A Brief History of Rotorcraft Aeroacoustics

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Categories of Rotorcraft Noise

• Thickness
• Loading
  – Steady
  – Unsteady
    ▪ Blade Vortex Interaction (BVI)
    ▪ Broadband
• High Speed Impulsive
Outline

• Introduction
  – VFS/AHS Forums

• History
  – Early acoustics (1747 – 1878)
  – Advent of aeroacoustics (1822 – 1952)
  – Beginnings of modern rotorcraft aeroacoustics (1936 – 1980)
  – Summary of noise sources

• Computational contributions

• Experimental contributions
  – Flight testing
  – Wind tunnel testing
  – Urban Air Mobility

• Looking forward
Introduction: VFS/AHS Forums

• VFS/AHS Forum
  – **1980**: First Acoustic Session for Forum 26 in Washington DC with (5 papers)
  – **2016**: 29th Alexander A. Nikolsky Honorary Lecture by Schmitz


• Various other AHS/VFS specialist conferences included acoustic sessions
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Early Acoustics

• **1747**: Classical wave equation derived by Jean-Baptiste le Rond d'Alembert

\[
\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}
\]

• **1878**: Strouhal found that the frequency \( f \) was related to the velocity \( u \), a characteristic length of the string \( d \), and the diameter of the string

\[
f = 0.185 \frac{u}{d}
\]
Advent of Aeroacoustics

• **1822**: Aerodynamics begins with Navier-Stokes equations by expressing momentum equilibrium with conservation of mass.

• **1952**: Sir James Lighthill’s theory rearranged mass and momentum equation to create a wave equation with sources:
  
  \[ T_{ij} = \rho v_i v_j + \sigma_{ij} - c^2 \rho' \delta_{ij} \]

  Did not include surfaces, only considers turbulence.

Lighthill’s theory was a catalyst to revolutionize the aeroacoustics field for jet engine aeroacoustics.
Beginnings of Modern Rotorcraft Aeroacoustics

- **1936**: Gutin analyzed sound produced by a 2-bladed airplane propeller (dipole)
- **1937**: Deming derived thickness noise formulation (monopole)
- **1954**: Garrick and Watkins extended Gutin’s work to account for forward motion for a propeller
- **1969**: Lowson and Ollerhead took Gutin’s work and applied it to helicopter main rotor noise

Other notable contributors include Yudin, Lyon, Lilley, Sharland, Hulse, and others
• **1969**: Ffowcs-Williams and Hawkings (FWH), rearranged the Navier-Stokes equations to an inhomogeneous wave equation for the density, with two surface terms and a volume source term.

\[
\left(\frac{1}{c_s^2} \frac{\partial^2}{\partial t^2} - \nabla^2\right) \tilde{p} = \frac{\partial^2}{\partial x_i \partial x_j} \left( T_{ij} H(f) \right) - \frac{\partial}{\partial x_i} \left( \ell_i |\nabla f| \delta(f) \right) + \frac{\partial}{\partial t} \left( \rho_0 v_n |\nabla f| \delta(f) \right)
\]

In the 1960’s, the increasing use of helicopters for U.S. military applications and later commercial certification requirements which resulted in a demand in an expansion for rotorcraft acoustics research.
1980: Farassat re-derived FWH using generalized functions and then derived solutions to the FWH equation using various acoustic analogies along with methods to solve the wave equation using Green’s Functions

- Numerous Formulations of Farassat exists (F1, G1, G1A, F2B, etc.), but F1A is the one most used in rotorcraft applications
- F1A uses impermeable subsonic surfaces and neglects quadrupole term

### Thickness noise term

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

### Loading noise term

\[
4 \pi p'_L(x, t) = \int_{f=0} \left[ \frac{\dot{p} \cos \theta}{c r (1 - M_r)^2} + \frac{\hat{r}_i \hat{M}_i p \cos \theta}{c r (1 - M_r)^3} \right]_{\text{ret}} dS + \int_{f=0} \left[ \frac{p (\cos \theta - M_i n_i)}{r^2 (1 - M_r)^2} + \frac{(M_r - M^2) p \cos \theta}{r^2 (1 - M_r)^3} \right]_{\text{ret}} dS
\]
Summary of Rotor Noise Sources

- **Thickness (monopole)**
- **Loading (dipole)**
  - Steady
  - Unsteady
    - Blade Vortex Interaction (BVI)
    - Broadband
- **High Speed Impulsive (quadrupole)**
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Computational Contributions

• **1986**: NASA development the *first widely* used rotor noise prediction code WOPWOP using F1A

• **1986 - present**: Various rotor acoustic prediction tools have been developed providing their own pros and cons beyond WOPWOP, such as PSU-WOPWOP, ANOPP2, UCD-Quietly, etc.

• Efforts of providing input from available/limited data have evolved including compact thickness, compact loading, full surface data from CFD, etc.

• How acoustic results are presented has evolved (e.g., hemispheres and spectrograms)

Greenwood (2011)
Computationa l Contributions: Empirical Models

- **1933**: Stowell and Deming looked at rods spinning (spinning like rotor blades) and found that the acoustic power (P) was related to the tip speed ($V_{\text{Tip}}$) to the power of 5.5

- **1989**: Brooks, Pope, and Marcolini (BPM) developed semi-empirical prediction method for self noise. BPM used within acoustic prediction tools
Advancements to comprehensive analysis, CFD/CSD Coupling, and CFD, are critical due to F1A input requirements (surface motion and surface loading), many efforts have been made to advance and validate such efforts.
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Experimental Contributions: Flight Testing

- 1976: Schmitz and Boxwell acquires far-field UH-1H acoustic measurements by placing a microphone on the tail of an OV-1C quiet aircraft
  - Showed differences in pulse behavior for various rotor noise sources
Experimental Contributions: Flight Testing

• **1991 - 1995:** In-Flight Rotorcraft Acoustics Program (IRAP) used microphones on the wing tips (matching wind-tunnel measurement locations) and tail fin of the YO-3A and acquired measurements from the following aircraft:
  – BO 105 (1993)
Experimental Contributions: Flight Testing

• **2015:** NASA and the U.S. Army performed a flight test for the AS350 SD1 and EH-60L to investigate the effects of altitude variation
  – 3 test sites (0, 4k, and 7k feet above mean SL)

• **2016 - 2019:** NASA, FAA, and the U.S. Army conducted the Maneuver Acoustics Test for 6 helicopters and then later for 4 helicopters
  – Characterized source for maneuver and approach
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Wind Tunnels Used for Rotor Testing

• Examples of anechoic wind tunnels used for rotor acoustic testing include:
  – National Full-Scale Aerodynamics Complex (NFAC) 40- by 80-/80- by 120-Foot Wind Tunnels (Ames)
  – German-Dutch Wind Tunnel (DNW)
  – Low Speed Aeroacoustic Wind Tunnel (LSWAT) (Langley)
Experimental Contributions: Wind Tunnel Testing

• **1989 - 2009**: NASA/Army UH-60A Airloads Program
  – **1989**: Model-scale rotor tested in DNW wind tunnel
  – **1993 - 1994**: Flight test
  – **2009**: Full-scale rotor tested in NFAC 40- by 80-Foot Wind Tunnel (same rotor used from flight vehicle)
  – Led to long running workshop (for analysis of experimental data, prediction/computation improvements, etc.)
Experimental Contributions: Wind Tunnel Testing

- **1994/2001**: Higher Harmonic Control Acoustic Rotor Test (HART I and HART II) test in DNW International program
  - Objective to understand rotor BVI noise generation/reduction mechanisms with higher-harmonic blade-pitch control inputs of a scaled BO 105 rotor
  - Extensive acoustic and wake flow field measurements
  - Led to a decade of workshops
Experimental Contributions: Wind Tunnel Testing

- **1997:** XV-15 rotor in the NFAC 80-by-120-Foot Wind Tunnel
  - Acquired baseline BVI noise and performance measurements for typical descending flight conditions

- **1998:** Tilt Rotor Aeroacoustic Model (TRAM) test in the DNW for a single ¼-scale tiltrotor in hover, helicopter flight, and low speed axial flight
  - Performance, airloads, structural loads, acoustics
Experimental Contributions: Wind Tunnel Testing

- **2009**: Boeing SMART rotor in the NFAC 40-by 80-Foot Wind Tunnel Full-Scale MD 900 Explorer rotor
  - On-blade piezoelectric actuators driving trailing edge flaps
  - Thickness noise peak levels are reduced by up to 50% (via directivity)

- **2015 - 2018**: Testing of small Unmanned Arial Vehicles (UAVs) (< 55 lbs.) in the LSAWT
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Urban Air Mobility: Testing

• **2022:** Moog Surefly hover flight test at Cincinnati Municipal Airport

• **2022:** Joby Aviation preproduction all-electric vertical takeoff and landing prototype flight test

• **2023:** Single Joby full-scale propeller tested in the NFAC 40- by 80-Foot Wind Tunnel
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Looking Forward

- **Experimental**
  - Need for more comprehensive data (high quality blade motion, blade loading, wake measurements, etc.)
  - Multi-rotor test articles
  - Improvements to measurement hardware (microphones, microphone stands, DAQ, tunnel improvements, etc.)

- **Computation**
  - Robust and reliable prediction of rotorcraft acoustics
  - Take advantage of future high computer capabilities
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