Towards Efficient Aero-Structural-Acoustic Optimization for Urban Air Mobility Vehicle Design

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What is UAM?

- Urban Air Mobility (UAM) is a field that aims to improve movement of people and goods within cities by relieving congestion within transportation networks.

- Facilitated by:
  1. Distributed electric propulsion
  2. Autonomous Technologies

www.nasa.gov
What does a UAM vehicle look like?

Joby

Archer

Hyundai

Beta
https://evtol.news/beta-technologies-alia/

Wisk
https://evtol.news/volocopter-volocity/

Volocopter
https://evtol.news/volocopter-volocity/
Ten Areas of Technological Development

- Ease of Certification
- Affordability
- Safety
- Ease of Use
- Door to Door Speed
- Average Trip Speed
- Community Noise
- Efficiency
- Ride Quality
- Lifecycle Emissions

Significant Technological Barriers to Development

How can OpenMDAO help solve the noise problem?
UAM Vehicle Design Process

**Preliminary Design**
- Weight and Loading Estimation
- Low-Fidelity Simulation and Analysis
- Vehicle Geometric Sizing
- Cabin Design
- Powerplant Development
- Mission Analysis
- Structural Analysis
- Aerodynamic Analysis

**Refined Design**

**Vehicle Analysis**
- Flight Testing
- Performance Analysis
- Aeroacoustic Analysis
- Regulatory Approval
What type of work does the MDO Lab do?

In the MDO Lab:

- **Electro-propulsive design optimization**
- **Aerodynamic optimization with packaging**
- **Aero-propulsive design optimization**
- **Trajectory optimization**
- **Aero-thermal shape optimization**

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**Design changes**

\[ \text{minimize} \quad f(x) \quad \text{objective} \]
\[ \text{with respect to} \quad x \quad \text{design variables} \]
\[ \text{subject to} \quad c(x) \leq 0 \quad \text{constraints} \]

Slide adapted from: *Martins et al, Exploiting Aircraft Electrification via Multidisciplinary Design Optimization*
Why do I care about MDO?

- Electric vehicles are highly-coupled systems that must be designed and optimized considering all aspects of the vehicle and configuration.
**Why do we need gradients specifically?**

Gradient Free Methods

Gradient Based Methods

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Coupled Aerodynamic and Aeroacoustic Optimization

eXtended Design Structure Matrix:
How can we predict UAM vehicle noise?
How can we characterize rotor noise?

Rotating Blade Noise

- **Tonal Noise**
  - Loading
  - Thickness
  - Interaction

- **Broadband Noise**
  - Inflow Turbulence Noise
  - Vortex Noise
  - Boundary Layer Noise

Tonal Noise Sources

Thickness and High-Speed Impulsive Noise  
Blade-Vortex-Interaction Noise  
Loading and Broadband Noise
Broadband Noise Sources

**Pegg Model**


**Brooks Model**


We are in the process of implementing a broadband noise model into our toolkit.
Computational Aeroacoustics

- Techniques for aeroacoustic analysis:

  1. Direct Numerical Simulation from Navier-Stokes Equation

  2. Integral-Based Formulations
     i. Lighthill’s Analogy
        • Exact rearrangement of the Navier-Stokes equation
     ii. Kirchhoff Method
        • Simplified acoustic source enclosed by a source-surface
     iii. Ffowcs Williams and Hawkings Model (FWH)
        • Based on Navier-Stokes equation with Lighthill’s analogy with surface integrals over monopole, dipole, and quadrupole noise sources

Inaccurate for rotorcraft applications
Used (and validated) extensively for rotorcraft applications
Computationally Prohibitive for Multidisciplinary Design Optimization

To n a l Noise Modeling

Ffowcs Williams and Hawking:

\[
4\pi a_0^2 \rho' = \frac{\partial}{\partial x_i} \int_J \frac{r_j}{r(1-M_r)^2} d^3 \eta
\]

Quadrupole

\[
\frac{\partial}{\partial x_i} \int_J \frac{P_{ij} + \rho v_i (v_j - u_j)}{r(1-M_r)^2} n_j dS(\eta)
\]

Dipole

\[
\frac{\partial}{\partial t} \int_J \frac{\rho_0 u_i + \rho (v_i - u_i)}{r(1-M_r)^2} n_i dS(\eta)
\]

Monopole

Noise due to density fluctuations
Noise due to loading
Noise due to thickness

Farassat Formulation 1A:

\[
p'_L(\tilde{x}, t) = \left. \frac{1}{4\pi a_0} \int_S \left[ \frac{\hat{L}_i \hat{r}_i}{r(1-M_r)^2} \right] dS \right|_{t^*}
\]

\[
p'_R(\tilde{x}, t) = \left. \frac{1}{4\pi} \int_S \left[ \frac{\rho_0 \hat{u}_n}{r(1-M_r)^2} \right] dS \right|_{t^*} + \left. \frac{1}{4\pi a_0} \int_S \left[ \frac{\rho u_n r\hat{M}_i \hat{r}_i + a_0 (M_i \hat{r}_i - M_i M_i)}{r^2 (1-M_r)^3} \right] dS \right|_{t^*}
\]

* This work uses a compact model for monopole noise, as opposed to the monopole component of Farassat Formulation 1A

Noise Metric: Sound Pressure Level [dB]:

\[
SPL = 10 \cdot \log_{10} \left( \frac{p_{rms}}{p_{ref}} \right)^2
\]

Noise Modeling is a Time-Accurate Problem

- Evaluate the pressure perturbation due to the rotor at each observer point of interest

- Compute the total sound pressure level based on the time-history of the pressure perturbation at each observer point
Aerodynamic Modeling

Hybrid Blade Element Momentum Theory (HBEM)

Momentum Theory

- Models a rotor as a disk, operating within a stream tube

Blade Element Theory

- Considers blade section data to compute aerodynamic loads along rotor blade span

Coefficient of Thrust:

- Model a rotor as a disk, operating within a stream tube
- Considers blade section data to compute aerodynamic loads along rotor blade span

\[
T = \frac{T_{des}}{\pi \rho V_t^2 R^2}
\]

\[
C_{T,BET} = \frac{N_b}{4 R^2 \pi^2} \int_0^R \int_0^{2\pi} C_l u^2 c(r) \cos(\phi) d\phi dr
\]

\[
R(T_{mag}) = C_{T,BET}(T_{mag}) - C_{T,MT}(T_{mag}) \Rightarrow 0
\]

\[\Rightarrow \text{This analysis is quasi-steady, making it more efficient and easier to manage than fully unsteady methods}\]
Computing Derivatives

Implicit Derivatives:
\( x : \text{Design Variables} \)
\( u : \text{State Variables} \)

\[
f = f(x, u(x)) : \text{Function of Interest}
\]
\[
\mathcal{R}(x, u(x)) = 0 : \text{Solution Residual}
\]

Dimensions:
- Design Variables: \( n_x = O(10) \)
- State Variables: \( n_u = O(100) \)
- Functions of Interest: \( n_f = O(1) \)
- Residual Values: \( n_R = O(100) \)

\[
\frac{df}{dx} = \frac{\partial f}{\partial x} + \frac{\partial f}{\partial u} \frac{du}{dx}
\]
\[
\frac{d\mathcal{R}}{dx} = \frac{\partial \mathcal{R}}{\partial x} + \frac{\partial \mathcal{R}}{\partial u} \frac{du}{dx} = 0
\]

\[
\Rightarrow \frac{du}{dx} = - \left[ \frac{\partial \mathcal{R}}{\partial u} \right]^{-1} \frac{\partial \mathcal{R}}{\partial x}
\]

\[
\frac{df}{dx} = \frac{\partial f}{\partial x} - \frac{\partial f}{\partial u} \frac{\partial [\mathcal{R}]^{-1} \partial \mathcal{R}}{\partial u} \frac{\partial \mathcal{R}}{\partial x}
\]

\[
\frac{\partial \mathcal{R}}{\partial u} \phi = \frac{\partial \mathcal{R}}{\partial x} : \text{Direct Method}
\]
\[
\left[ \frac{\partial \mathcal{R}}{\partial u} \right]^T \psi = \left[ \frac{\partial f}{\partial u} \right]^T : \text{Adjoint Method}
\]

\( \rightarrow \text{Derivatives computed using algorithmic differentiation, leveraging graph coloring} \)
Coupled Aerodynamic and Aeroacoustic Optimization

- Aerodynamic and aeroacoustic analysis tools wrapped with OpenMDAO for model coupling

- Derivatives computed and passed between models internally within OpenMDAO
How does this workflow perform?
Example Optimization Problem: NASA N+1 UAM Quadrotor Concept Vehicle

- Single-pasenger
- Fully electric
- RPM control
Quadrotor Optimization: Baseline Analysis

- Performed simulations and optimizations at three spanwise design variable resolutions: 5, 10, 15 variables.
- Blade loads and SPL for 15 spanwise variable analyses:

<table>
<thead>
<tr>
<th>Maximum SPL [dB]</th>
<th>Thrust [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>80.464555</td>
<td>1438.324294</td>
</tr>
</tbody>
</table>

Blade Loads

Sound Pressure Level
**Optimization Problem Statement:**

<table>
<thead>
<tr>
<th>Function or Variable</th>
<th>Units</th>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize KS(SPL) dB</td>
<td>dB</td>
<td>KS aggregated sound pressure level</td>
<td>1</td>
</tr>
<tr>
<td>With respect to Twist</td>
<td>°</td>
<td>Blade twist distribution</td>
<td>5/10/15</td>
</tr>
<tr>
<td>Chord m</td>
<td>m</td>
<td>Blade chord distribution</td>
<td>5/10/15</td>
</tr>
<tr>
<td>ω rad/s</td>
<td>rad/s</td>
<td>Rotor rotation rate</td>
<td>1</td>
</tr>
</tbody>
</table>

Total design variables: 11/21/31

Subject to Thrust z = 1429.175345 N

Single rotor thrust required for ¼ vehicle weight

Total constraints: 1

**Optimization Results:**

<table>
<thead>
<tr>
<th>SPL [dB]</th>
<th>73.856633</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust z [N]</td>
<td>1429.174531</td>
</tr>
<tr>
<td>ω [rad/s]</td>
<td>61.128316</td>
</tr>
</tbody>
</table>

**Spanwise Distribution:**

- **7dB reduction in noise**

**Blade Loading**

**Sound Pressure Level**
How can we implement this for aero-structural-acoustic optimization?
Aero-structural-acoustic Optimization

- Mixed-fidelity analysis to combine time-accurate and steady-state analyses within a single optimization

→ Built into the MPphys framework
Aerodynamic Analysis

- Analyzing the NASA Tiltwing Concept vehicle performance using DAFOam and actuator disk theory
DAFoam + TACS: Aerostructural Optimization

- Adapted MPhys, DAFoam, and aerostructural coupling with FUNtoFEM and TACS to allow for propeller deflection under wing deformation
Conclusions and Next Steps

• Implemented a set of gradient-based optimization tools within OpenMDAO to work towards enabling aero-structural-acoustic optimization

• Working to implement our adjoint-based HBEM solver and aeroacoustic analysis tool into MPHYS

• Actively working towards aero-structural-acoustic optimization of a UAM tiltwing vehicle
  • We’ll have more to say about this tomorrow during the MPhys workshop

• Broader methods development needed to move to higher fidelity aerodynamic analysis
  • How do we implement a coupled unsteady adjoint?
Thank you! Questions?
BACKUP
Aerodynamic Analysis Tool

**DUST** Mid-Fidelity Aerodynamic Analysis Tool

- Relies on Helmholtz decomposition of velocity field

- Mixed boundary elements – vortex particle method and based on free vorticity evolution

- Allows for range of different fidelity aerodynamic models
Single Fan Aerodynamic Analysis

Particle evolution in hover flight condition

Cut plane of averaged velocity contours in hover flight
Single Fan Aeroacoustic Analysis

- Contour plots of Sound Pressure Level on planes below and in front of fan
  - Observer plane in front of fan:
    - \([X,Y,Z] = [-250, 100, -250] - [250, 100, 250][m]\)
    - Grid of [50 x 50] observer probes
  - Observer plane below fan:
    - \([X,Y,Z] = [-250, -250, -50] - [250, 250, -50][m]\)
    - Grid of [50 x 50] observer probes

*Sound Pressure Level normalized to scale 0 – 1 between minimum and maximum recorded values*
Two Fan Aerodynamic Analysis

Particle evolution and wake interaction in hover flight condition

Cut plane of averaged velocity contours showing wake interaction in hover flight
Two Fan Aeroacoustic Analysis

- Contour plot of Sound Pressure Level on plane below fans
- \([X,Y,Z] = [-300, -300, -100] - [300, 300, -100][m]\)
- Grid of \([20 \times 20]\) observer probes

*Sound Pressure Level normalized to scale 0 – 1 between minimum and maximum recorded values*
Parametric Study

- Study of the change in noise footprint with respect to horizontal, vertical, and phase offset between fans

<table>
<thead>
<tr>
<th>Case</th>
<th>Param.</th>
<th>Sampled Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>$\Delta Y$</td>
<td>$2.00, 2.50, 3.00, 3.50, 4.00$</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>$\Delta Z$</td>
<td>$0.00, 0.25, 0.50, 0.75, 1.00$</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>$\phi$</td>
<td>$0.00$</td>
<td>[°]</td>
</tr>
<tr>
<td>Case 2</td>
<td>$\Delta Y$</td>
<td>$2.00, 2.50, 3.00, 3.50, 4.00$</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>$\Delta Z$</td>
<td>$0.00$</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>$\phi$</td>
<td>$0, 24, 48, 72, 96$</td>
<td>[°]</td>
</tr>
<tr>
<td>Case 3</td>
<td>$\Delta Y$</td>
<td>$3.00$</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>$\Delta Z$</td>
<td>$0.00, 0.25, 0.50, 0.75, 1.00$</td>
<td>[m]</td>
</tr>
<tr>
<td></td>
<td>$\phi$</td>
<td>$0, 24, 48, 72, 96$</td>
<td>[°]</td>
</tr>
</tbody>
</table>
Parametric Study: Results

- Clear contours that show noise increases with increasing Y-offset
- Slight Z-offset dependence especially at low values of Y-offset
- Clear dependence on phase offset at large values of Y-offset
  - In phase: increased noise
  - Out of phase: decreased noise
- Phase offset has distinct effect
  - In phase: increased noise
  - Out of phase: decreased noise
- Z-offset has only minimal effect

→ Without even changing the rotor design or operating conditions, we can substantially change the noise footprint of multiple rotors in operation

*Sound Pressure Level normalized to scale 0–1 between minimum and maximum recorded values*
Hybrid Blade Element Momentum Theory

Momentum Theory $C_T$: 

$$C_{T,MT} = \frac{T_{des}}{\pi \rho V_t^2 R^2}$$

Inflow Ratio: 

$$\lambda_0 = \lambda_c + \frac{C_T}{2 \sqrt{\mu^2 + \lambda_0^2}}$$

Where: $\mu = \frac{\sqrt{\mu_x^2 + \mu_y^2}}{V_{tip}}$ and $\lambda_c = - \frac{\lambda_0}{V_{tip}}$

$\Rightarrow$ Iteratively solve for $\lambda_0$ using Newton-Raphson method

Linear Inflow Model: 

$$\lambda = \lambda_0 (1 + k_x r \cos(\psi) + k_y r \sin(\psi))$$

Where: $k_x = \frac{15\pi}{23} \tan \left( \frac{x}{2} \right)$; $k_y = 0$; $x = \tan^{-1} \left( \frac{\mu}{\lambda_0} \right)$

Coefficient of Lift: 

For each cross-section at each azimuthal angle: 

$$C_l = C_{la} \alpha_{eff}$$

Stall Model: 

Adjust $C_l$ for each section using stall model:

$$C_l = (1 - \sigma) C_{la} \alpha_{eff} + \sigma [2 \text{sign}(\alpha_{eff} - \alpha_{L=0}) \sin^2(\alpha_{eff} - \alpha_{L=0}) \cos(\alpha_{eff} - \alpha_{L=0})]$$

Where: $\sigma = \frac{1 + e^{-M(\alpha_{eff} - \alpha_{L=0} - \alpha_0)} + e^{-M(\alpha_{eff} - \alpha_{L=0} + \alpha_0)}}{1 + e^{-M(\alpha_{eff} - \alpha_{L=0} - \alpha_0)} + e^{-M(\alpha_{eff} - \alpha_{L=0} + \alpha_0)}}$

Blade Element Theory $C_T$: 

Integrate Lift over rotor disk for Thrust:

$$C_{T,BET} = N_b \frac{N}{4R \pi^2} \int_{r_{min}}^{1} \int_{0}^{2\pi} C_l u^2 c(r) \cos(\phi) \, d\psi \, dr$$

Bracket root of function $f(x)$ within domain $a, b$:

Repeat until $f(b \text{ or } s) = 0$ or $|b - a|$ is small enough:

If $f(a) \neq f(c)$ and $f(b) \neq f(c)$ then:

Inverse Quadratic Interpolation:

$$s = \frac{af(b)f(c)}{(f(a) - f(b))(f(a) - f(c))} + \frac{bf(a)f(c)}{(f(b) - f(a))(f(b) - f(c))} + \frac{cf(a)f(b)}{(f(c) - f(a))(f(c) - f(b))}$$

Else:

Secant Method

$$s = b - f(b) \frac{b-a}{f(b)-f(a)}$$

If $s$ is not between $\frac{3a+b}{4}$ and $b$ or mflag is set and $|s - b| \geq \frac{|b-c|}{2}$ or mflag is cleared and $|s - b| \geq \frac{|c-d|}{2}$ or mflag is cleared and $|c - d| < |\delta|$ or mflag is cleared and $|c - d| < |\delta|$:

Bisection Method

$$s = \frac{a+b}{2} \text{; Set mflag}$$

Else:

Clear mflag

Bracket root using linesearch starting at $x = 0$ and searching for change in sign of residual function

Elements such as lifting-lines and flat plates can be reconstructed using a compact source-sink method. A source-sink pair is ‘placed’ at each discretized airfoil section to mimic the actual airfoil geometry.

Modified monopole (thickness) pressure perturbation equation based on source-sink method:

\[
\begin{align*}
    p'_T(x, t) &= \frac{1}{4\pi} \left[ \frac{\rho_0 u_0 t dS}{r(1 - M_r)^2} \right]_{\text{source}, \tau^*} + \frac{1}{4\pi} \left[ -\rho_0 u_0 t dS \right]_{\text{sink}, \tau^*} \\
    &+ \frac{1}{4\pi} \left[ \rho_0 u_0 t dS \left( r \hat{M}_i \hat{f}_i + a_0 (M_i \hat{f}_i - M_iM_i) \right) \right]_{\text{source}, \tau^*} \\
    &+ \frac{1}{4\pi} \left[ -\rho_0 u_0 t dS \left( r \hat{M}_i \hat{f}_i + a_0 (M_i \hat{f}_i - M_iM_i) \right) \right]_{\text{sink}, \tau^*}
\end{align*}
\]

• Simulated baseline hover operating condition at each airfoil section

• Viscous formulation with $0.1^\circ$ analysis steps

• Values needed for Hybrid Blade Element Momentum Theory model:
  • Lift-curve slopes ($C_l$ vs. $\alpha$) values
  • Stall onset angle of attack

• Sections 3 & 4 are more challenging to converge – assumed to stall approximately where Xfoil fails to converge
Quadrotor Optimization: Rotor Data

- Rotor blade data defined at radial locations along span, obtained from OpenVSP model
  - Four airfoil sections, interpolated across span
- Airfoil sections simulated using pyXLIGHT / XFOil in hover flight condition ($\omega = 75 \text{ rad/s}$)

![Twist and Chord Distributions](image)

$C_i$ vs. $\alpha$

- Sec. 1: NACA 5412
- Sec. 2: NACA 5412
- Sec. 3: NACA 5403
- Sec. 4: NACA 1403
Kreisselmeier-Steinhauser (KS) Aggregation

- Minimizing a maximum value can be challenging as it may be discontinuous.

- The Kreisselmeier-Steinhauser (KS) function aggregates all of the recorded values and smooths the design space so the overall function is continuous.

- Each independent function, \( g_j(x) \), is aggregated using an aggregation parameter, \( \rho \), in the equation below:

\[
KS \left( g_j(x) \right) = \frac{1}{\rho} \log_e \left( \sum_{i}^{n_g} e^{\rho g_j(x)} \right)
\]

- \( KS \left( g_j(x) \right) \) represents the maximum function value that can be constrained or minimized.