The Impact of Wind and Turbulence on UAS

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Rigid Body Eqs. Of Motion (EOM)

- In three dimensions, we need six degrees of freedom. EOM are related to the time rate of change of linear ($m\boldsymbol{v}$) and angular momentum ($\boldsymbol{I\omega}$):
  - Three translational velocities ($\mathbf{v}$) of the center of gravity.

$$\mathbf{F} = d(m\mathbf{v})/dt$$

  - Three rotational velocities ($\boldsymbol{\omega}$) around the center of gravity.

$$\mathbf{M} = d(\mathbf{I}\boldsymbol{\omega})/dt$$

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Forces

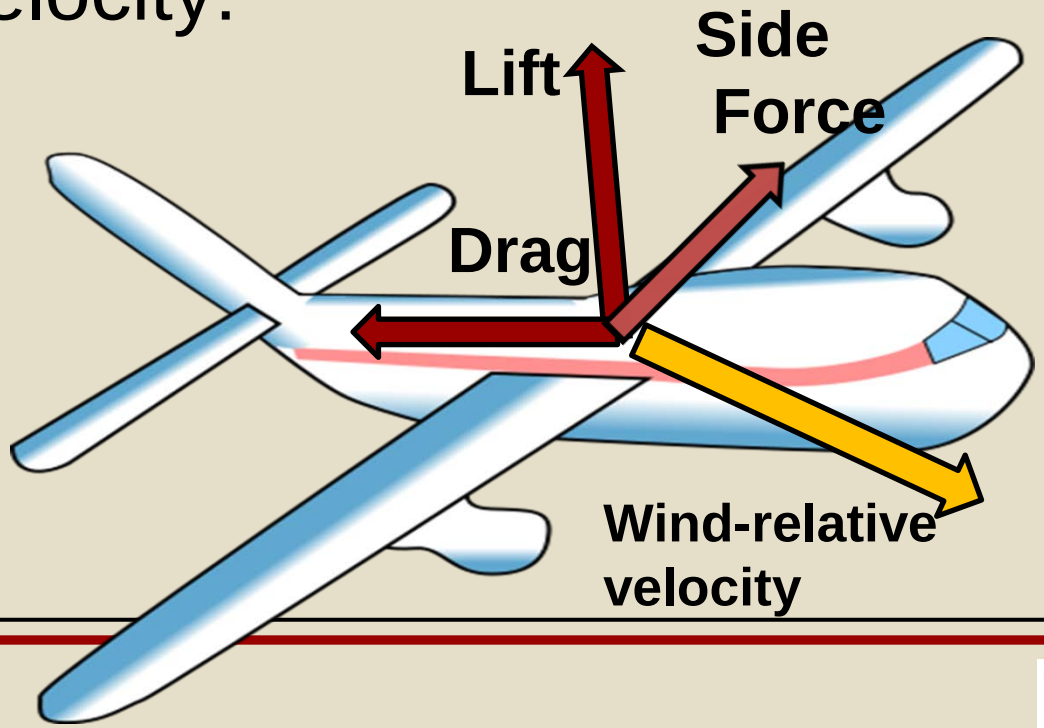
- The moments are products of forces and moment arms, so we only need to focus on the former.
- There are three classes of forces:
  - Aerodynamic
  - Propulsive
  - Gravitational

The effect of wind and turbulence manifest through aerodynamic forces

We consider control forces (e.g., elevator, ailerons, rudder) as aerodynamic in nature.

Aerodynamic Forces

- Ignoring control forces, there are three fundamental aerodynamic forces – anti-parallel and anti-perpendicular to the local wind-relative velocity:
  - **Lift**
  - **Drag**
  - **Side Force**



Lift Force

- For longitudinal aircraft motions, (u, w, θ), the lift force is dominant ($L/D > 5$).
- In level, unaccelerated flight (to first order):

$$L_0 = \frac{1}{2}\rho V^2 S a\, \alpha_0 = mg$$

ρ is air density, V is airspeed, S is a reference area, a is lift curve slope, and α_0 is the trim angle of attack.

For fixed vehicle: decreasing ρ decreases lift; increasing V or α (below stall) increases lift.

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Relative Change in Lift Due to Incremental Gusts

- Longitudinal gust (u_g): changing airspeed without changing angle of attack ($\alpha \approx w_g/V$).
- Vertical gust (w_g): changing angle of attack, without changing airspeed.

$$\frac{\left(\frac{\Delta L}{L_0}\right)_{u_g}}{\left(\frac{\Delta L}{L_0}\right)_{w_g}} \approx \frac{2u_g/V}{\frac{w_g/V}{\alpha_0}} = 2\alpha_0 \frac{u_g}{w_g}$$

So, if $u_g \sim w_g$, and since α_0 is small ($2\alpha_0 \approx 1/8$), the impact due to longitudinal gusts will be much smaller than that due to vertical ones.

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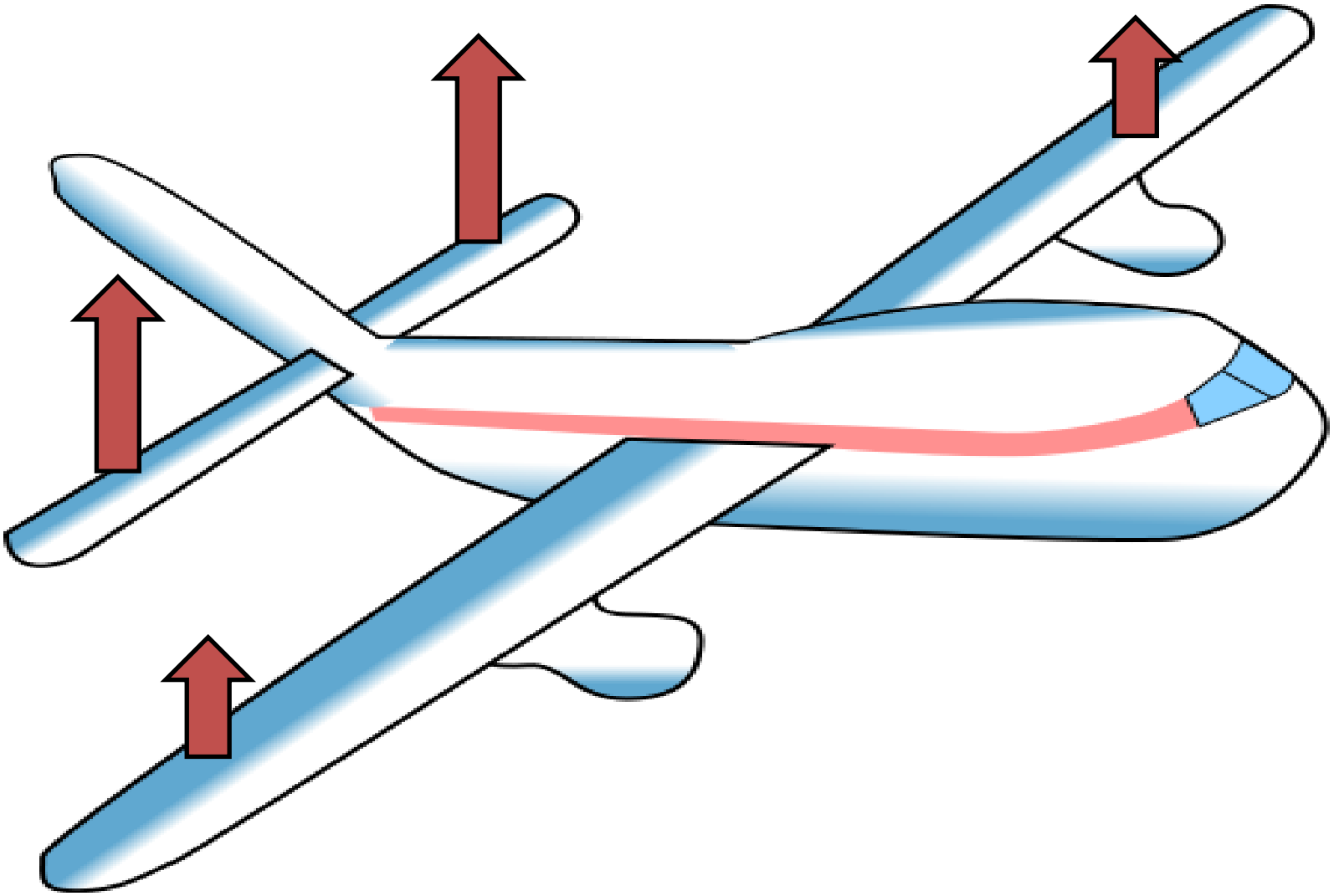
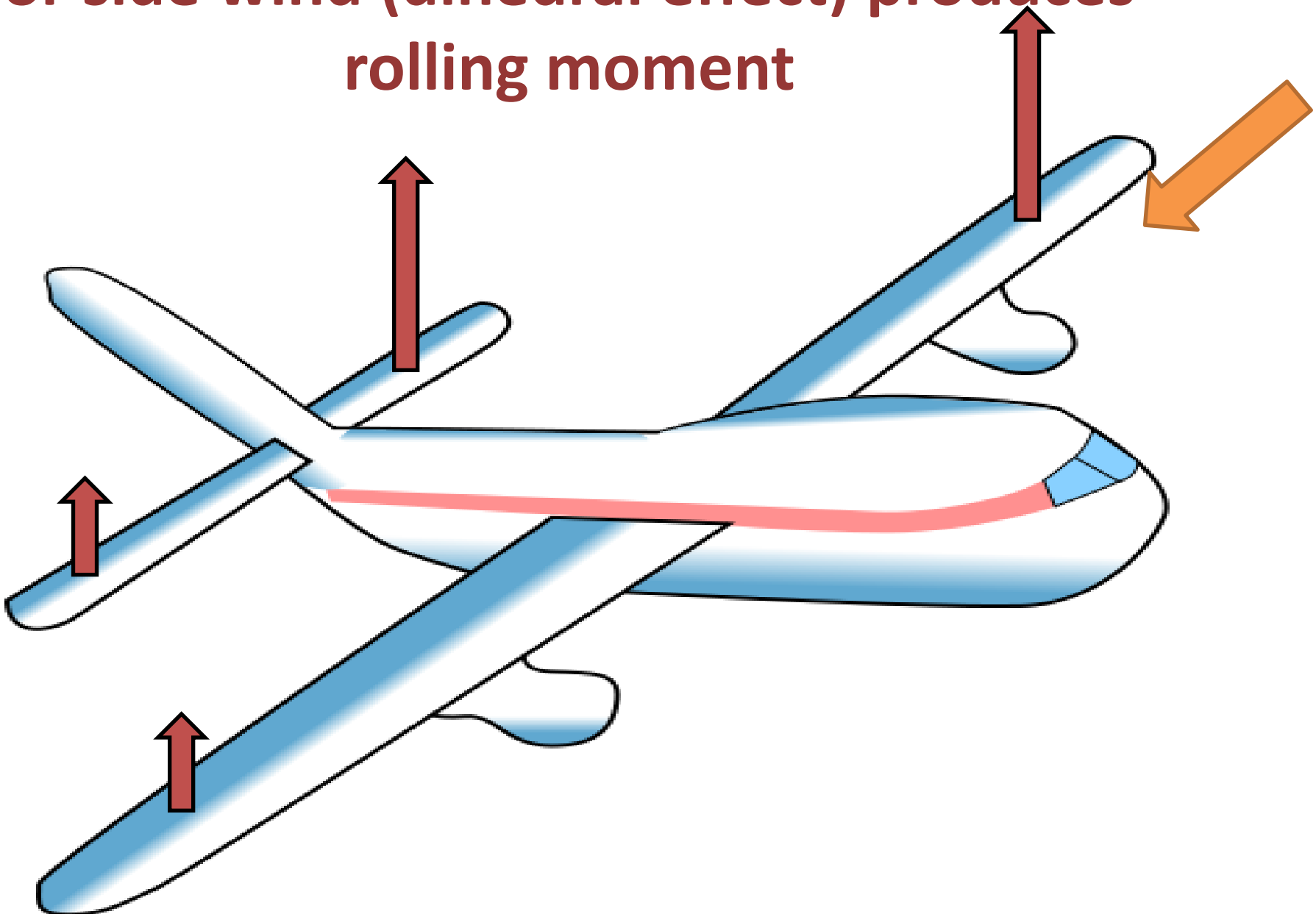
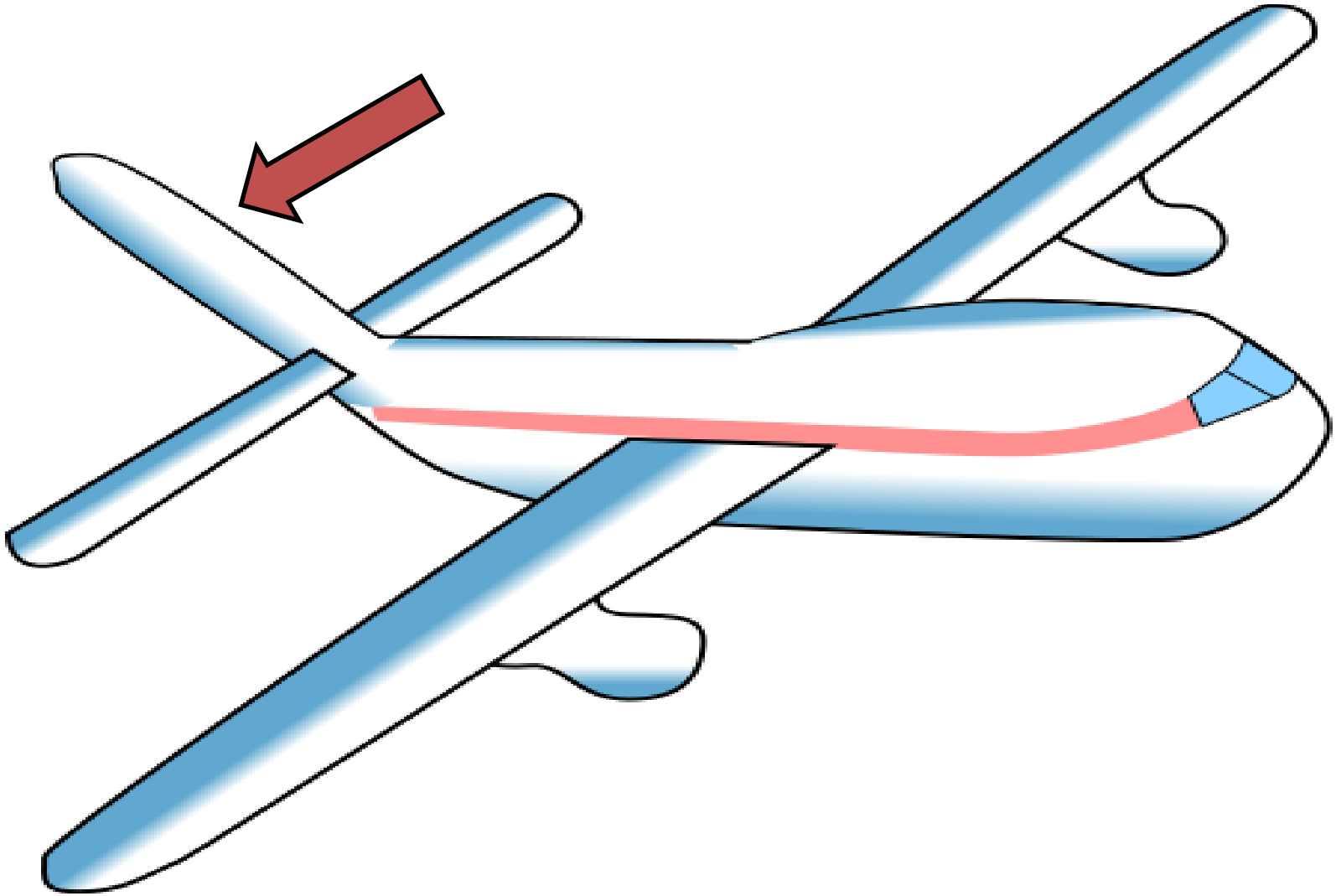
Differential lift on wing and tail produces pitching moment



Differential lift across wing (or tail) or side wind (dihedral effect) produces rolling moment



Side wind on vertical tail surface produces yawing moment



Performance vs. Stability and Control

- Wind vs. wind shear vs. turbulence is a matter of scale:
  - Large scale and large scale shears can affect lift and drag, thereby affecting performance (wind and wind shear)
  - Small scale changes affect lift, and hence stability and control (wind shear and turbulence)

Note that turbulence can affect performance via increased energy use in operating control surfaces.

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Aircraft Dynamics (cont'd)

Note that we consider the atmosphere as a spatial quantity, whereas the aircraft flying through the atmosphere is sensing it as a function of time. This relationship is given by (for large enough V):

$$f = \frac{V}{\lambda}$$

Where λ is a spatial wavelength, *V* is airspeed, and *f* is temporal frequency (s^{-1}). *Note, this is akin to "$x = Vt$" (Taylor hypothesis).*

So: for the same airspeed, a larger wavelength means smaller frequency; and for the same wavelength, a smaller airspeed means a smaller frequency.

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Example: Longitudinal Dynamics

- Two main rigid-body longitudinal modes – *without automatic control*, *(i.e., "Open Loop" or "OL")*:
  - Low-frequency "phugoid" mode: slow airspeed variations with small pitch/vertical translations
  - High-frequency "short period" mode: rapid vertical translations and pitching, with small airspeed changes

Note: at very high frequencies, unsteady aerodynamics will kick-in, damping the response.

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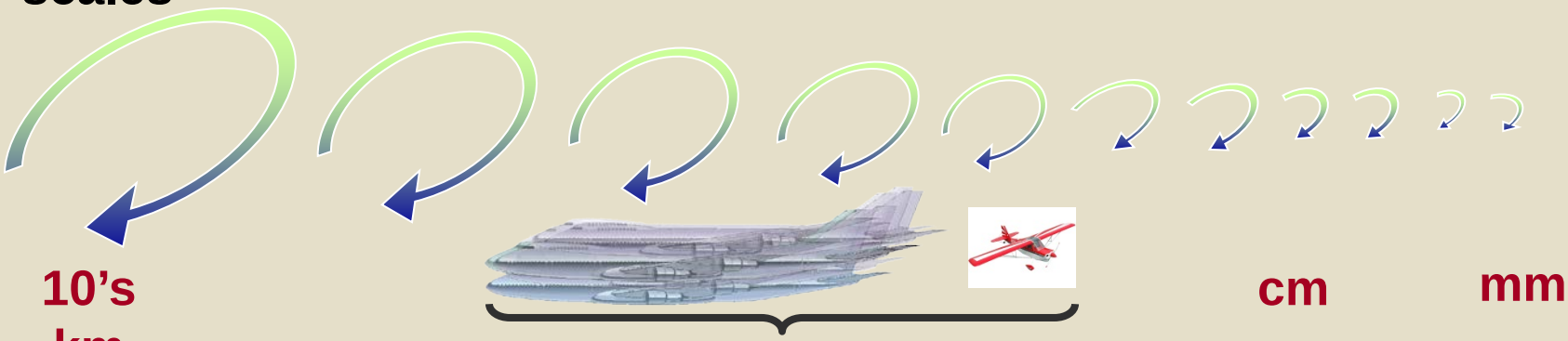
Aircraft Response to Turbulence

Energy production scales

Dissipation scales



Aircraft/UAV respond to scales from 10's cm to 2-3 km

Aircraft/autopilot can adjust to ride smoothly over "waves"

Excites rapid pitching, rolling, and vertical motions

Excites flexible modes – but typically small amplitude

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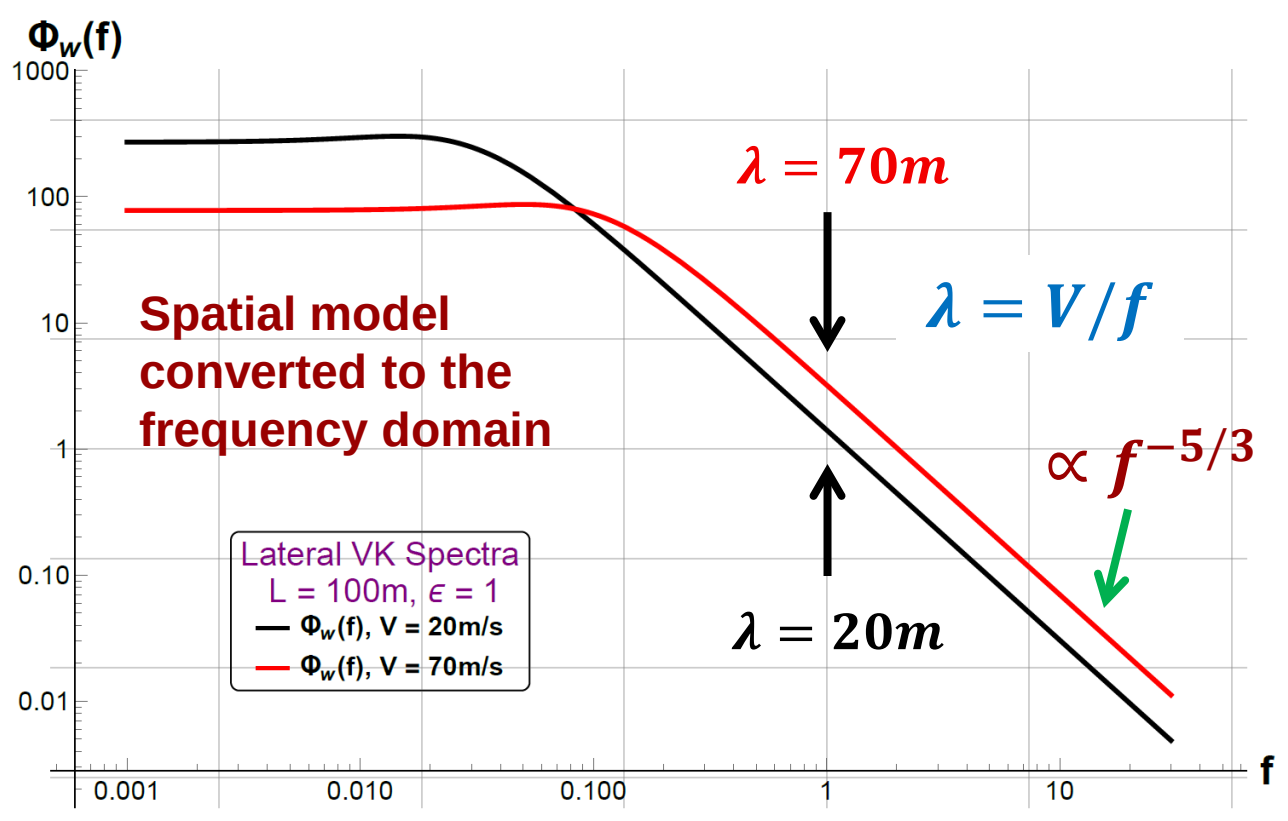
Von Karman Turbulence Model

- The von Karman model is a function of a turbulence intensity parameter (energy dissipation rate, ε) and a correlation length scale (L).

large λ



small λ

von Karman model for airspeed of UAV and landing transport aircraft

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Frequency Response Function (FRF)

- Frequency response functions describe steady state aircraft state variable output for a given input variable.
- The FRF has magnitude and phase information. (We’re just going to deal with magnitude or magnitude squared here.)

Frequency Response Function (cont'd)

- Inputs could include:
  - Control deflections
  - Throttle
  - Airspeed
  - Wind and turbulence
- State outputs could include:
  - Positions, or their rates (velocities and accelerations)
  - Attitudes, or their rates

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Frequency Response Function and Power Spectrum

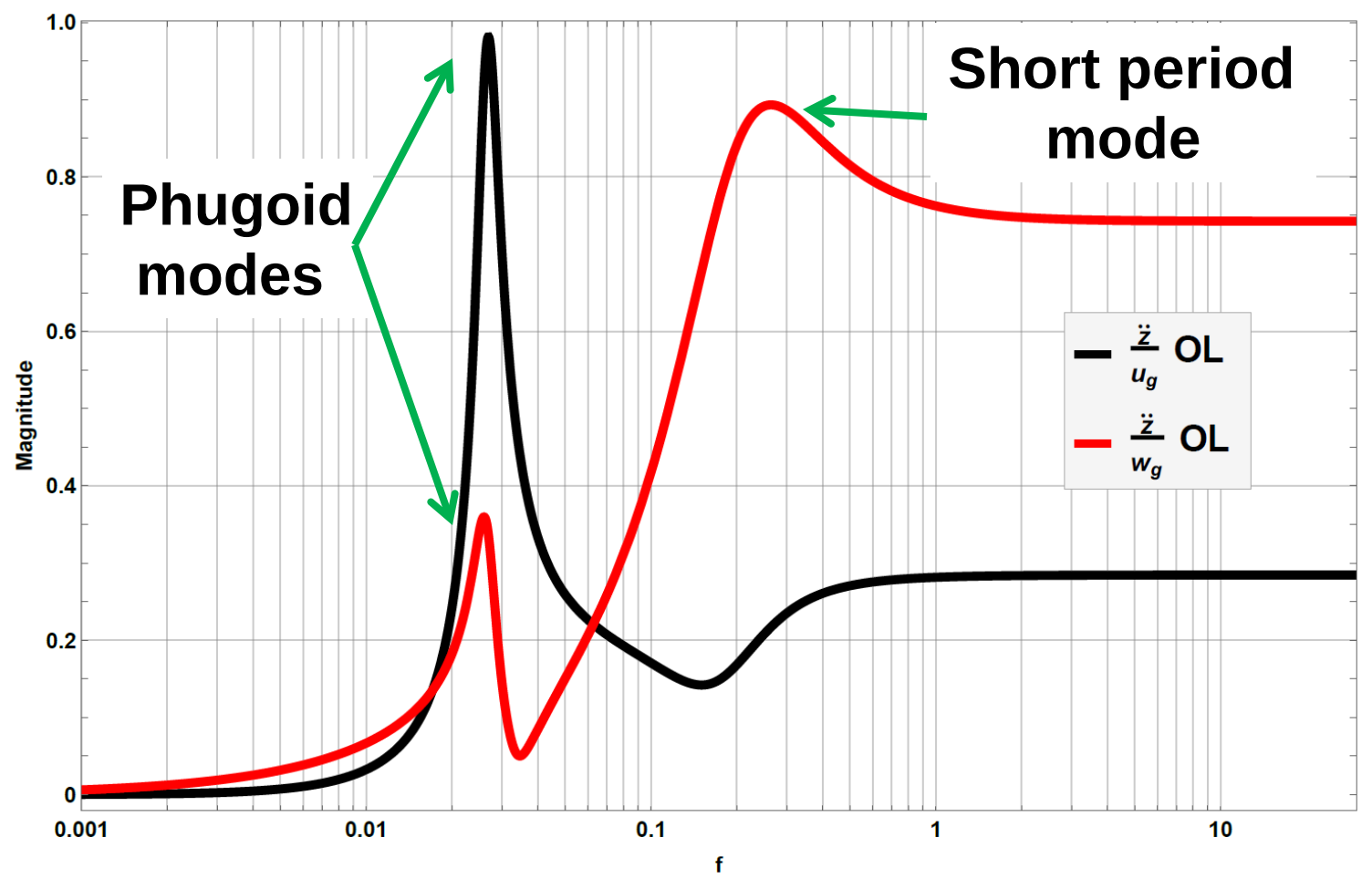
Example: body axis vertical acceleration given vertical gust input.

$$\ddot{z}(f) = \left[\frac{\ddot{z}}{w_g}\right](f) \times w_g\,(f)$$

Power spectrum relation is modulus square of input/output relation:

$$\Phi_{\ddot{z}}(f) = \left\|\frac{\ddot{z}}{w_g}(f)\right\|^2 \times \Phi_{w_g}\,(f)$$

Vertical Acceleration FRF for u_g and w_g - OL



Mid-Sized Transport Aircraft (landing config.)

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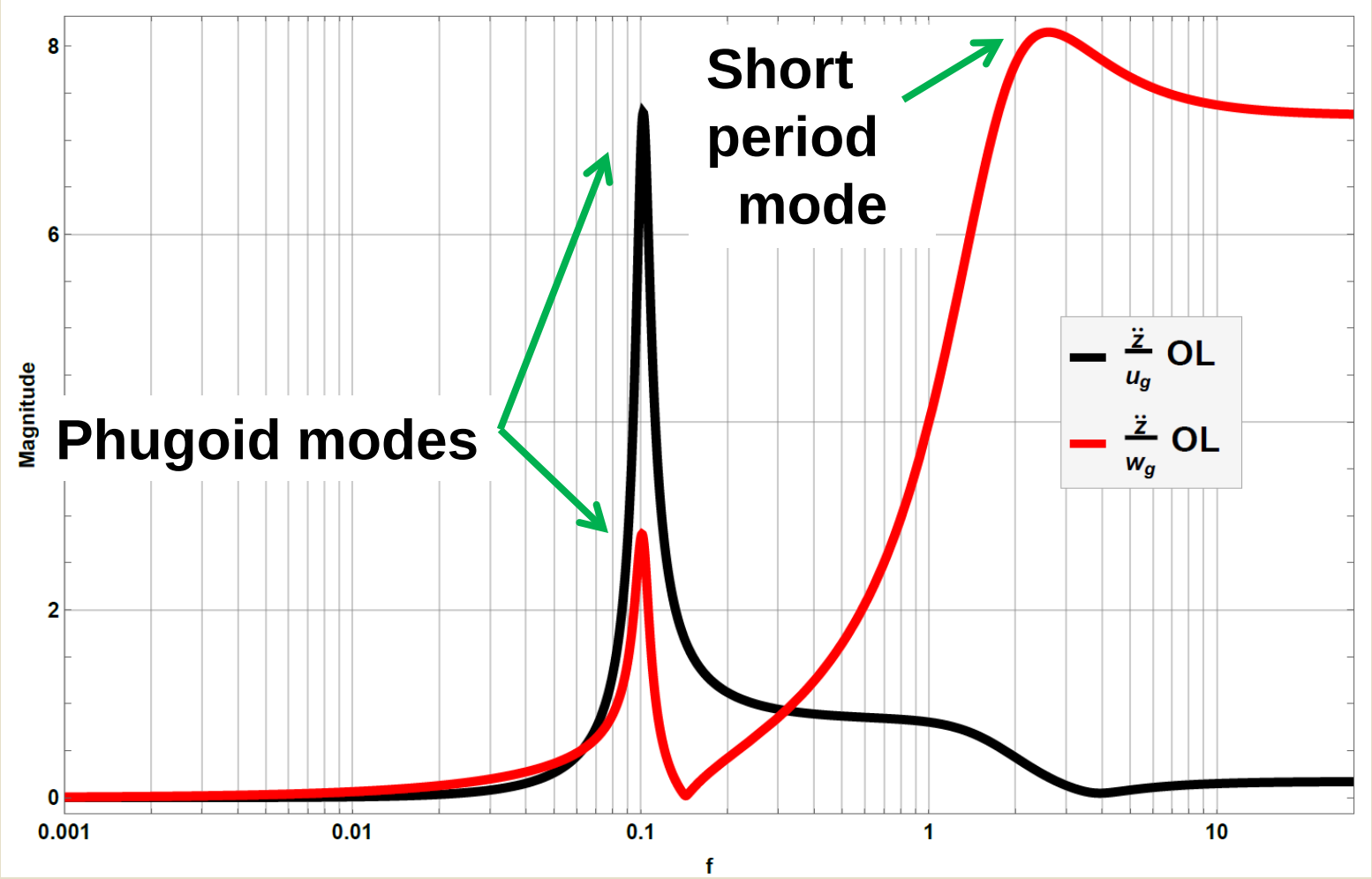
Vertical Acceleration FRF for u_g and w_g - OL



Small UAV

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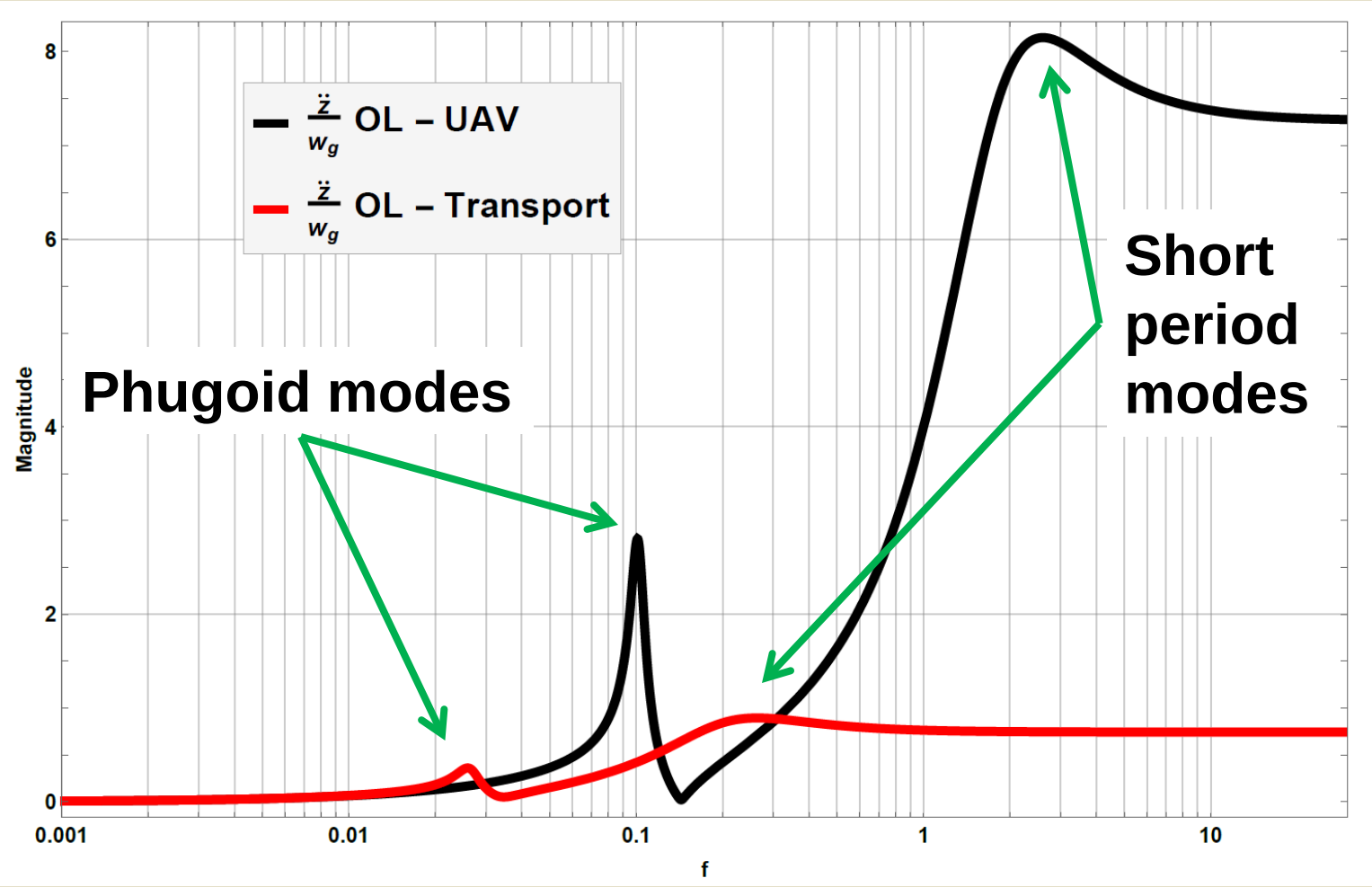
Vertical Acceleration FRF for w_g - OL



UAV has stronger response, and at higher freq's

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Automatic Control

- A pilot or autopilot is almost always used to help stabilize and control the vehicle. “Closed Loop” (CL).
- Standard autopilot modes include attitude (e.g., pitch or roll) hold, altitude hold, and airspeed hold.
  - Altitude hold typically includes pitch/pitch-rate control to dampen the phugoid response.

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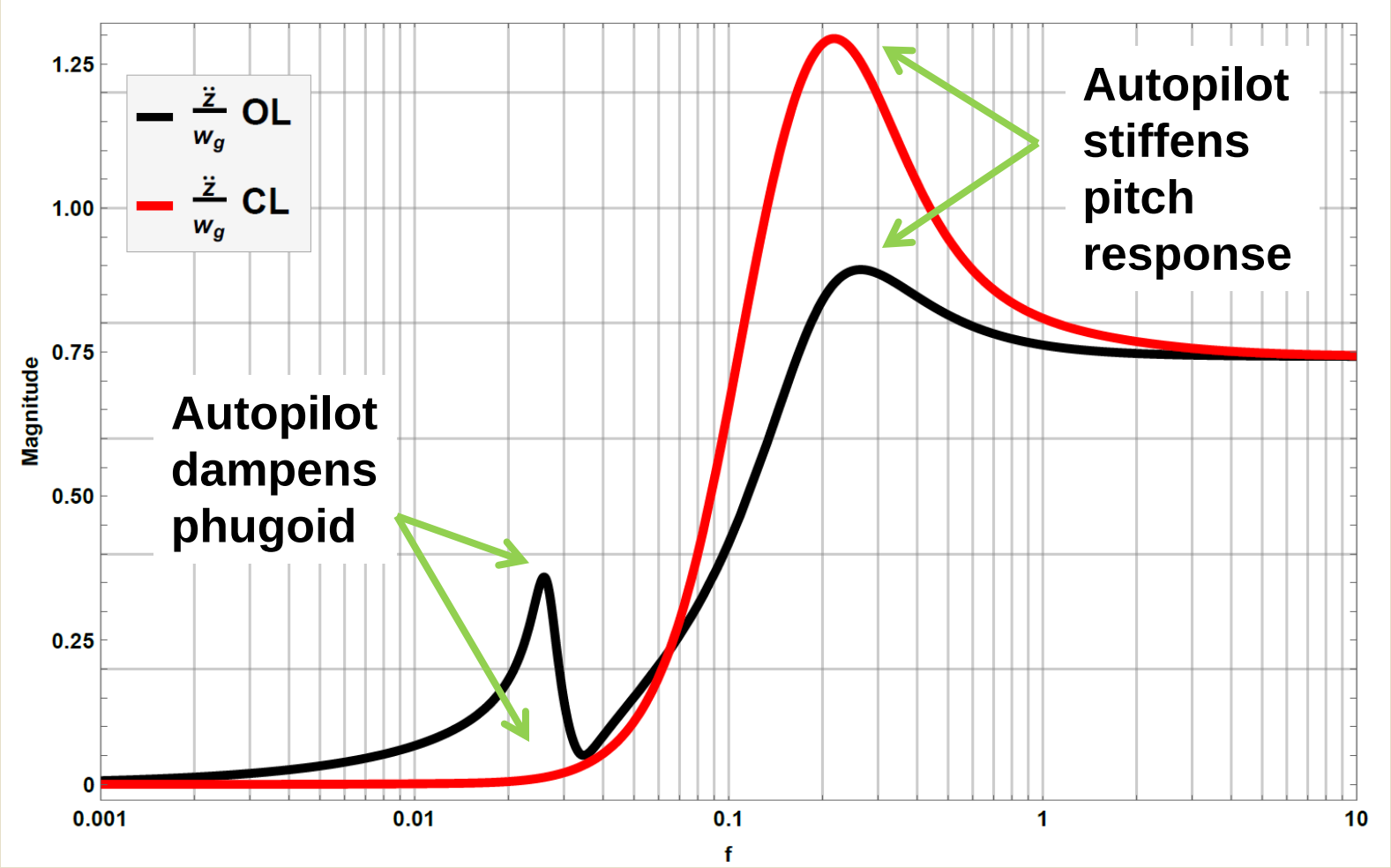
Vertical Acceleration Response to w_g - OL vs CL



Mid-Sized Transport Aircraft

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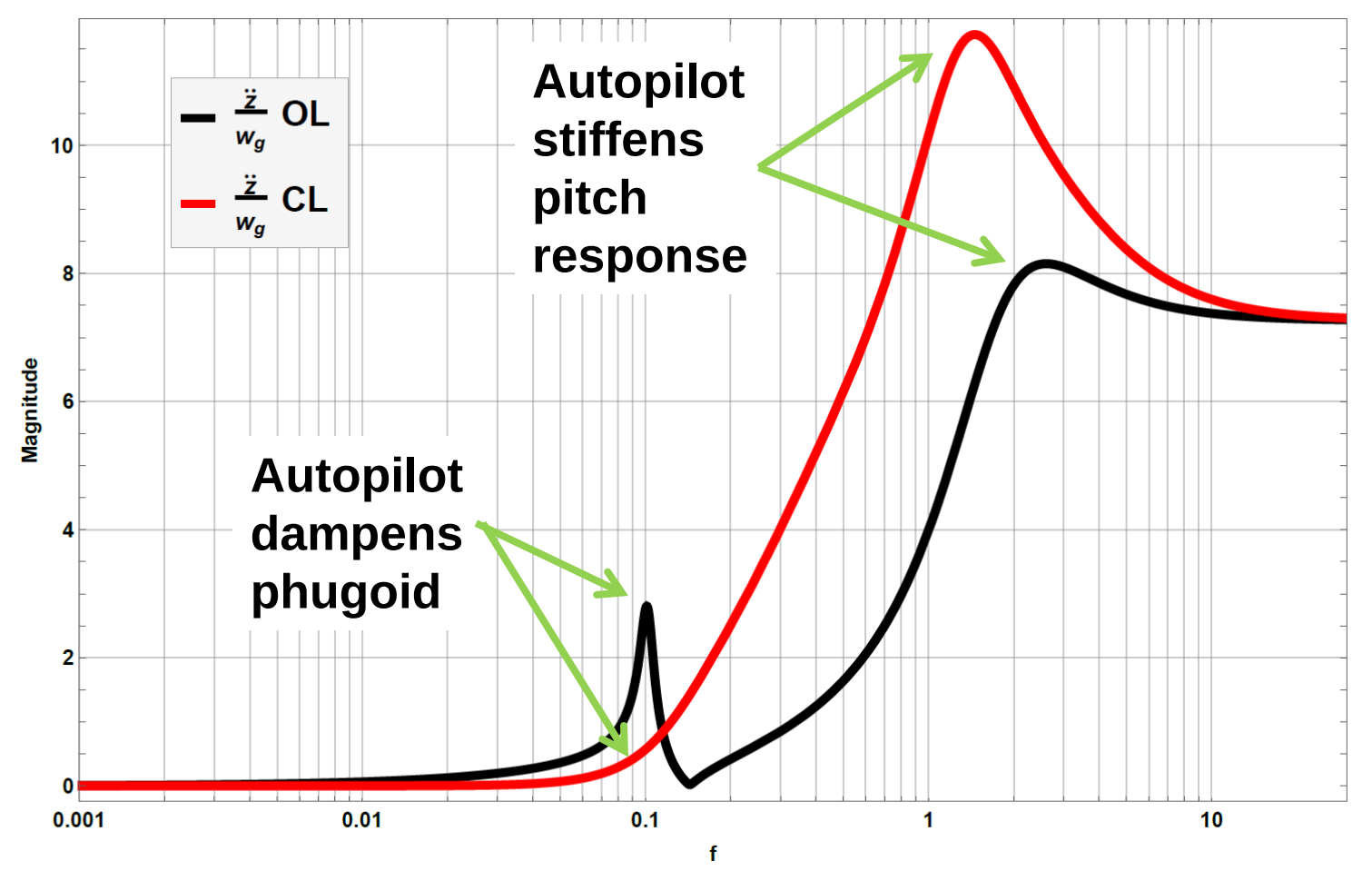
Vertical Acceleration Response to w_g - OL vs. CL



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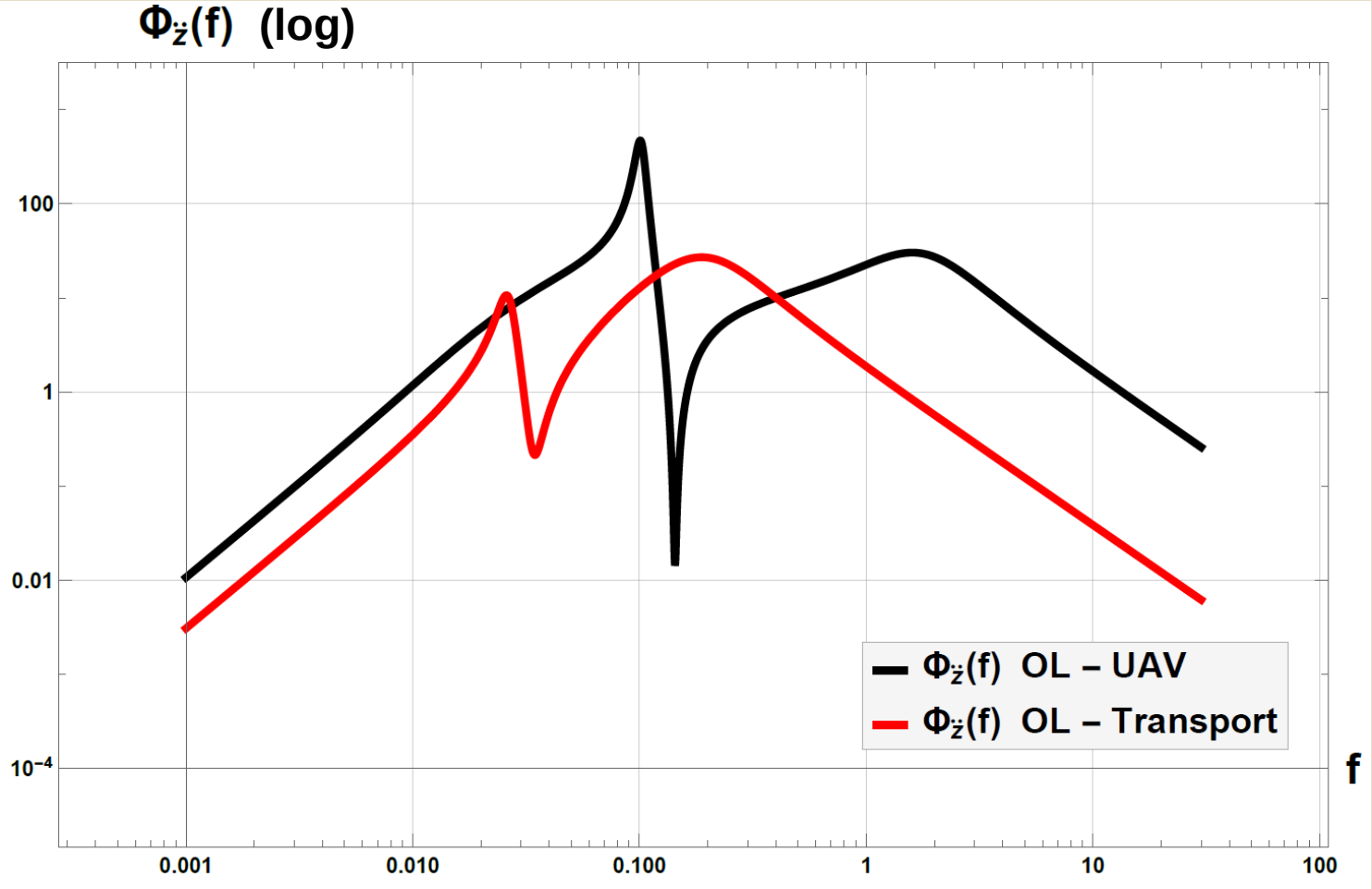
Vertical Acceleration Power Spectrum from w_g input - OL



Product of FRF and von Karman turbulence spectrum

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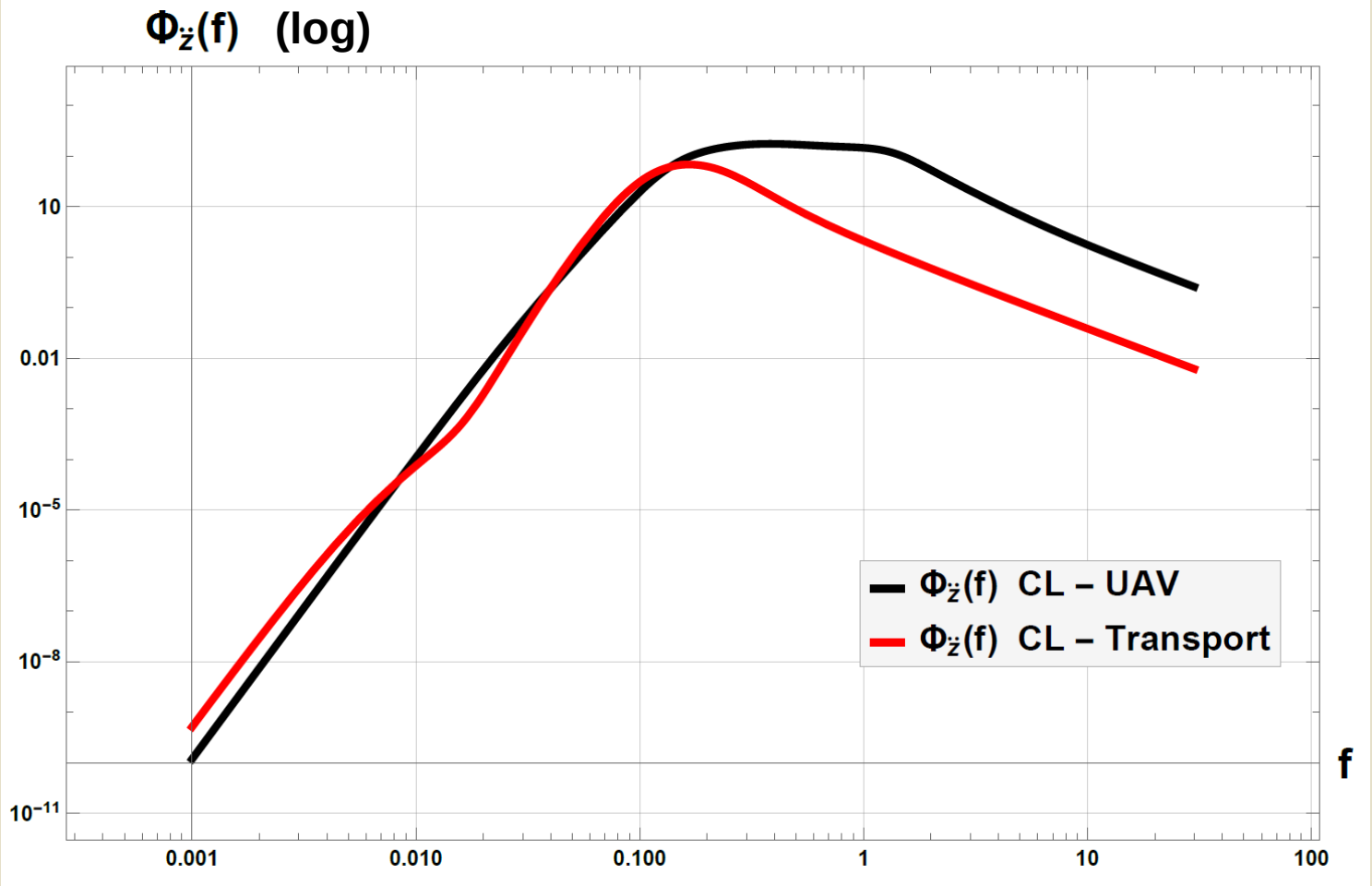
Vertical Acceleration Power Spectrum from w_g input - CL



Phugoid damping makes the response similar at low f

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Summary

- Vertical gusts are dominant in changing lift forces, affecting stability and control.
- Horizontal gust gradients of large enough magnitude can also affect lift, mainly affecting performance.
- Differential vertical gusts can generate rolling and pitching moments, affecting stability and control.
- Side wind gusts can produce rolling and yawing moments, affecting stability and control.
- Autopilots have a strong effect on frequency response – especially at low frequencies.
- Not surprisingly, UAV is much more gust sensitive than larger transport aircraft.

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User/Research Issues

- For manned a/c, vertical acceleration is the key impact metric. What is appropriate for unmanned vehicles?
  - Performance and/or stability & control metrics?
  - Airspeed loss/gain?
  - Vertical accelerations?
  - Attitude or attitude rates?
  - Position or position rates?
  - Kinetic energy rate? $\frac{dT}{dt}$
  - What about rotorcraft? What are the similarities/differences in vehicle motions, response to wind/turbulence, and operational usage?

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