kinematical equations**
   C. **Translational and Rotational Dynamics**
   D. **Euler Angles / Kinematics**

II. Overview of Rotorcraft Modeling and Simulation
   A. Modular Model Structure
   B. Simple Helicopter Model
   C. Numerical Integration
   D. Numerical Linearization
   E. Trim

III. Rotor Dynamic Model
   A. Flapping Equations of Motion
   B. Multi-blade Coordinates
   C. Rotor Forces and Moments
   D. Dynamic Inflow

IV. Complete Modular Rotorcraft Simulation Model
   A. Tail Rotor
   B. Fuselage and Empennage Aerodynamics
   C. Engine Dynamics
   D. Flight Controls
   E. Integrated Simulation Model
   F. Other Configurations (tandem rotors, tilt-rotors, compounds, multi-copters)

# Equations of Motion

Want to develop a set of differential equations that describe aircraft motion.

First order non-linear ODE’s (ordinary differential equations) where the independent variable is time.

$f\left(x,\dot{x},u,t\right)=0$ Implicit State Equations

$f\left(x,\dot{x},u\right)=0$ Time invartiant (usually a good assumption)

$\dot{x}=f\left(x,u\right)$ Explicit State Equations (sometimes a good approximation)

$x =$ State Vector

$u =$ Control Vector

$t =$ Time

$$\dot{x}=\frac{dx}{dt}$$

Will apply Newton's Laws of motion:

$$\mathbf{F}=m\frac{{}^{N}d\mathbf{V}}{dt} \qquad \mathbf{M}=\frac{{}^{N}d\mathbf{H}}{dt}$$

$\mathbf{F} =$ Force Vector

$\mathbf{M} =$ Moment Vector

$\mathbf{V} =$ Velocity Vector

$\mathbf{H} =$ Angular Momentum Vector

$\dfrac{{}^{N}d}{dt} =$ Derivative Taken in Newtonian Frame

ASSUMPTIONS:

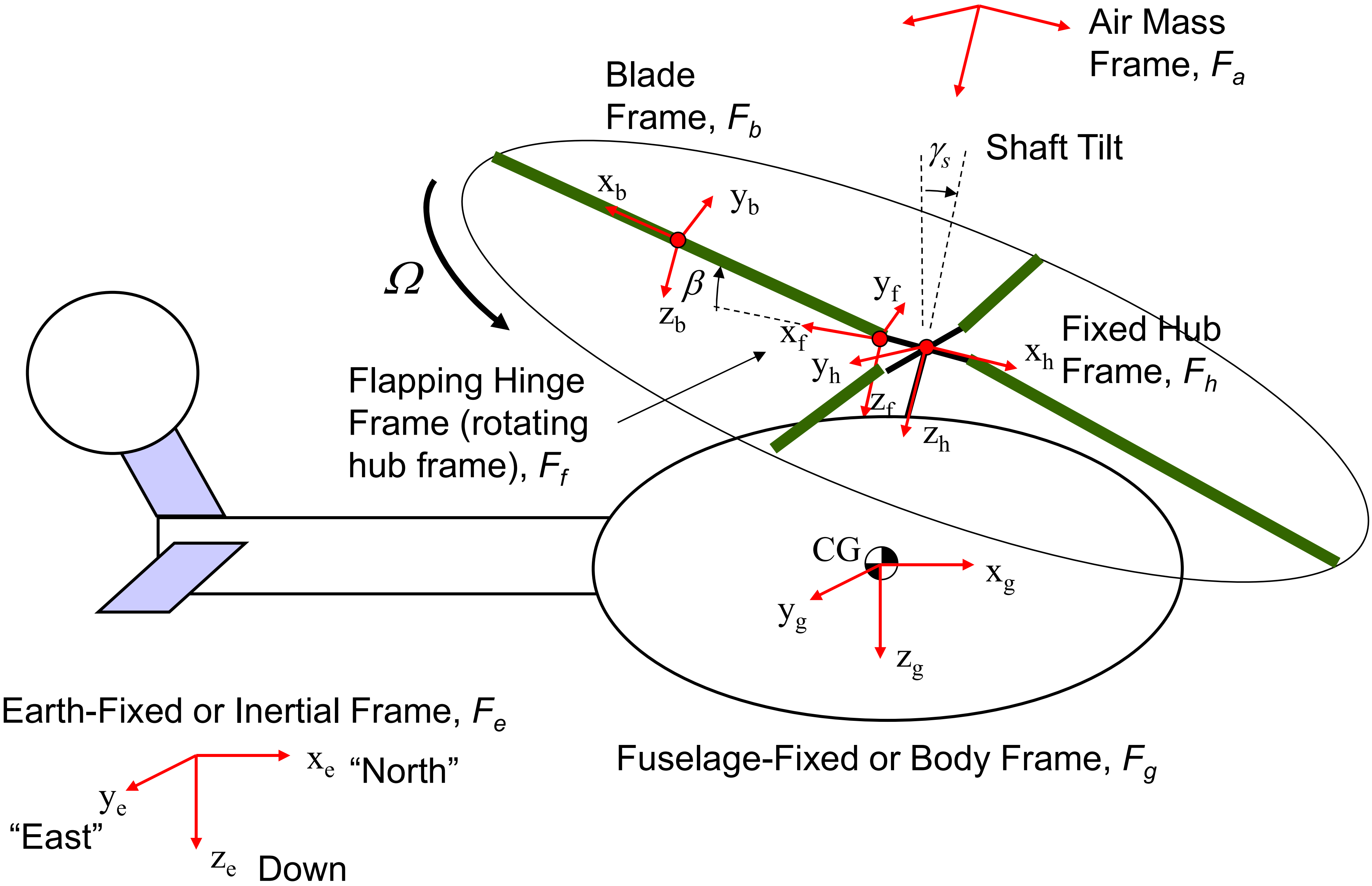
1. Fuselage and rotor blades are rigid bodies, no elastic deformation.

2.“Flat Earth” assumption – surface of the Earth is defined by a flat plane and is a Newtonian reference frame. Ignore curvature of Earth or effect of Earth’s rotation.

( Because helicopter is usually slow,

3.Constant gravitational field, and constant aircraft weight.

# Reference Frames / Coordinate Systems



# Notation

## Vector Notation, Velocity and Accelerations:

$\mathbf{V}_{P/f} =$ Velocity vector of point $P$ in frame $F_f$

$\mathbf{r}_{P/O} =$ Position vector from point $O$ to point $P$

If $O$ is fixed in reference frame $F_f$, then

$\mathbf{V}_{P/f} = \dfrac{{}^{f}d\mathbf{r}_{P/O}}{dt}$, left superscript indicates the derivative is taken in the frame $F_f$

$\mathbf{a}_{P/f} = \dfrac{{}^{f}d\mathbf{V}_{P/f}}{dt} =$ acceleration vector of point $P$ in frame $F_f$

Right superscript denotes coordinate system that defines components:

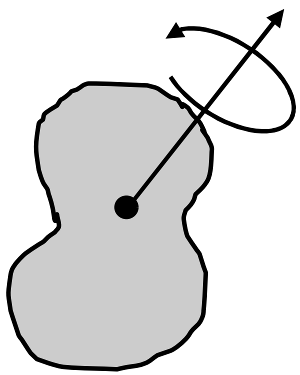
$$\mathbf{V}_{P/f}^{f} = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}$$

where $v_x, v_y, v_z$ are components of $\mathbf{V}_{P/f}^{f}$ in coordinate system $f$

# Notation

Angular Velocity Vector:

$\vec{\omega}_{g/e} =$ Angular velocity of body frame $g$ in reference frame $e$



- Note that a rigid body defines a reference frame
- Angular velocity vector defines axis of rotation at an instant in time
- Magnitude defines rate of rotation in right hand sense

$$\vec{\omega}^{g}_{g/e} = \begin{bmatrix} p \\ q \\ r \end{bmatrix}, \text{ Components in of body frame coordinate system } g$$

Aircraft Attitude:

Use standard 3-2-1 Euler angles

$\phi =$ Roll Attitude (bank angle)

$\theta =$ Pitch Attitude

$\psi =$ Yaw Attitude (heading)

# Notation

Force and Moment Vectors:

也就是B-Frame

$$\mathbf{F}^g = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + m\mathbf{g}^g$$

Gravity

Aerodynamic forces

$$\mathbf{M}^g = \begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{matrix} \text{Roll Moment} \\ \text{Pitch Moment} \\ \text{Yaw Moment} \end{matrix} \quad \text{about CG}$$

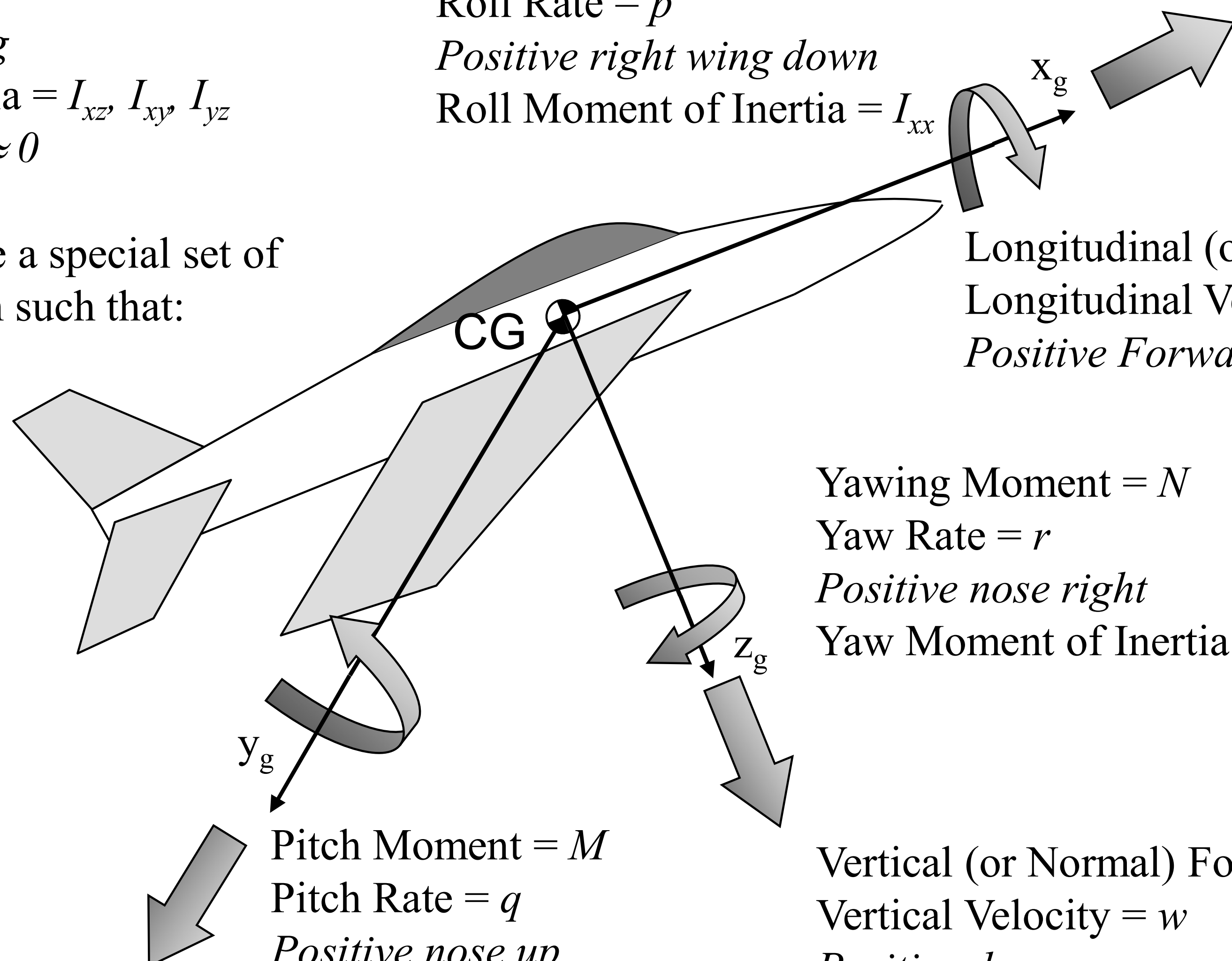
A subscript on force and moment terms denotes contribution of a specific rotorcraft component, e.g. $L_R$ is roll moment due to Main Rotor

# Body Axis Coordinate System:
## Forces, Moments, Velocities, Angular Rates, and Mass Properties

Mass = $m$
Weight = $W = mg$
Products of Inertia = $I_{xz}$, $I_{xy}$, $I_{yz}$
Typically $I_{xy}$, $I_{yz} \approx 0$

Principal axes are a special set of body axes chosen such that:
$I_{xz} = I_{xy} = I_{yz} = 0$

Roll Moment = $L$
Roll Rate = $p$
*Positive right wing down*
Roll Moment of Inertia = $I_{xx}$




Longitudinal (or Axial) Force = $X$
Longitudinal Velocity = u
*Positive Forward*

Yawing Moment = $N$
Yaw Rate = $r$
*Positive nose right*
Yaw Moment of Inertia = $I_{zz}$

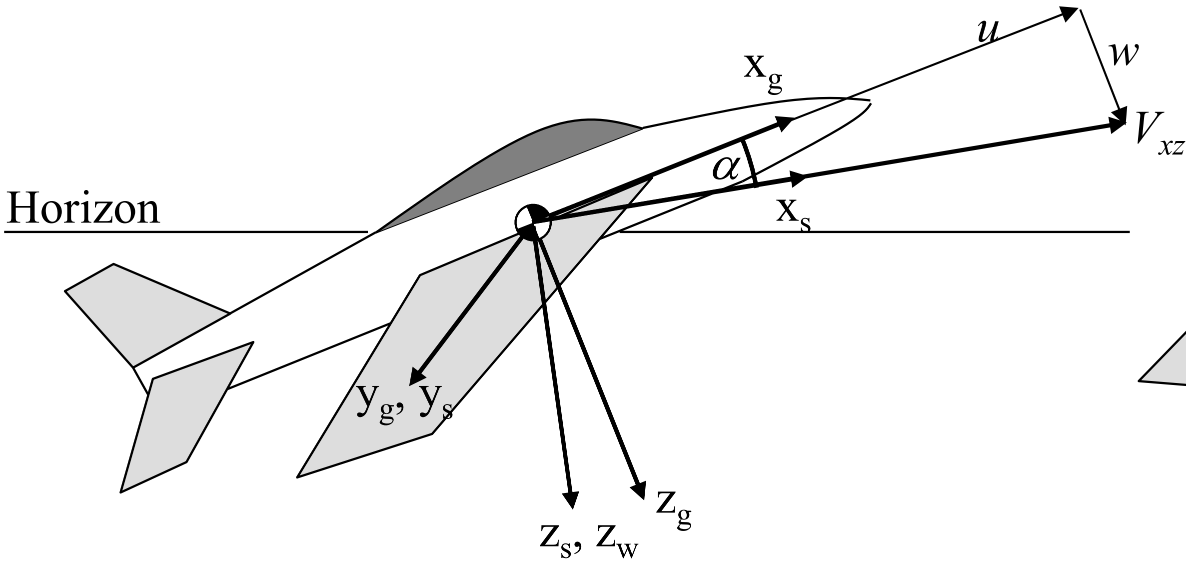
Pitch Moment = $M$
Pitch Rate = $q$
*Positive nose up*
Pitch Moment of Inertia = $I_{yy}$

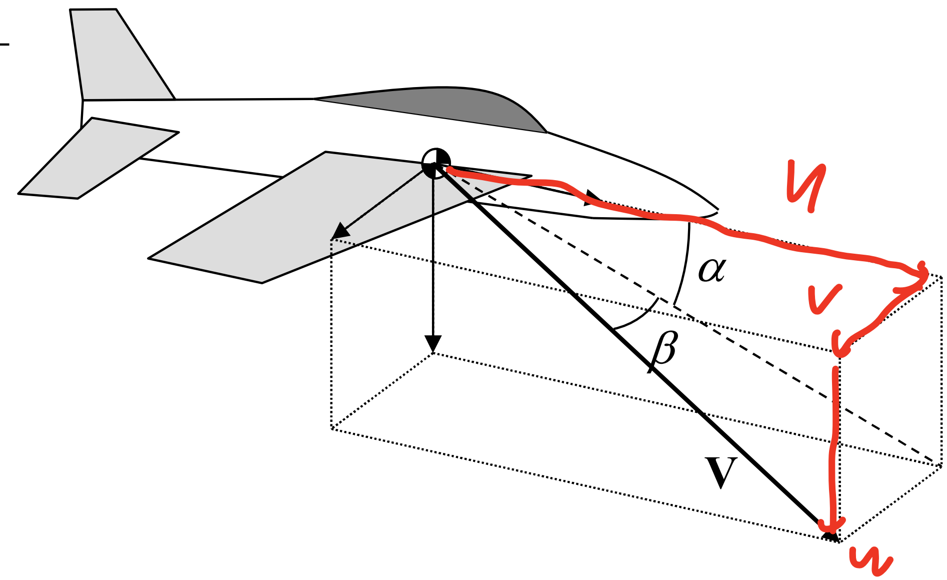
Vertical (or Normal) Force = $Z$
Vertical Velocity = $w$
*Positive down*

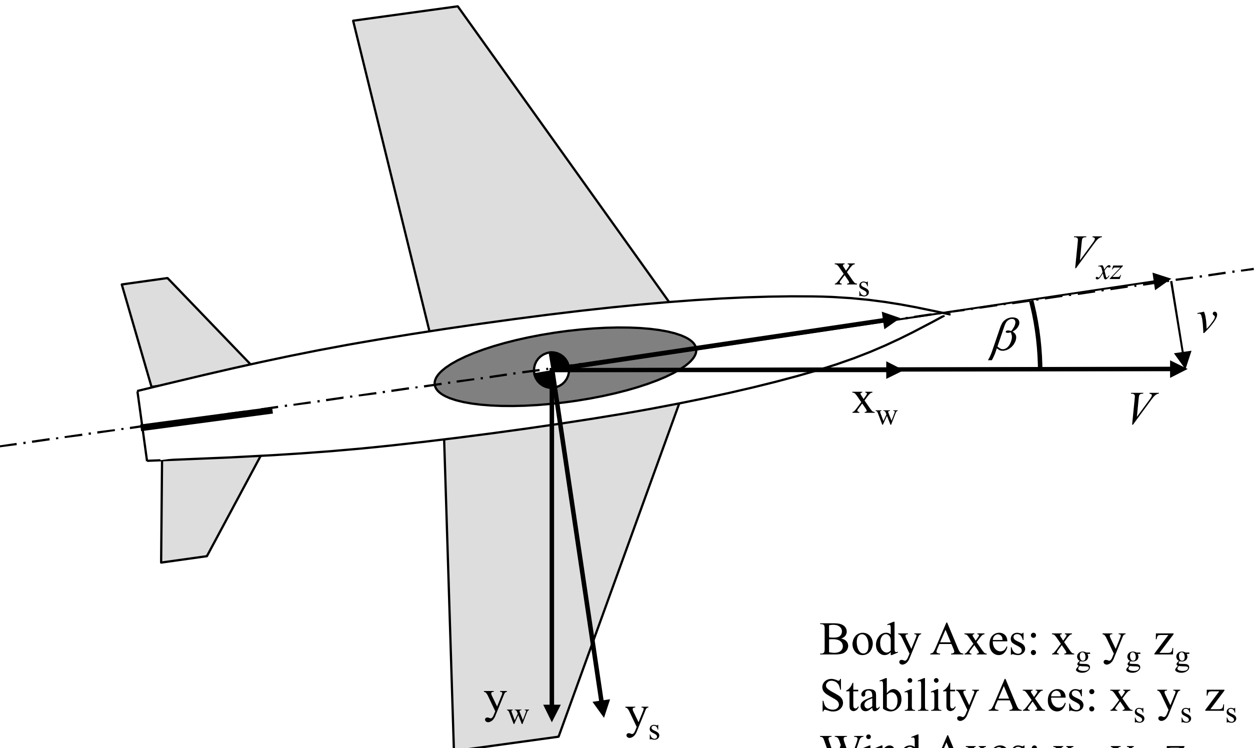
Lateral (or Side) Force = $Y$
Lateral Velocity = $v$
*Positive Right*

# Stability and Wind Axes

$\alpha$, $\beta$ = Angle of Attack and Sideslip Angle (note they are ill-defined in hover, $V = 0$)




$$\alpha = \tan^{-1}\left(\frac{w}{u}\right), \quad \beta = \sin^{-1}\left(\frac{v}{V}\right)$$

$$u = V\cos\alpha\cos\beta$$

$$v = V\sin\beta$$

$$w = V\sin\alpha\cos\beta$$

Body Axes: $x_g$ $y_g$ $z_g$

Stability Axes: $x_s$ $y_s$ $z_s$

Wind Axes: $x_w$ $y_w$ $z_w$

$$V = \sqrt{u^2 + v^2 + w^2}$$

$$V_{xz} = \sqrt{u^2 + w^2}$$

# Vector Derivative Transport Theorem

- Suppose we have two reference frames $F_a$ and $F_b$ that are rotating relative to one another
- For clarity we can consider $F_a$ a "fixed frame" and a $F_b$ "rotating frame"
- Consider a vector $\mathbf{V}$ defined in terms of unit vectors fixed in $F_b$

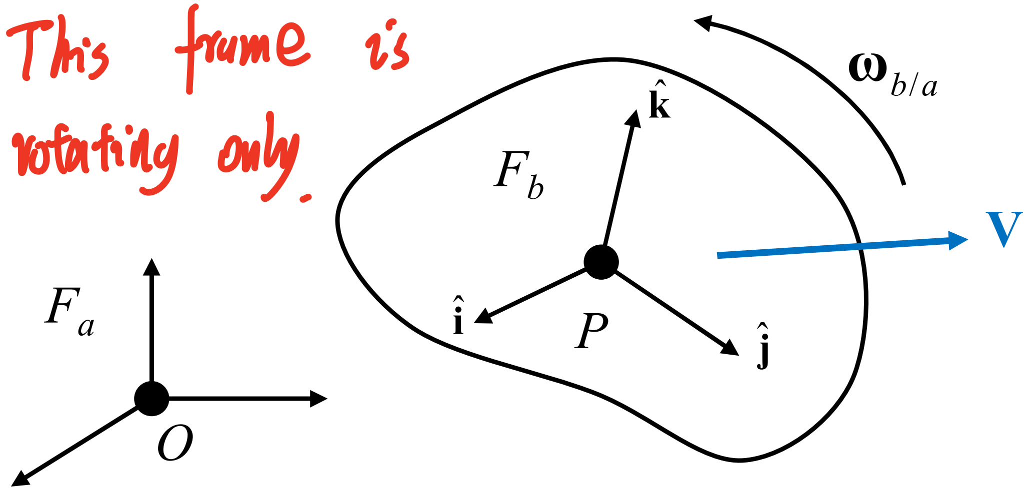
$$\mathbf{V} = V_x\hat{\mathbf{i}} + V_y\hat{\mathbf{j}} + V_z\hat{\mathbf{k}}$$

- We can take derivative $\mathbf{V}$ in $F_a$ or in $F_b$. The results will be different

$$\frac{{}^a d\mathbf{V}}{dt} \neq \frac{{}^b d\mathbf{V}}{dt}$$

- But we can use transport theorem to relate to the two derivatives

This frame is rotating only.




$$\frac{{}^a d\mathbf{V}}{dt} = \frac{dV_x}{dt}\hat{\mathbf{i}} + V_x\frac{{}^a d\hat{\mathbf{i}}}{dt} + \frac{dV_y}{dt}\hat{\mathbf{j}} + V_y\frac{{}^a d\hat{\mathbf{j}}}{dt} + \frac{dV_z}{dt}\hat{\mathbf{k}} + V_z\frac{{}^a d\hat{\mathbf{k}}}{dt}$$

$$\frac{{}^a d\mathbf{V}}{dt} = \left(\frac{dV_x}{dt}\hat{\mathbf{i}} + \frac{dV_y}{dt}\hat{\mathbf{j}} + \frac{dV_z}{dt}\hat{\mathbf{k}}\right) + V_x\frac{{}^a d\hat{\mathbf{i}}}{dt} + V_y\frac{{}^a d\hat{\mathbf{j}}}{dt} + V_z\frac{{}^a d\hat{\mathbf{k}}}{dt}$$

Note that:

$$\frac{{}^b d\mathbf{V}}{dt} = \frac{dV_x}{dt}\hat{\mathbf{i}} + \frac{dV_y}{dt}\hat{\mathbf{j}} + \frac{dV_z}{dt}\hat{\mathbf{k}} \text{ since } \hat{\mathbf{i}}, \hat{\mathbf{j}}, \hat{\mathbf{k}} \text{ are fixed in } F_b$$

$$\text{and } \frac{{}^a d\hat{\mathbf{i}}}{dt} = \boldsymbol{\omega}_{b/a} \times \hat{\mathbf{i}}, \quad \frac{{}^a d\hat{\mathbf{j}}}{dt} = \boldsymbol{\omega}_{b/a} \times \hat{\mathbf{j}}, \quad \frac{{}^a d\hat{\mathbf{k}}}{dt} = \boldsymbol{\omega}_{b/a} \times \hat{\mathbf{k}}$$

$$\frac{{}^a d\mathbf{V}}{dt} = \frac{{}^b d\mathbf{V}}{dt} + V_x\left(\boldsymbol{\omega}_{b/a} \times \hat{\mathbf{i}}\right) + V_y\left(\boldsymbol{\omega}_{b/a} \times \hat{\mathbf{j}}\right) + V_z\left(\boldsymbol{\omega}_{b/a} \times \hat{\mathbf{k}}\right)$$

$$\frac{{}^a d\mathbf{V}}{dt} = \frac{{}^b d\mathbf{V}}{dt} + \boldsymbol{\omega}_{b/a} \times \left(V_x\hat{\mathbf{i}} + V_y\hat{\mathbf{j}} + V_z\hat{\mathbf{k}}\right)$$

$$\frac{{}^a d\mathbf{V}}{dt} = \frac{{}^b d\mathbf{V}}{dt} + \boldsymbol{\omega}_{b/a} \times \mathbf{V}$$

# Useful Kinematical Relationships

## Vector Derivative Transport Theorem (Equation of Coriolis)

$$\frac{{}^{a}d\mathbf{V}}{dt} = \frac{{}^{b}d\mathbf{V}}{dt} + \boldsymbol{\omega}_{b/a} \times \mathbf{V}$$

## Properties of Angular Velocity and Angular Acceleration

$$\left.\begin{aligned} \boldsymbol{\omega}_{c/a} &= \boldsymbol{\omega}_{c/b} + \boldsymbol{\omega}_{b/a} \\ \boldsymbol{\omega}_{b/a} &= -\boldsymbol{\omega}_{a/b} \end{aligned}\right\} \text{这两个性质还是很重要的}$$

$$\boldsymbol{\alpha}_{b/a} = \frac{{}^{a}d\boldsymbol{\omega}_{b/a}}{dt}$$

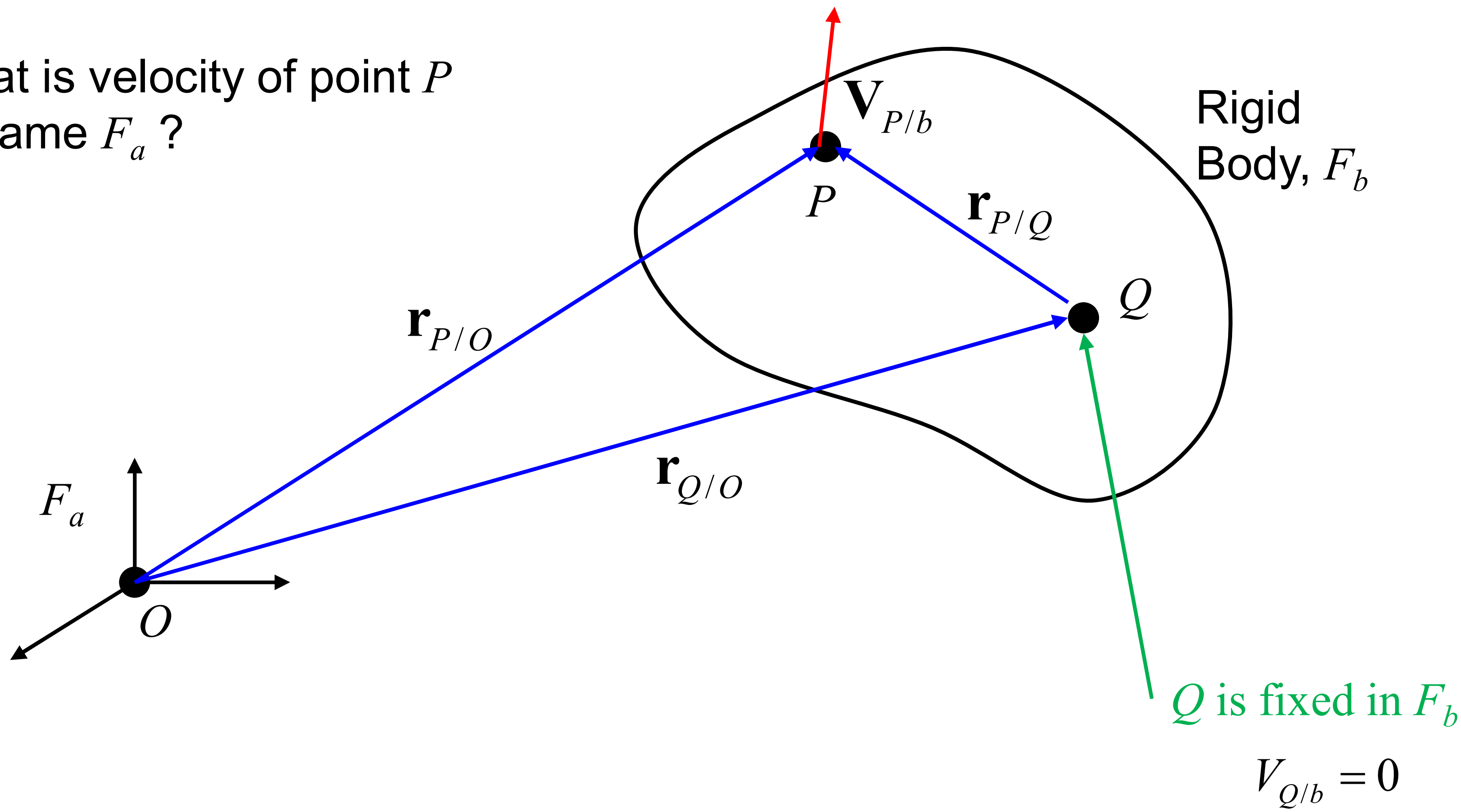
Using transport theorem: $\boldsymbol{\alpha}_{b/a} = \dfrac{{}^{a}d\boldsymbol{\omega}_{b/a}}{dt} = \dfrac{{}^{b}d\boldsymbol{\omega}_{b/a}}{dt} + \boldsymbol{\omega}_{b/a} \times \boldsymbol{\omega}_{b/a}$

$$\boldsymbol{\omega}_{b/a} \times \boldsymbol{\omega}_{b/a} = 0$$

$$\Rightarrow \boldsymbol{\alpha}_{b/a} = \frac{{}^{a}d\boldsymbol{\omega}_{b/a}}{dt} = \frac{{}^{b}d\boldsymbol{\omega}_{b/a}}{dt}$$

# Velocity in Moving Body (or Moving Reference Frame)

What is velocity of point $P$ in frame $F_a$ ?

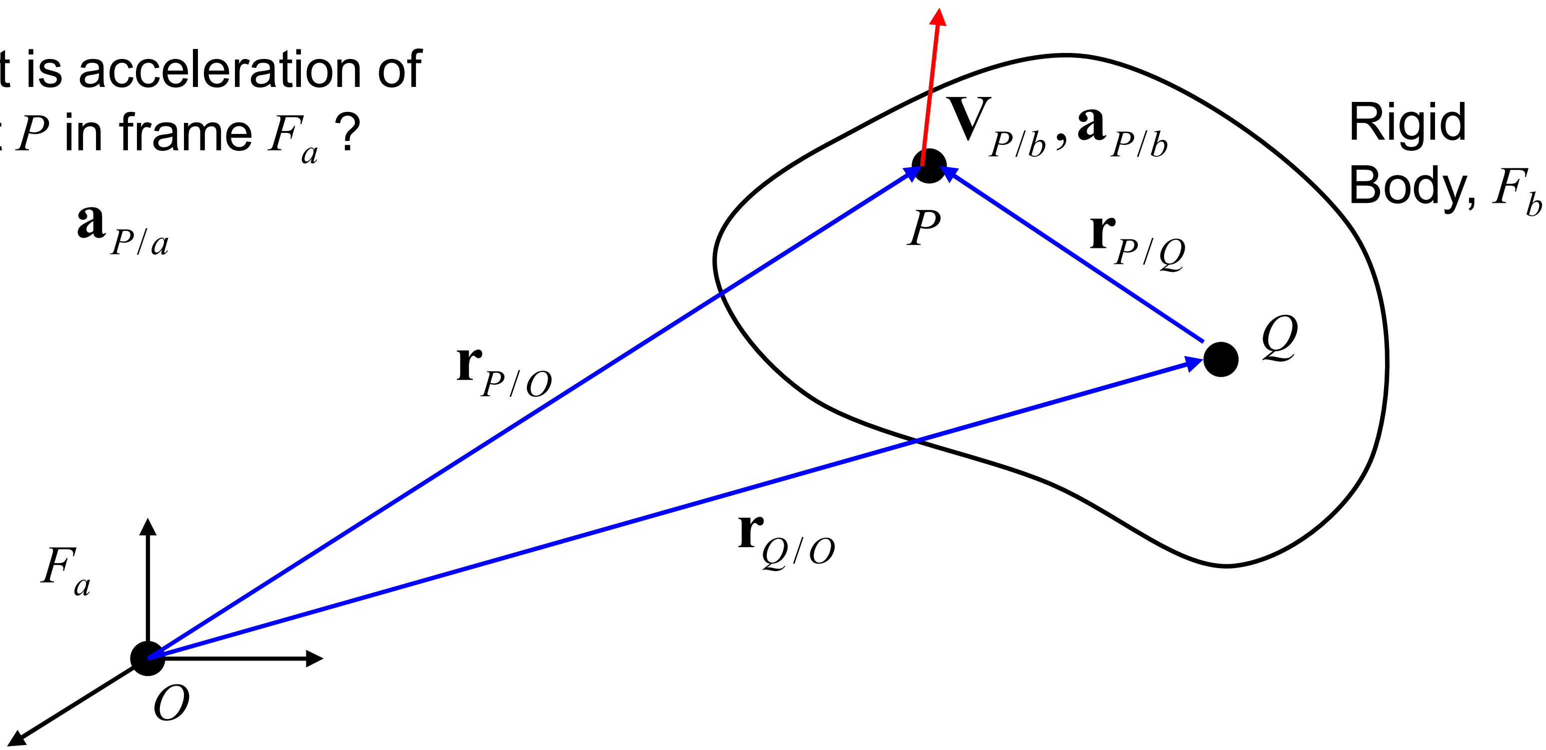



$$\mathbf{V}_{P/a} = \mathbf{V}_{P/b} + \mathbf{V}_{Q/a} + \boldsymbol{\omega}_{b/a} \times \mathbf{r}_{P/Q}$$

# Moving Body (or Moving Reference Frame)

What is acceleration of point $P$ in frame $F_a$ ?

$\mathbf{a}_{P/a}$




$$\mathbf{a}_{P/a} = \frac{d\mathbf{V}_{P/a}}{dt}$$

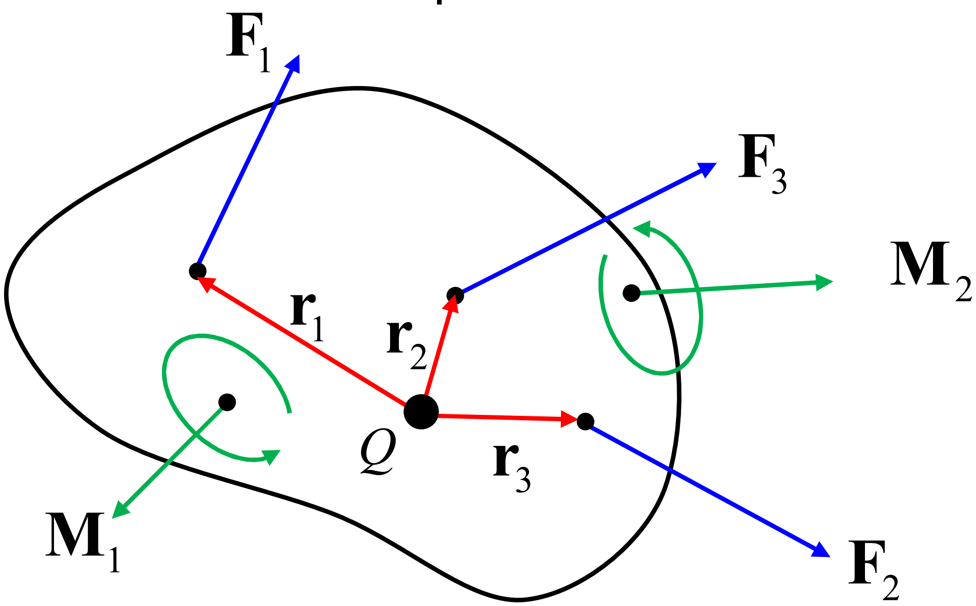
$$\mathbf{a}_{P/a} = \mathbf{a}_{P/b} + \mathbf{a}_{Q/a} + \boldsymbol{\alpha}_{b/a} \times \mathbf{r}_{P/Q} + \boldsymbol{\omega}_{b/a} \times \left(\boldsymbol{\omega}_{b/a} \times \mathbf{r}_{P/Q}\right) + 2\boldsymbol{\omega}_{b/a} \times \mathbf{V}_{P/b}$$

Centripetal Acceleration

Coriolis Acceleration

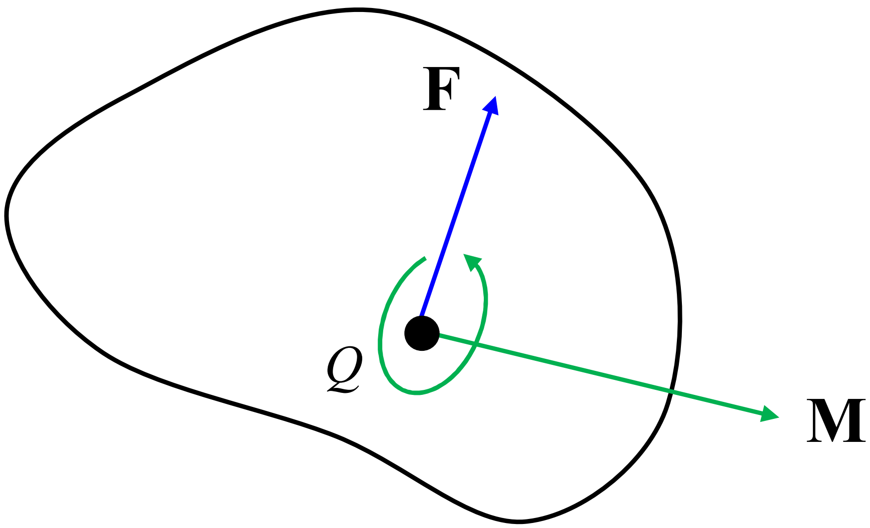
# Resultant Force and Moment on a Rigid Body

What if we have multiple forces and moments acting on a rigid body?




For forces need the force vector and a position vector to its line of action

For applied moments (a.ka. torques), point of action is irrelevant for rigid body dynamics




<u>Resultant force and moment</u>

$$\mathbf{F} = \sum_i \mathbf{F}_i$$

$$\mathbf{M} = \sum_i \left( \mathbf{M}_i + \mathbf{r}_i \times \mathbf{F}_i \right)$$

# Rigid Body Equations of Motion

Applying Newton's Laws We Can Derive Equations of Motion of an un constrained Rigid Body.

Translational Dynamics in Inertial Coordinates:

$$\mathbf{V} = \mathbf{V}_{G/e}, \text{ where G = origin of the body frame coordinate system (typically the rotorcraft CG)}$$

$$\mathbf{F} = m\frac{{}^{e}d\mathbf{V}}{dt}$$

$$\begin{bmatrix} F_N \\ F_E \\ F_D \end{bmatrix} = m\begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix}$$

Translational Dynamics in Body Coordinates:
Apply equation of Coriolis (derivative transport theorem)

We analyze force and moments in B.

$$\mathbf{F}^g = m\left(\frac{{}^{g}d\mathbf{V}^g}{dt} + \boldsymbol{\omega}^g_{g/e} \times \mathbf{V}^g\right)$$

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = m\left(\begin{bmatrix} \dot{u} + qw - rv \\ \dot{v} + ru - pw \\ \dot{w} + pv - qu \end{bmatrix}\right)$$

# Rigid Body Equations of Motion

## Rotational Dynamics in Inertial Coordinates:

$$\mathbf{M} = \frac{{}^{e}d\mathbf{H}}{dt}$$

$\mathbf{H}$ = Angular momentum vector

## Rotational Dynamics in Body Coordinates:

$$\mathbf{H}^{g} = \mathbf{I}^{g}\boldsymbol{\omega}^{g}$$

$\underline{\omega}^g = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$

Because $\underline{\underline{I}}$ does not change in B

$$\mathbf{I}^{g} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} = \text{ Inertia Matrix in Body Coordinate System}$$

$$\mathbf{M}^{g} = \mathbf{I}^{g}\frac{{}^{g}d\boldsymbol{\omega}_{g/e}^{g}}{dt} + \boldsymbol{\omega}_{g/e}^{g} \times \mathbf{I}^{g}\boldsymbol{\omega}_{g/e}^{g}$$

# Rigid Body Equations of Motion

Rotational Dynamics in Body Coordinates:

$$\begin{bmatrix} L \\ M \\ N \end{bmatrix} = \mathbf{I_B} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} \left(I_z - I_y\right)qr + I_{yz}\left(r^2 - q^2\right) + I_{xy}rp - I_{xz}pq \\ \left(I_x - I_z\right)rp + I_{xz}\left(p^2 - r^2\right) + I_{yz}pq - I_{xy}qr \\ \left(I_y - I_x\right)pq + I_{xy}\left(q^2 - p^2\right) + I_{xz}qr - I_{yz}rp \end{bmatrix}$$

$$\begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{bmatrix} I_x\dot{p} \\ I_y\dot{q} \\ I_z\dot{r} \end{bmatrix} + \begin{bmatrix} -I_{xy}\dot{q} - I_{xz}\dot{r} \\ -I_{xy}\dot{p} - I_{yz}\dot{r} \\ -I_{xz}\dot{p} - I_{yz}\dot{q} \end{bmatrix} + \begin{bmatrix} \left(I_z - I_y\right)qr + I_{yz}\left(r^2 - q^2\right) + I_{xy}rp - I_{xz}pq \\ \left(I_x - I_z\right)rp + I_{xz}\left(p^2 - r^2\right) + I_{yz}pq - I_{xy}qr \\ \left(I_y - I_x\right)pq + I_{xy}\left(q^2 - p^2\right) + I_{xz}qr - I_{yz}rp \end{bmatrix}$$

Inertia coupling

( Can usually assume the xz plane of the body frame is a plane of symmetry. This implies that $I_{xy} = I_{yz} = 0$. )

# Euler Angles

Euler angles define the aircraft attitude or the orientation of the aircraft and its body-fixed coordinate system relative to the Earth-fixed coordinate system.

$\phi$ = Roll Attitude or Bank Angle
$\theta$ = Pitch Attitude
$\psi$ = Yaw Attitude or Heading

Defined using a sequence of three rotations that transform a set of axes that are initially aligned with the Earth-fixed system so that they are aligned with the body-fixed coordinate system of the aircraft.

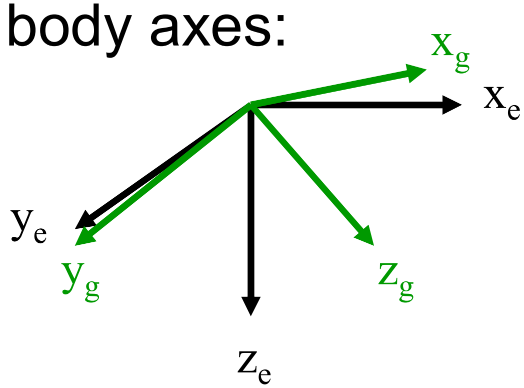
***The order of the sequence of rotations is very important***. Using a different order of rotations will result in different values for the Euler angles.

For aircraft, the standard order of the sequence of rotations is always:
***Yaw (about z-axis), then pitch (about y-axis), then roll (about x-axis).***

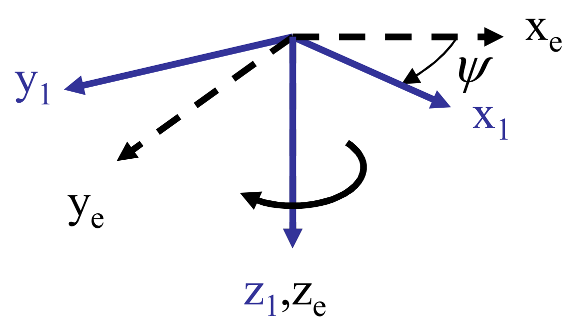
Euler angles are used to do coordinate system transformations between Earth-fixed and body-fixed systems.

# Euler Angles – Standard Sequence of Rotations

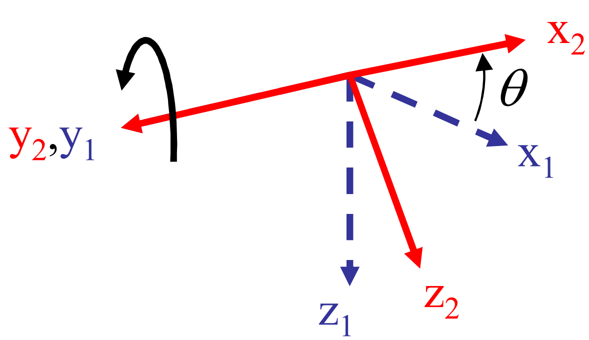
Starting with earth-fixed axes, find sequence of rotations that align it with body axes:



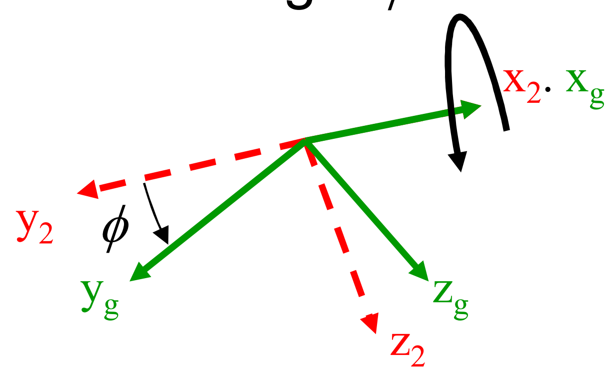

1. Rotate about $z_E$ axis by heading angle $\psi$




2. Rotate about $y_1$ axis by pitch attitude angle $\theta$



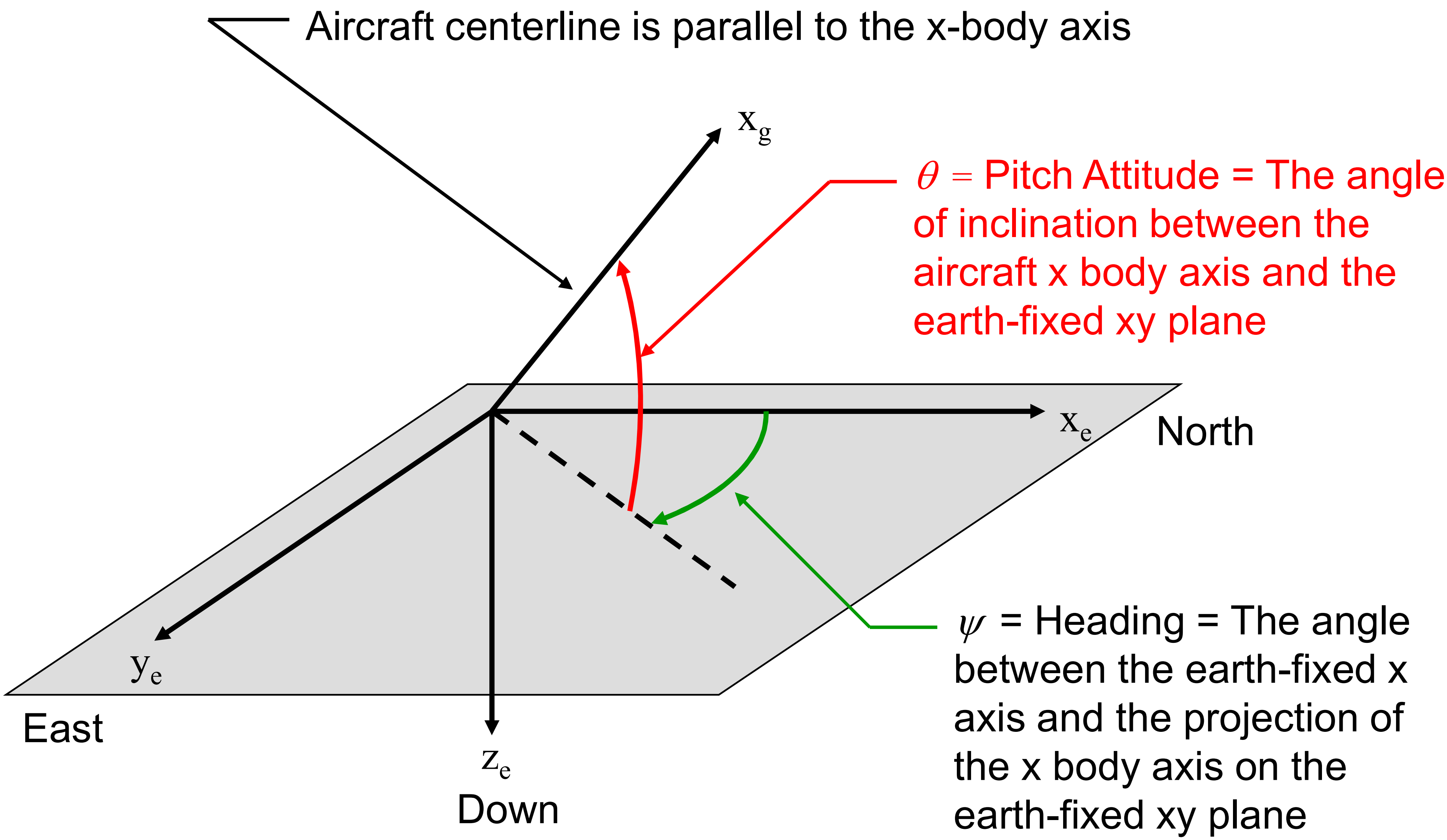

3. Rotate about $x_2$ axis by roll attitude angle $\phi$




$O \xrightarrow{\psi\ \theta\ \phi} B$

推导一下 p q r 与 ψ, θ, φ 的关系.

# Euler Angles – interpretation of pitch and heading



# Euler Angles

To eliminate some of the ambiguity we normally we constrain the Euler angles as follows:

$$\boxed{\begin{aligned} &-180^\circ \le \phi \le 180^\circ \\ &-90^\circ \le \theta \le 90^\circ \\ &-180^\circ \le \psi \le 180^\circ \quad \text{or} \quad 0^\circ \le \psi \le 360^\circ \end{aligned}}$$

Euler Angle Kinematics: Time rate of change of Euler angles are related to the body-axis angular rates by the following equations:

$$\boxed{\begin{aligned} \dot{\phi} &= p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \\ \dot{\theta} &= q\cos\phi - r\sin\phi \\ \dot{\psi} &= q\frac{\sin\phi}{\cos\theta} + r\frac{\cos\phi}{\cos\theta} \end{aligned}}$$

这有了，但我还是自己
推导一下.

# Coordinate System Transformations

Can derive transformation matrices between Earth-fixed coordinate system and body coordinate system using Euler angles:

$$T_{g/e} = \text{Coordinate system tranform from Earth coordinate system to Body coordinate system}$$

$$\mathbf{V}^g = T_{g/e}\mathbf{V}^e$$

$$T_{g/e} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}}_{T_\phi} \underbrace{\begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}}_{T_\theta} \underbrace{\begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{T_\psi}$$

$$T_{g/e} = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi & \cos\phi\cos\theta \end{bmatrix}$$

# Coordinate System Transformations (cont'd)

Can use to write gravity vector in body coordinate system:

$$\mathbf{g}^g = T_{g/e}\mathbf{g}^e = T_{g/e}\begin{bmatrix} 0 \\ 0 \\ g_D \end{bmatrix}, \; g_D \approx 9.81 \text{ m/s}^2 \approx 32.2 \text{ ft/s}^2, \qquad \mathbf{g}^g = g_D\begin{bmatrix} -\sin\theta \\ \cos\theta\sin\phi \\ \cos\theta\cos\phi \end{bmatrix}$$

Use inverse transform to determine North, East, Down velocities from body velocities. Direction Cosine Matrices are orthogonal – can get inverse by taking transpose of matrix:

$$T_{e/g} = T_{g/e}^{-1} = T_{g/e}^{T}$$

$$\mathbf{V}^e = \begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix} = T_{e/g}\mathbf{V}^g = T_{e/g}\begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

# Aircraft 6-DOF Rigid Body Equations of Motion

$$\dot{u} = \frac{X}{m} - g\sin\theta - qw + rv$$

$$\dot{v} = \frac{Y}{m} + g\cos\theta\sin\phi - ru + pw$$

$$\dot{w} = \frac{Z}{m} + g\cos\theta\cos\phi - pv + qu$$

$$\dot{p} = \frac{1}{I_x I_z - I_{xz}^2}\left(I_z L + I_{xz} N + I_{xz}\left(I_x - I_y + I_z\right)pq - \left(I_z^2 - I_z I_y + I_{xz}^2\right)qr\right)$$

$$\dot{q} = \frac{1}{I_y}\left(M - \left(I_x - I_z\right)rp - I_{xz}\left(p^2 - r^2\right)\right)$$

$$\dot{r} = \frac{1}{I_x I_z - I_{xz}^2}\left(I_x N + I_{xz} L - I_{xz}\left(I_x - I_y + I_z\right)qr + \left(I_x^2 - I_x I_y + I_{xz}^2\right)pq\right)$$

$$\dot{\phi} = p + q\sin\phi\tan\theta + r\cos\phi\tan\theta$$

$$\dot{\theta} = q\cos\phi - r\sin\phi$$

$$\dot{\psi} = q\sin\phi/\cos\theta + r\cos\phi/\cos\theta$$

$$\dot{x} = u\cos\theta\cos\psi + v\left(\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi\right) + w\left(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi\right)$$

$$\dot{y} = u\cos\theta\sin\psi + v\left(\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi\right) + w\left(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi\right)$$

$$\dot{z} = -u\sin\theta + v\sin\phi\cos\theta + w\cos\phi\cos\theta$$

# Flight Simulation

- Note that the equations of motion include 6 parameters: $X,Y,Z,L,M,N$ that represent the total aerodynamic forces and moments resolved at the aircraft CG
- Flight simulation involves the calculation of these forces and moments and the integration of the equations of motion based on prescribed control inputs and external disturbances

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- For fixed-wing aircraft, the forces and moments can be represented with look-up tables based on wind-tunnel data. helicopter cannot use
- For helicopters the problem is more difficult: is because too much DoF, we cannot capture all information using wind-tunnel,
  - Additional differential equations need to be solved to account for rotor dynamics and the engine dynamics
  - There are complex aerodynamic interactions between the rotor and the fuselage and tail
- Helicopter simulation is usually formulated using a modular approach, in which the forces and moments due to sub-components (fuselage, main rotor, tail surfaces, tail rotor) are calculated individually and summed to get the total resultant forces and moments