Discussion of Rotorcraft and eVTOL Noise

Presented to:
Georgia Institute of Technology
Aerospace Engineering Department Design II Class

D. Douglas Boyd, Jr., PhD
NASA Langley Research Center
Aeroacoustics Branch
Hampton, Virginia

d.d.boyd@nasa.gov

Goal and Outline

Goal:

- Become acquainted with *some* issues of rotorcraft / eVTOL noise

Outline:

- Importance of Terminology
- Some Working Definitions
- Generic Configuration
- Sources, FWH, F1A, BPM ← Acronyms will be clear later.
- Propagation
- Cautions, Myths, More to Read

Importance of Terminology

Example Conversation

- “I want to design a low noise rotor”
- “Can you be specific about what you mean by low noise?”
- “I want to reduce the loudness by 40%”
- “Something that is less loud is not necessarily less noisy”
- “Ok, I want it to be quieter by 20 dB”
- “What is it that you want to be quieter by 20 dB?”
- “The noise”
- “But 20 dB is just a number with a unit… But itself, this is not a measure/metric of ‘noise’ ”
- “What metric should I use?”
- “That depends on what you are trying to do with your rotor”
- “I want to design a low noise rotor”

This demonstrates the colloquial use of noise along with a vague, ill-defined metric … which is a terminology problem.

It just goes downhill from there...

Aeromechanics Example

"I want to design a high performance vehicle."

What do you mean by high performance?

Do you want:

- More lift?
- Less drag?
- More endurance?
- More range?
- Higher Figure of Merit?
- More payload?
- …

Some of these are conflicting requirements…

For common reference, examine some working definitions regarding noise.

Some Working Definitions

Noise and Sound

Working definition: ***Noise*** is unwanted sound.

- Obviously, these two items must be there:
  - Sound
  - Unwanted

We will start with the easier of the two: Sound

Working definition: ***Sound*** is pressure fluctuations perceived by the ear.

- Now there are two additional phrases we need to examine:
  - perceived by the ear – means it must be heard
  - pressure fluctuations – changes in pressure (e.g.: $\frac{\partial p}{\partial t}$)
    - "Acoustic waves" that travel at U $\pm$ c
    - U = local fluid speed
    - c = $\sqrt{\left(\frac{\partial P}{\partial \rho}\right)}$

Unwanted

We previously defined noise as unwanted sound – we've already examined sound

What is unwanted?

- Vague adjective referring to human likes and dislikes
- Likes and dislikes vary between humans
- Difficult to quantify

This human element associate with noise is part of the realm of psychoacoustics

- Psychoacoustics will not be directly addressed in this presentation

We have a working definition…

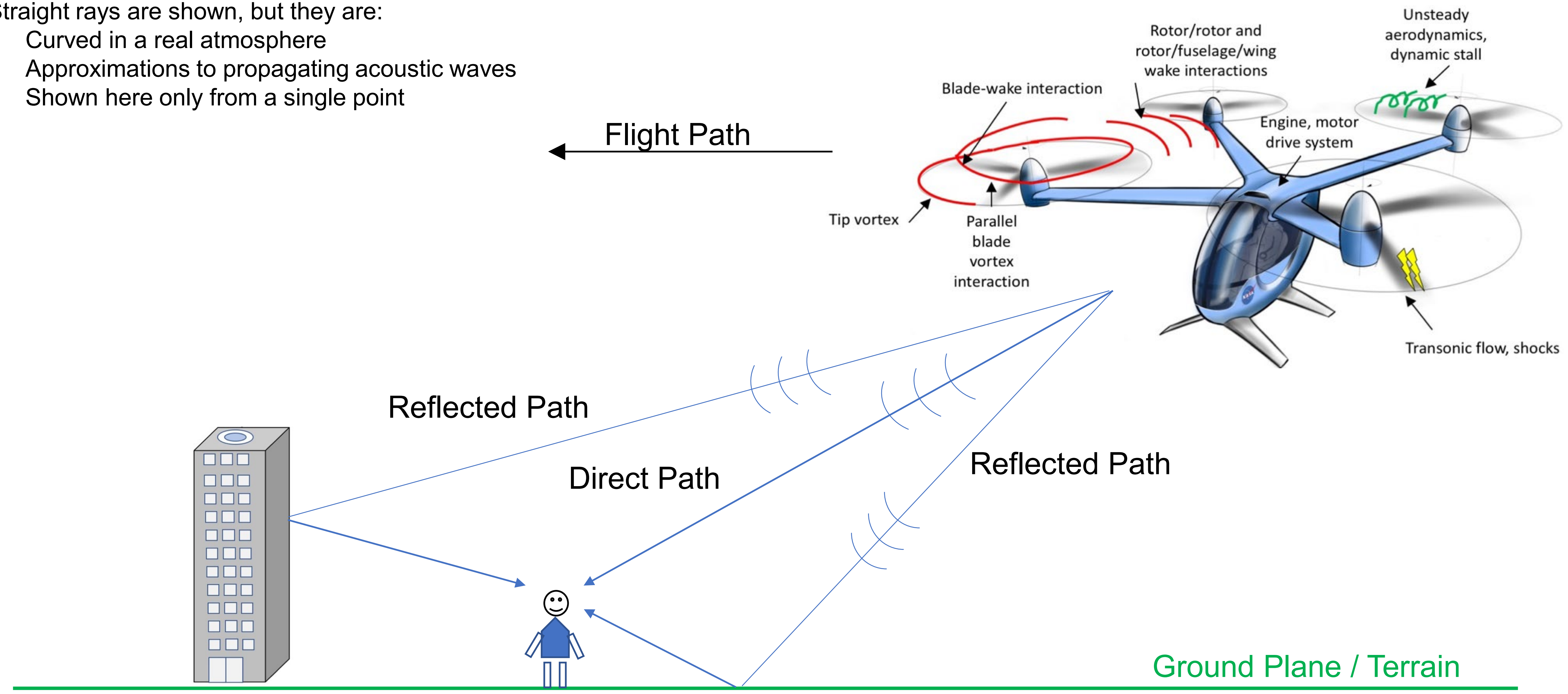
- now we will look at a Generic Configuration

Generic Configuration

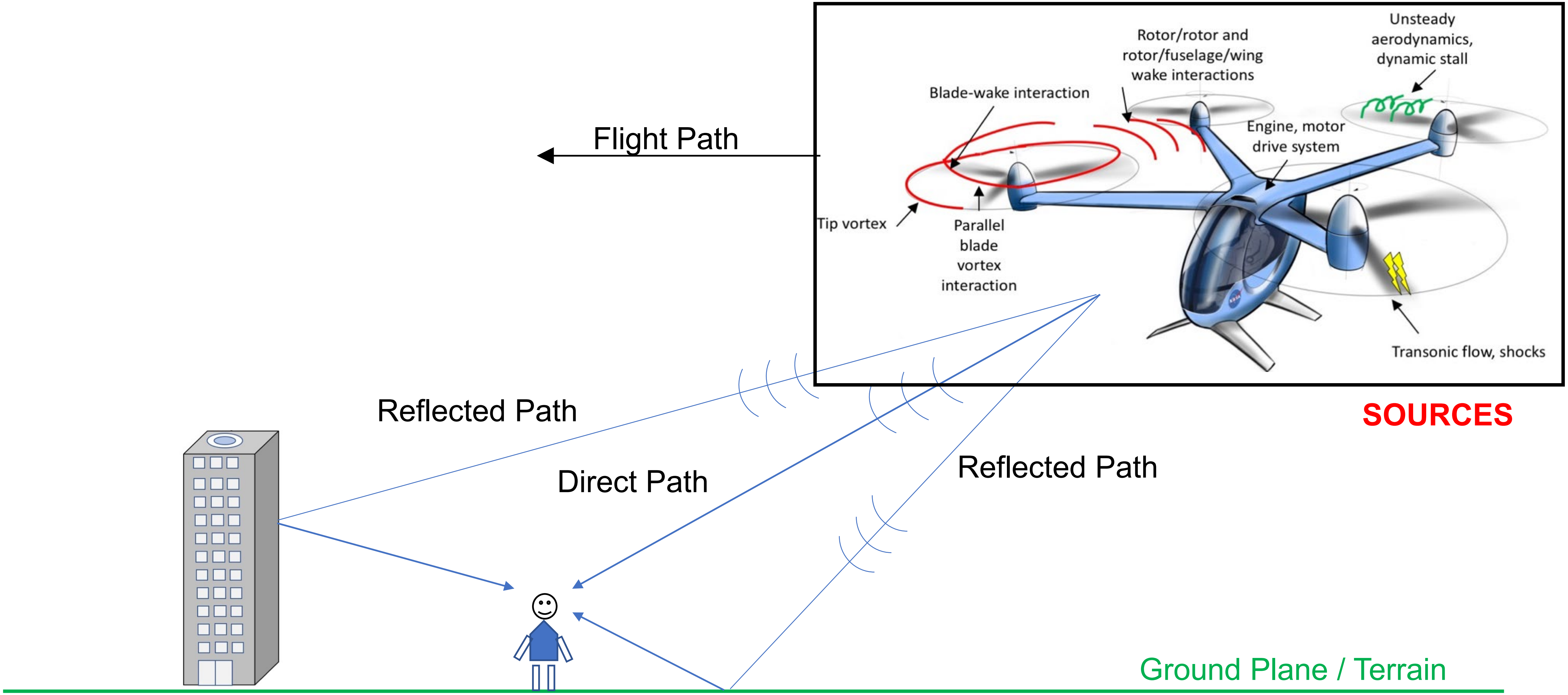
Generic Configuration

Straight rays are shown, but they are:

- Curved in a real atmosphere
- Approximations to propagating acoustic waves
- Shown here only from a single point



Sources

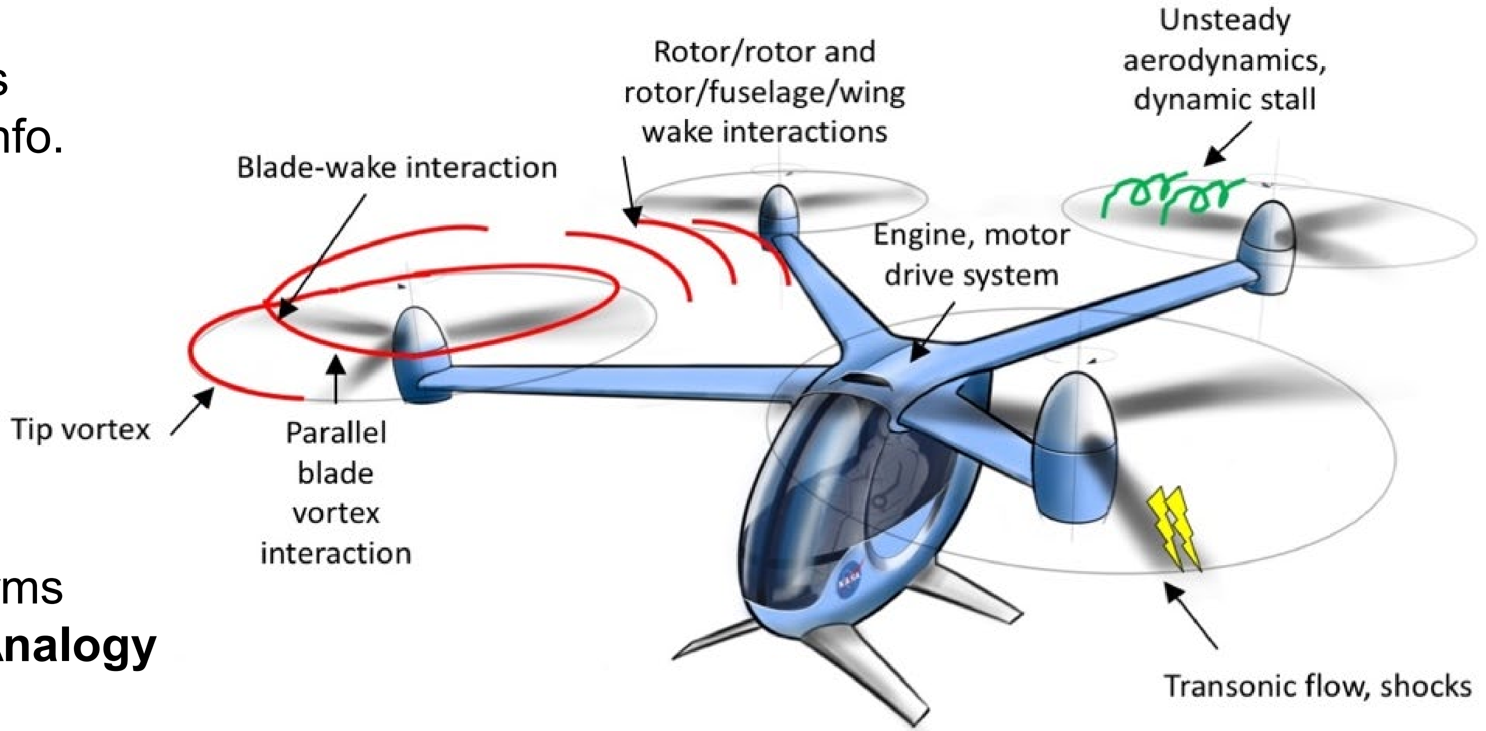

Flight Path
Unsteady aerodynamics, dynamic stall
Rotor/rotor and rotor/fuselage/wing wake interactions
Blade-wake interaction
Engine, motor drive system
Tip vortex
Parallel blade vortex interaction
Transonic flow, shocks
SOURCES
Reflected Path
Direct Path
Reflected Path
Ground Plane / Terrain

Sources, FWH, F1A, BPM

Source

For the moment, let us assume we *magically* have:

- All aerodynamics
- All motion/deformation of all surfaces
  - Including vehicle configuration info.



How do we compute acoustics today?

- Typically: "Acoustic Analogy"

"Acoustic Analogy".. Think:

- Rearrange fluid equations into a:
  - Wave Equation with Source terms
  - Example: **Lighthill Acoustic Analogy**

Best known in rotorcraft applications is solution to:

- **Ffowcs Williams and Hawkings (FWH) Equation**
  - Rearrangement of momentum conservation (Navier-Stokes) along with mass conservation
  - Allows for flow "discontinuities" using Generalized Functions, Generalized Derivatives, etc.

FWH

Mass conservation

$$\frac{\bar{\partial}}{\partial t}(\rho) + \frac{\bar{\partial}}{\partial x_i}(\rho u_i) = [\rho_0 v_n + \rho(u_n - v_n)]\delta(f)$$

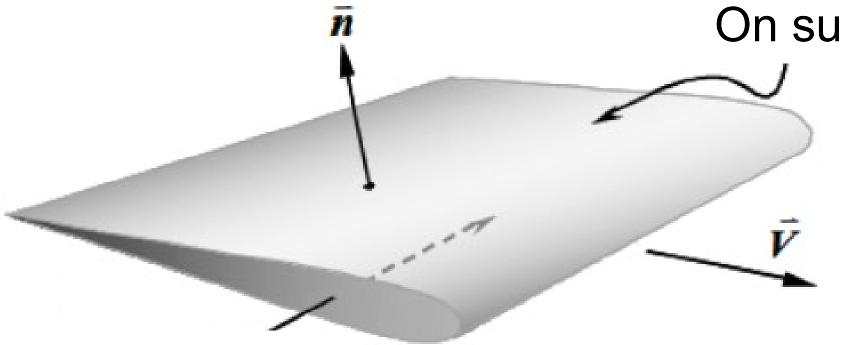
Take: $\frac{\bar{\partial}}{\partial t}$

Momentum conservation

$$\frac{\bar{\partial}}{\partial t}(\rho u_i) + \frac{\bar{\partial}}{\partial x_j}\left(\rho u_i u_j + P_{ij}\right) = \left[\rho_0 u_i(u_n - v_n) + \Delta P_{ij} n_j\right]\delta(f)$$

Take: $\frac{\bar{\partial}}{\partial x_i}$

Outside surface: $f > 0$



On surface: $f = 0$

Inside surface: $f < 0$

$\delta(f) = 1$ for $f = 0$

$\delta(f) = 0$ for $f \neq 0$

FWH

(1) Subtract later from former
(2) Make appropriate substitutions
(3) Put wave operator on the LHS
(4) Leave everything else on the RHS
(5) (For now) Assume surfaces are impermeable to get the common form of **FWH** equation used:

$$\bar{\Box}^2 p'(\boldsymbol{x}, t) = \frac{\bar{\partial}}{\partial t}\left[\rho_0 v_n \delta(f)\right] - \frac{\bar{\partial}}{\partial x_i}\left[l_i \delta(f)\right] + \frac{\bar{\partial}^2}{\partial x_i x_j}\left[T_{ij} H(f)\right]$$

Wave Propagation | **"Thickness" or "Monopole" (Surface Term)** | **"Loading" or "Dipole" (Surface Term)** | **"Quadrupole" (Volume Term)**

$H(f) = 1$ for $f > 0$
$H(f) = 0$ for $f \leq 0$

ρ_0 = Background density
v_n = normal surface velocity
l_i = i-th component of loading (pn_i)

$T_{ij} = \rho u_i u_j - \sigma_{ij} + (p' - c^2\rho')\delta_{ij}$
= Lighthill's stress tensor

NOTE: If you **remove** the first two integrals, you will have the **Lighthill Acoustic Analogy**, which pre-dates **FWH.**

Solution(s) to FWH

Farassat's Formulations (there are many) are probably the best known and most used solutions

- For rotorcraft – by far – the most common solution is Farassat's Formulation 1A (**F1A**)
- (F1A equations are on next slide)

Main assumptions for **F1A**:

- The quadrupole (volume) term is neglected… so, just thickness and loading (surface) terms
- Surfaces are subsonic

Features:

- Integral equation for the acoustic pressure in the time domain
- RHS is only related to the *source* position and time $(\boldsymbol{y}, \tau)$
- LHS is only related to the *observer* position and time $(\boldsymbol{x}, t)$
- $(\boldsymbol{y}, \tau)$ and $(\boldsymbol{x}, t)$ connected through a "retarded time equation" → $\tau = t - \frac{|\boldsymbol{x} - \boldsymbol{y}|}{c}$
- Most common solution method is evaluation with a "source time dominant algorithm"

F1A

Acoustic Pressure Time History … thickness term:

$$4\pi p'_T(\boldsymbol{x},t) = \int_{f=0}\left[\frac{\rho_0\left(\dot{v}_n + v_{\dot{n}}\right)}{r|1 - M_r|^2} + \frac{\rho_0\, v_n\, \dot{M}_r}{r|1 - M_r|^3}\right]_{ret} dS + \int_{f=0}\left[\frac{\rho_0\, v_n c\left(M_r - M^2\right)}{r^2|1 - M_r|^3}\right]_{ret} dS$$

Acoustic Pressure Time History … loading term:

$$4\pi p'_L(\boldsymbol{x},t) = \frac{1}{c}\int_{f=0}\left[\frac{\dot{l}_r}{r|1 - M_r|^2} + \frac{l_r\, \dot{M}_r}{r|1 - M_r|^3}\right]_{ret} dS + \int_{f=0}\left[\frac{l_r - l_M}{r^2|1 - M_r|^2} + \frac{l_r\,(M_r - M^2)}{r^2|1 - M_r|^3}\right]_{ret} dS$$

Far Field Terms **Near Field Terms**

$$p' = p'_T + p'_L$$

F1A intentionally neglects the quadrupole term… all RHS terms are surface terms.

F1A – The Crux of the Problem

We assumed we *magically* had all aerodynamic and surface motion information.

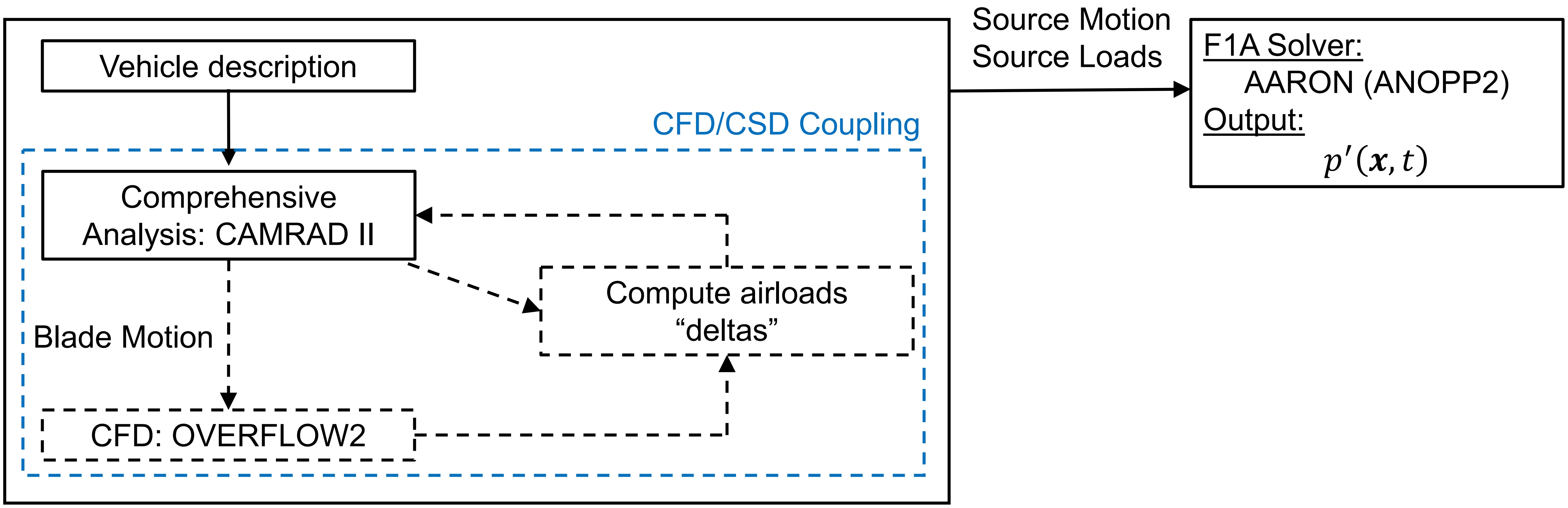
- **Where do we get this information?**
- This has been **a** primary focus since the F1A was developed
- Methods to evaluate F1A integrals have improved since the early 1980s, but the *source* problem remains

How do you get these quantities for a rotorcraft (VTOL, eVTOL, etc.)?

Usually, "Rotorcraft Comprehensive Analysis"

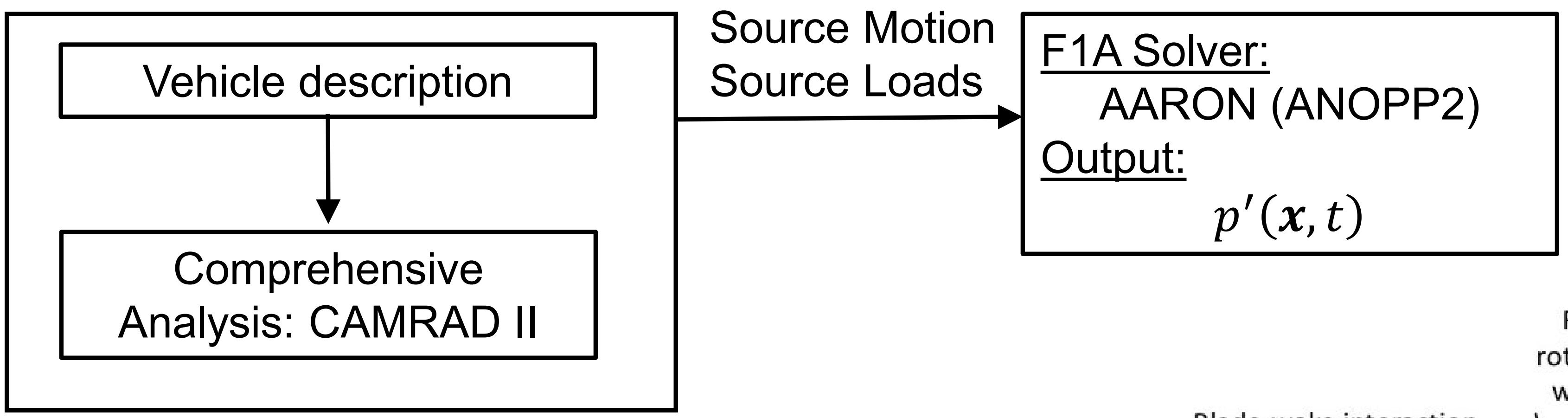
- Determines vehicle state at a flight condition – orientation, trim, motion, forces, etc.
- Provides lifting line motion and forces on the lifting line ("blades") for **F1A Compact Formulation**
- Alternately, can:
  - Couple with CFD (CFD/CSD) … full surface geometry / pressures for **F1A Formulation**
    - CSD refers the Rotorcraft Comprehensive Analysis (motion, trim, etc.)
    - CFD essentially "replaces" the lifting line aerodynamic model

Outline of a Deterministic(*) Acoustic Prediction with Sample Code Names



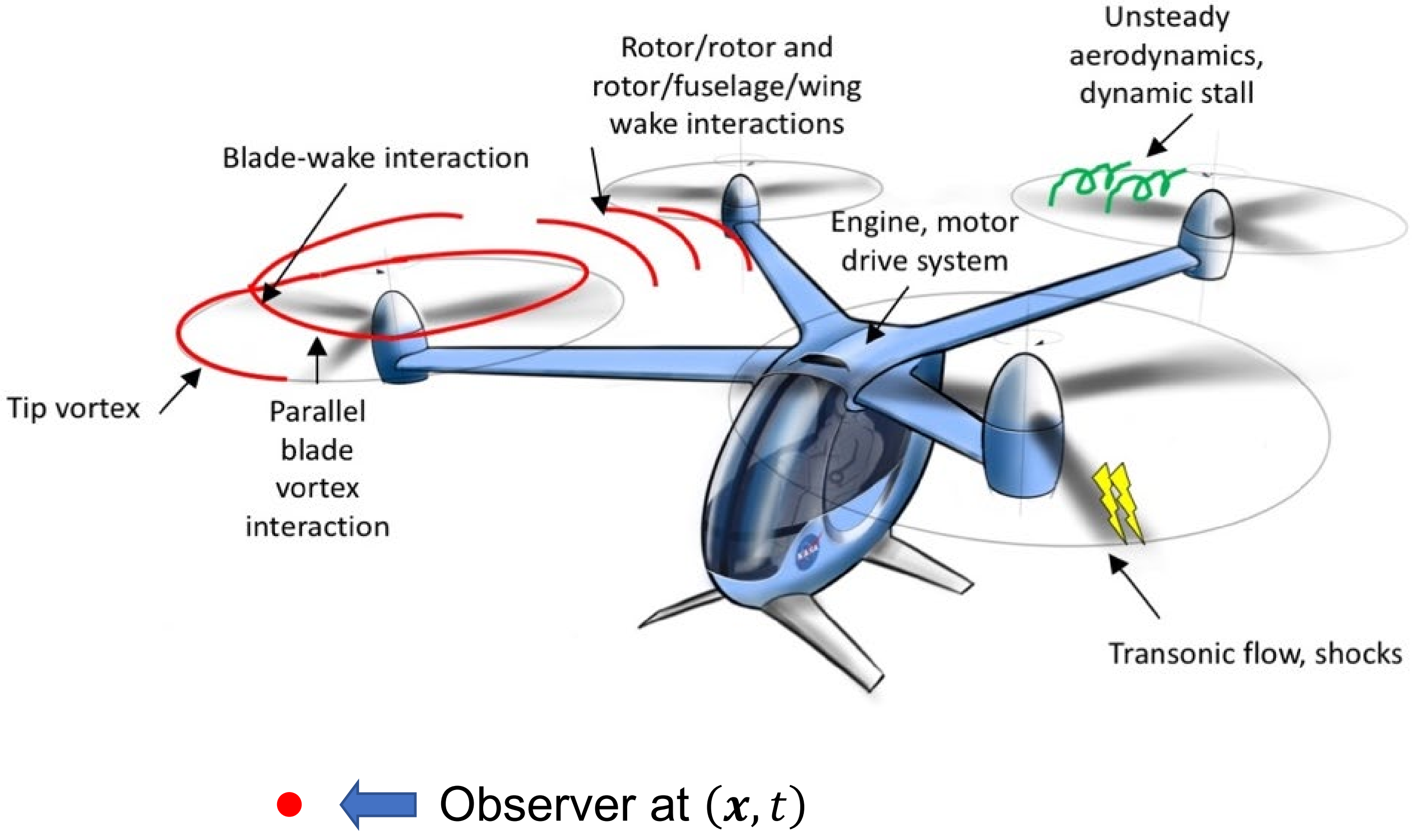
(*) Deterministic in this context means periodic or aperiodic, but not random (“broadband”)

For Simplicity, Drop CFD/CSD Coupling

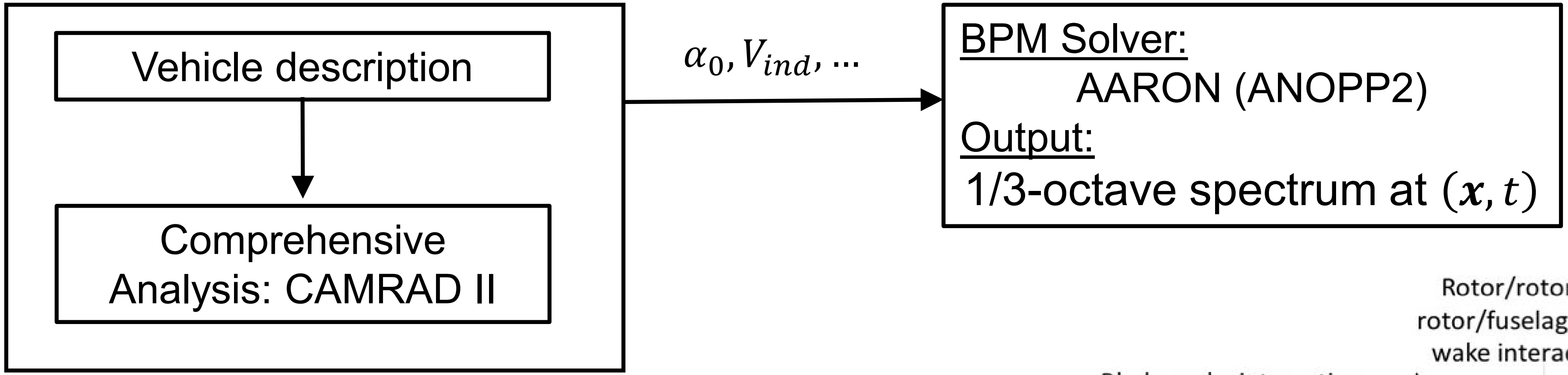


<u>What can we include:</u>

- Constant loads moving rel. observer
- Unsteady loading:
  - Blade-Vortex Interaction (BVI)
  - Rotor-rotor aero interaction
  - Rotor-rotor wake interaction
  - etc.



What About Non-Deterministic Sources?

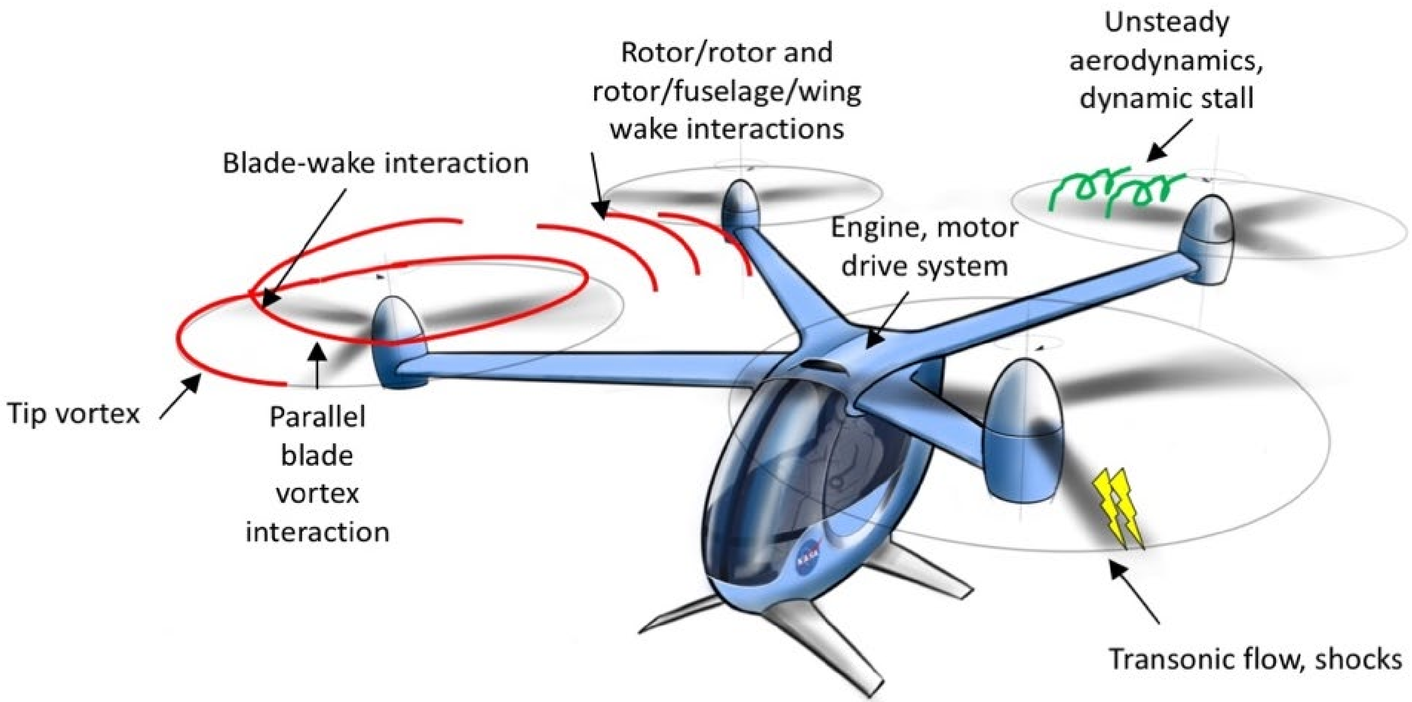


<u>Brooks-Pope-Marcolini (BPM):</u>

- Semi-empirical model for trailing edge effects
- Few other models available currently

<u>Prospects – LBM … some potential for:</u>

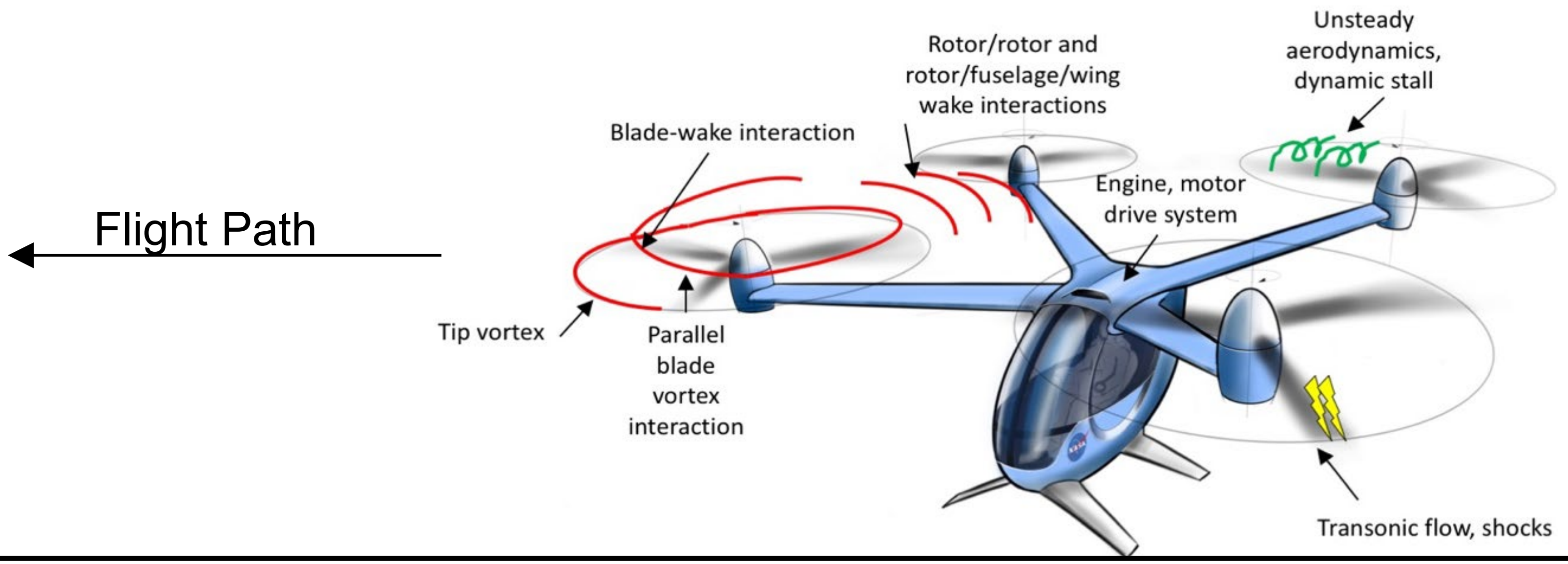
- Trailing edge effects
- Blade-Wake Interaction (BWI)
- “Entire” problem



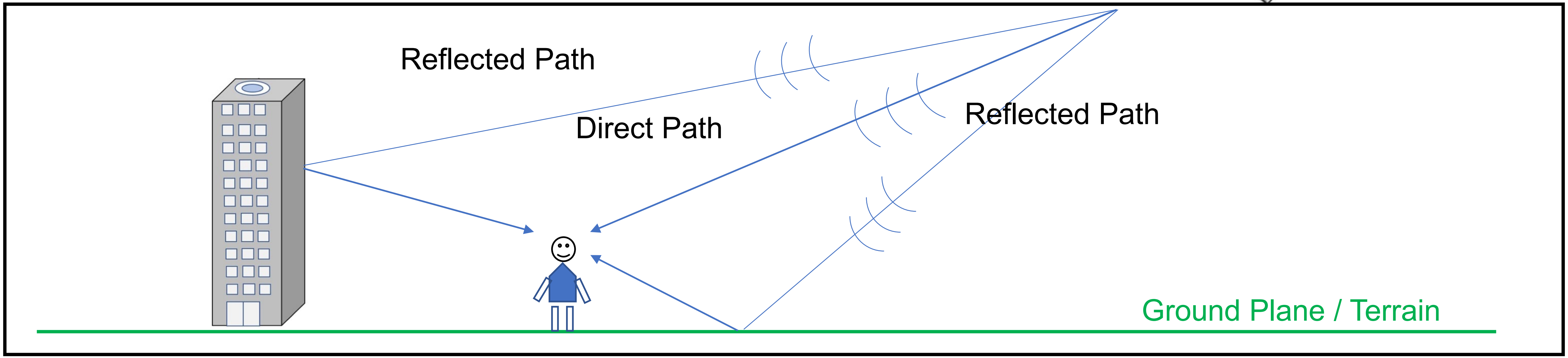
Observer at $(\boldsymbol{x}, t)$

Propagation

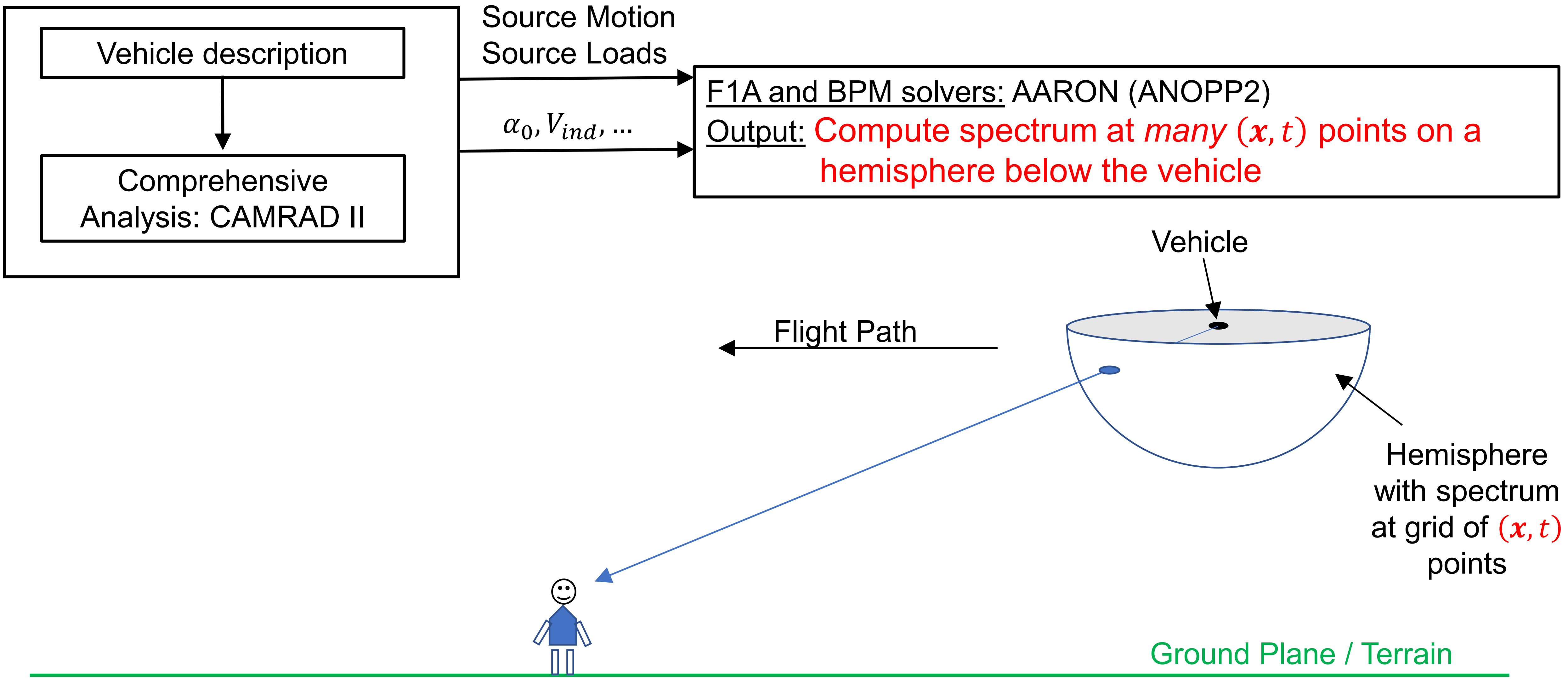
Propagation



PROPAGATION



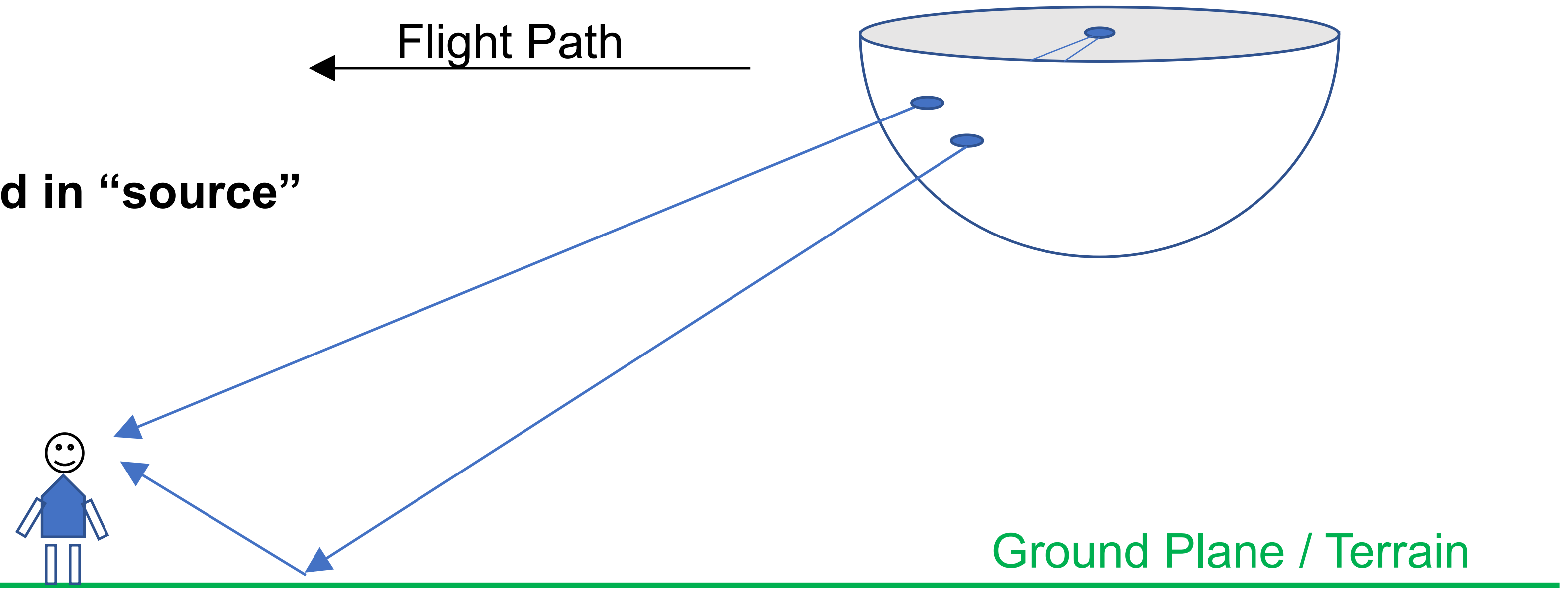
What About Propagation?



What About Propagation?

Includes effects:
- Straight (or possibly curved) rays from center to observer
- Doppler shift
- Atmospheric attenuation
- Spherical spreading
- Ground impedance
- Time delays for different path lengths
- etc.

For your design effort:
- **You are probably more interested in “source”**



Cautions, Myths, More to Read…

Caution: Permeable Surface

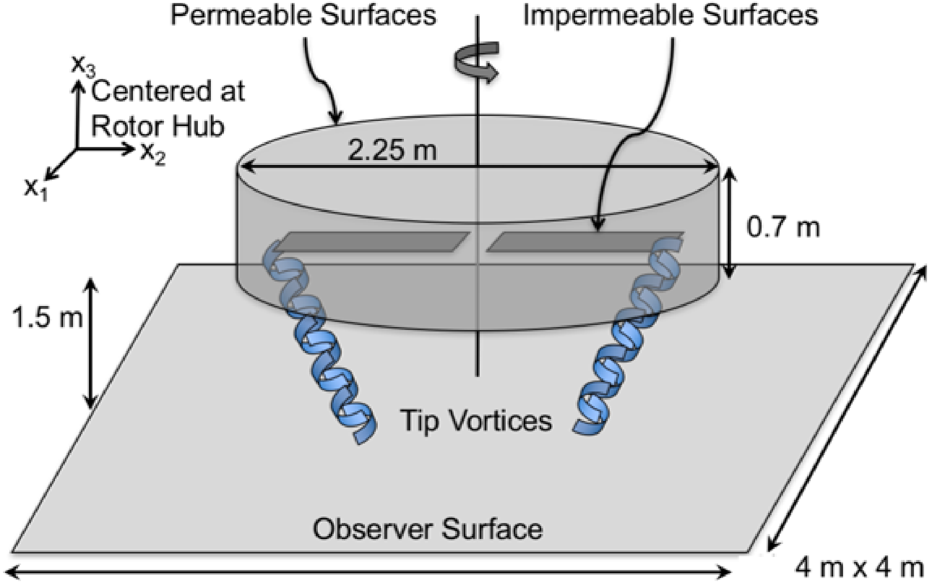
We have discussed mainly **impermeable ("solid") surfaces**… these can come from CFD, for example.

There is a **permeable** version of FWH and F1A (in fact, original FWH was with permeable surfaces)

- This is an *off-body* surface in the flowfield and needs: $\rho', (\rho u_i)', p'$
- Assumes: "All quadrupole sources are inside the permeable surface"

For rotorcraft, this is rarely the case…

- For example, wakes traverse the permeable surface…
- This leads directly to what Farassat called:
  - The "Spurious Signals" problem…
  - Only accounting for PART of the quadrupole term



Lopes, L.V., Boyd, Jr., D.D., Nark, D.M., Wiedemann, K.E.: "Identification of Spurious Signals from Permeable Ffowcs Williams and Hawkings Surfaces", 73rd AHS Annual Forum, Fort Worth, TX, May 9-11, 2017.

Caution: Kirchhoff Surface Method

An easy method to implement with CFD is the Kirchhoff method.

This, too, is a **permeable**, off-body surface in the flowfield and needs: $p, \frac{\partial p}{\partial t}, \nabla p$

- Assumes: Surface is in the region of linear acoustics

- However, it has been shown conclusively that:
  - **The solution depends on placement of the surface**… This is not good.
  - Kirchhoff Surface Method (for rotorcraft) has largely been abandoned because of this.

Brentner, K.S.: "Modeling Aerodynamically Generated Sound: Recent Advances in Rotor Noise Prediction", AIAA Paper 2000-0345, 38th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10-13, 2000.

- Permeable FWH does not have this dependence… but, still has the spurious signals problem.

Myth: Reducing the Tip Speed Will Reduce Noise

This was often stated because it was thought:

- “With electric motors, we can reduce the tip speed”
- While that may be true, remember that *everything* in a rotorcraft (or eVTOL) is connected
  - Tip Speed for a design cannot be reduced independent of the design
  - Lower tip speed means you need more solidity (blade surface area) to generate required thrust
    - … which means more blade weight
    - … which means you need more structure to hold that weight
    - … which increases your vehicle gross weight
    - … which means you need to generate more thrust
    - etc.

This effect has been shown using NASA Reference vehicles and the EPNL metric:

Silva, C., Johnson, W., "Practical Conceptual Design of Quieter Urban VTOL Aircraft," Presented at the Vertical Flight Society’s 77th Annual Forum & Technology Display, Virtual, May 10–14, 2021.

Myth: Variable RPM Will Fix Everything

With electric motors,

- There is no interconnect shaft between rotors
- Often one motor per rotor, so, RPM can be set by each motor independently

This leads to the notion of RPM control as the primary control method

- Non-unique, redundant controls (so, a controls issue)
- Works well for very small rotors – like the DJI Phantom
- For “large” rotors, inertia is expected to:
  - Reduce the response time of RPM changes
  - Require large torque changes, which means larger motors, more weight, etc.
- Might be impractical for “large” rotors

Variable RPM also means that all rotors are asynchronous:

- Aperiodic noise
  - F1A can do this… but you need a long enough source record
- “Swarm of bees”

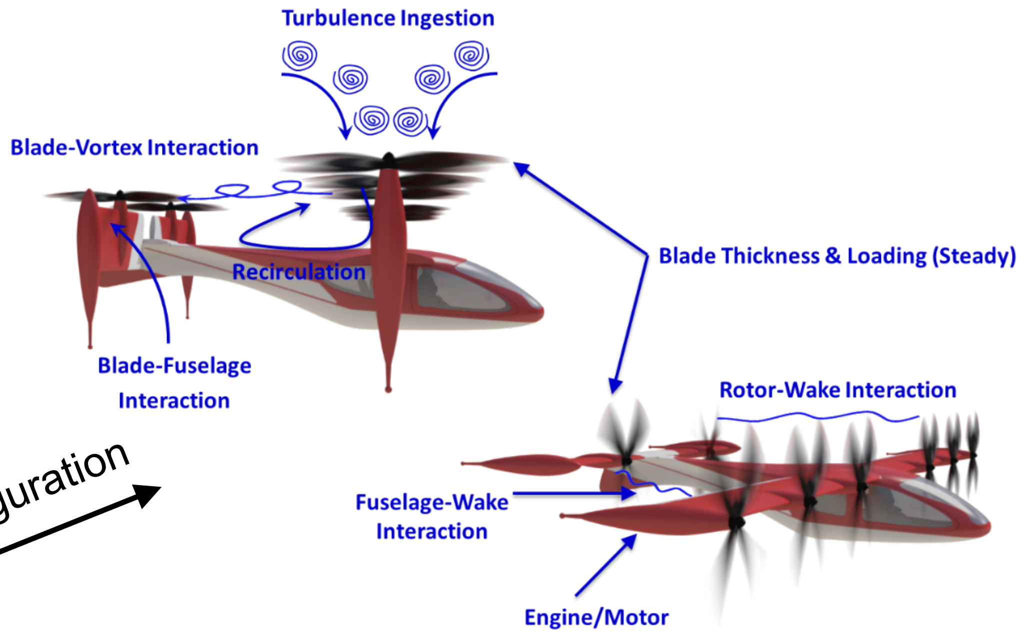
More to Read: Urban Air Mobility (UAM) Noise Working Group

NASA hosts an Urban Air Mobility (**U**AM) **N**oise **W**orking **G**roup (**UNWG**)

- Each April (NASA LaRC) and each October (NASA GRC)
- In conjunction with the **A**coustics **T**echnical **W**orking **G**roup (**TWG**)

NASA UNWG Organization

- Executive Committee
- Subgroup 1: Tools and Technologies
- Subgroup 2: Ground and Flight Testing
- Subgroup 3: Human Response and Metrics
- Subgroup 4: Regulation and Policy
- To participate in Subgroups … just ask.



Another Generic Configuration

"White Paper": Rizzi, S.A., Huff, D.L., Boyd, Jr., D.D., Bent, P., Henderson, B.S., Pascioni, K.A., Sargent, D.C., Josephson, D.L., Marsan, M., He., H., Snider, R.: "Urban Air Mobility Noise: Current Practice, Gaps, and Recommendations", NASA TP-2020-5007433, October 2020.

Some References to Get You Started

- Lighthill, M.J.: “On Sound Generated Aerodynamically. I. General Theory”, *Proceedings of the Royal Society A*, 1952, vol 211, pp 564-587

- Ffowcs Williams, J.E., Hawkings, D.L.: “Sound Generated by Turbulence and Surfaces in Arbitrary Motion”, *Philosophical Transactions of the Royal Society A*, 1969, vol 264**,** pp 321-342

- Brentner, K.S.: “Modeling Aerodynamically Generated Sound: Recent Advances in Rotor Noise Prediction”, AIAA Paper 2000-0345, 38th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10-13, 2000.

- Lopes, L.V., Boyd, Jr., D.D., Nark, D.M., Wiedemann, K.E.: “Identification of Spurious Signals from Permeable Ffowcs Williams and Hawkings Surfaces”, 73rd AHS Annual Forum, Fort Worth, TX, May 9-11, 2017.

- Lopes, L.V.: “Compact Assumption Applied to the Monopole Term of Farassat’s Formulations”, *Journal of Aircraft,* vol 54 no 5, pp 1649-1663, September 2017.

- Lopes, L.V.: “ANOPP2’s Farassat Formulations Internal Functional Modules (AFFIFMs) Reference Manual, NASA TM-20210021111, December 2021.

Questions / Discussions?

Backup material

Some other topics

A few other *example* topics/cautions/myths:

- Airframe/support can be as important (acoustically) as the rotor:
  - Engine rotor/stator problem
  - DJI test in SALT: isolated rotor vs. rotor + rod/cone experiment
  - Electric motors make noise, too.
  - Lowering the RPM can bring out broadband noise
  - …

- Other sources:
  - Engine rotor/stator problem
  - Electric motors make noise, too
  - Lowering the RPM can bring out broadband noise
  - Turbulence ingestion noise (TIN)
  - …

Loudness, Noisiness, EPNL

Equal Loudness

- 1933: Fletcher & Munson – comparison between two pure tones
  - Played a reference tone at 1 kHz at 40 dB
  - Then another tone at a different frequency
  - Asked people to adjust the *loudness* of the 2nd tone to match the *loudness* of the reference
  - Performed same task for a wide range of frequencies

This produced a curve - as a function of frequency - called the *40-phon equal loudness curve*

Repeat process for different reference dB levels at 1 kHz … 60 dB, 80 dB, 100 dB

Each reference level produces a *different* curve.

A curve fit to the *40-phon equal loudness curve* is called ***A-weighting***

- There are other "weightings" (B, C, D, Z…), usually tied to different phon levels
- However, A-weighting is nearly universal – regardless of the actual level.

Levels that use this weighting scaled are labeled "dBA" or "dB(A)"

Equal Noisiness

- 1959: Kryter – comparison between random signals (geared toward jet noise)
  - Played a reference signal at 1 kHz center frequency at 40 dB
  - Then another at a different center frequency
  - Asked people to adjust the *noisiness* of the second signal to match the *noisiness* of the reference
  - Performed same task for a wide range of center frequencies

This produced a curve an *equal noisiness curve* that was assigned a “noy” value = 1

Repeat process for different reference dB levels at 1 kHz

Each reference level produces a *different* curve.

A metric “Perceived Noise Level (PNdB)” was devised as this:

$$PNdB = 40 + \log_2(noy)$$

Fortuitously, for many problems of interest (*very* roughly speaking):

$$PNdB \approx dBA + 12$$

Effective Perceived Noise Level (EPNdB)

Another metric was also created: "Effective Perceived Noise Level (EPNdB)":

$$EPNL = PNL_{max} + 10\log\left(\frac{t_{10}}{20}\right) + F(dB)$$

≈ 3 dB

Max $PNdB$ for a flyover

t_{10} = time range that PNdB is 10 below PNL_{max}

EPNL is used for FAA Noise Certification for "Appendix J Helicopters" and "Appendix K TiltRotors"

Questions / Discussions?