A Brief History of Rotorcraft Aeroacoustics

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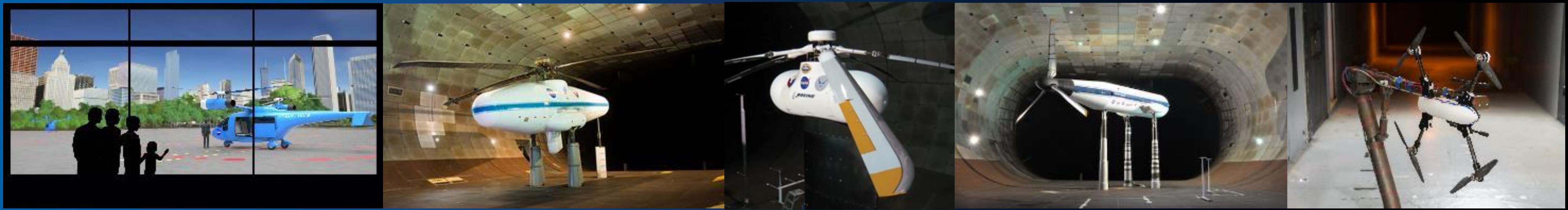


Categories of Rotorcraft Noise

- **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

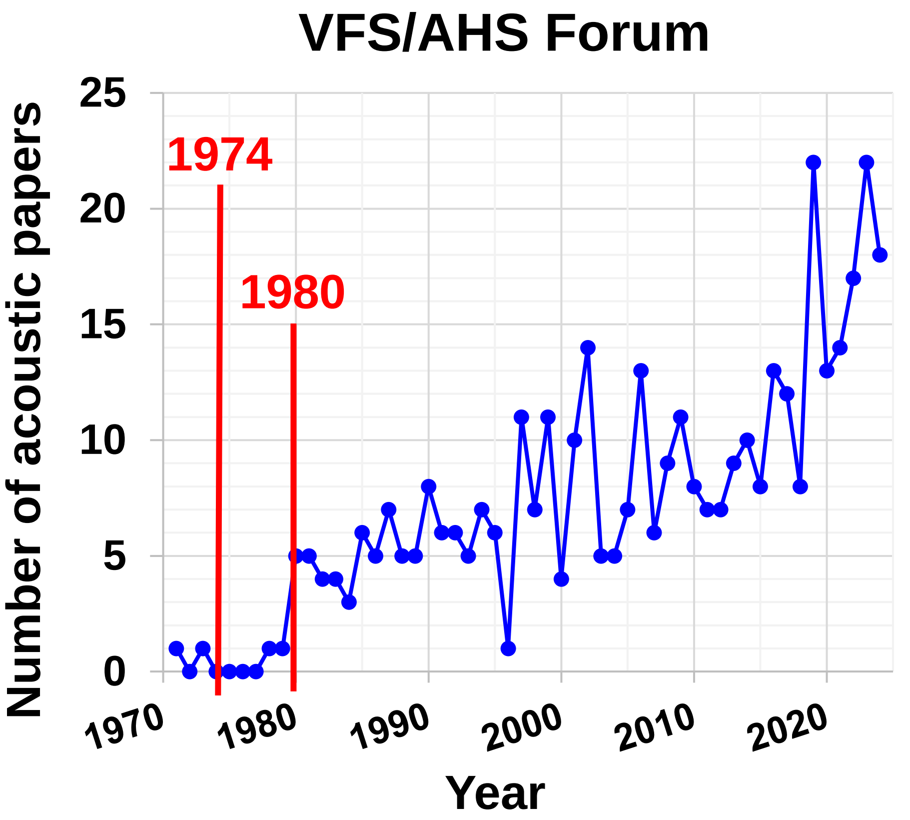
- Computational contributions

- 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
  - **2020:** Best Forum paper “Development and Validation of Generic Maneuvering Flight Noise Abatement Guidance for Helicopters”, by Stephenson, Watts, Greenwood, and Pascioni



- **Technical Fellows:** Schmitz (1993), Leverton (1995), Brooks (2000), Tung (2006), Farassat (2011), JanakiRam (2014), Boyd (2021), and Brentner (2022)

- **Various other AHS/VFS specialist conferences included acoustic sessions**

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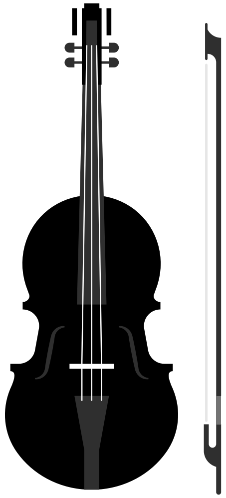
Early Acoustics

- **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
  - Did not include surfaces, only considers turbulence

$$\mathbf{T_{ij} = \rho v_i v_j + \sigma_{ij} - c^2 \rho' \delta_{ij}}$$

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

Beginnings of Modern Rotorcraft Aeroacoustics

- **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

https://www.youtube.com/watch?v=8BmESsMroRM

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

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

Beginnings of Modern Rotorcraft Aeroacoustics

- **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

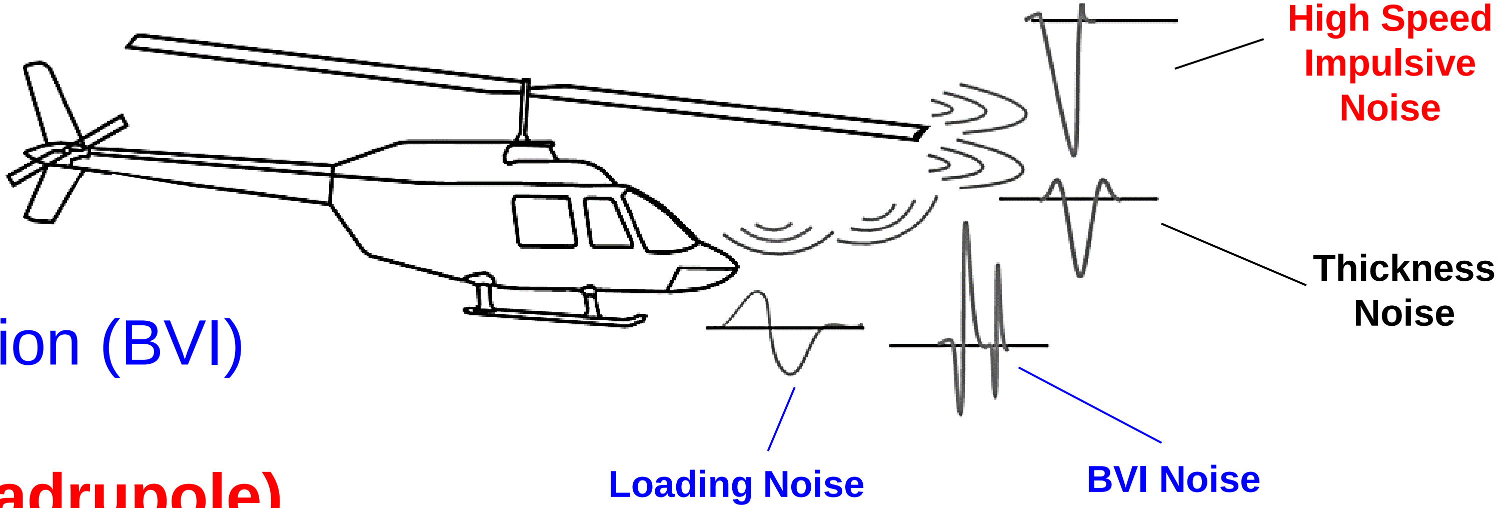
$$4\pi p'_T(x,t) = \int_{f=0} \left[\frac{\rho_0 \dot{v}_n}{r(1-M_r)^2} + \frac{\rho_0 v_n \hat{r}_i \dot{M}_i}{r(1-M_r)^3} \right]_{ret} dS + \int_{f=0} \left[\frac{\rho_0 c v_n \left(M_r - M^2\right)}{r^2(1-M_r)^3} \right]_{ret} dS$$

Loading noise term

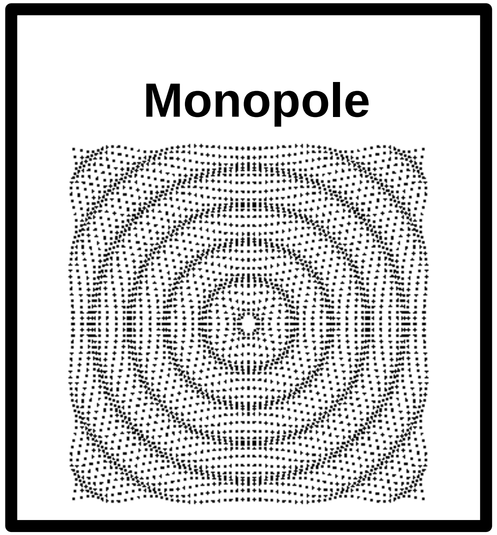
$$4\pi p'_L(x,t) = \int_{f=0} \left[\frac{\dot{p}\cos\theta}{c\, r(1-M_r)^2} + \frac{\hat{r}_i \dot{M}_i p \cos\theta}{c\, r\left(1-M_r\right)^3} \right]_{ret} dS + \int_{f=0} \left[\frac{p\left(\cos\theta - M_i n_i\right)}{r^2\left(1-M_r\right)^2} + \frac{\left(M_r - M^2\right) p\cos\theta}{r^2\left(1-M_r\right)^3}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

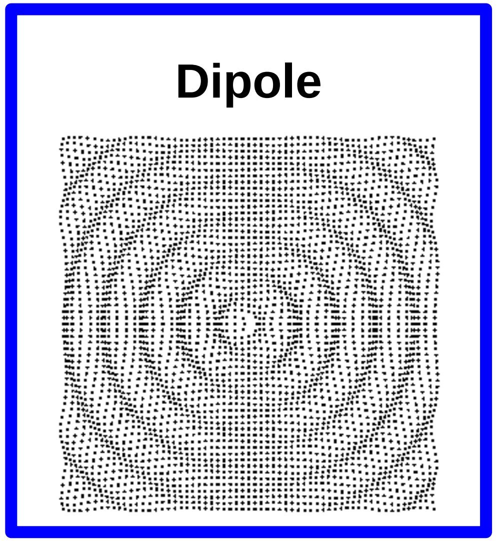
Summary of Rotor Noise Sources

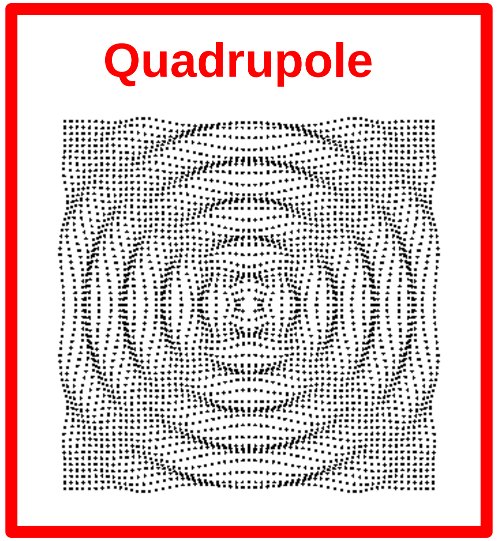
- **Thickness (monopole)**
- **Loading (dipole)**
  - Steady
  - Unsteady
    - Blade Vortex Interaction (BVI)
    - Broadband
- **High Speed Impulsive (quadrupole)**



Greenwood (2011)







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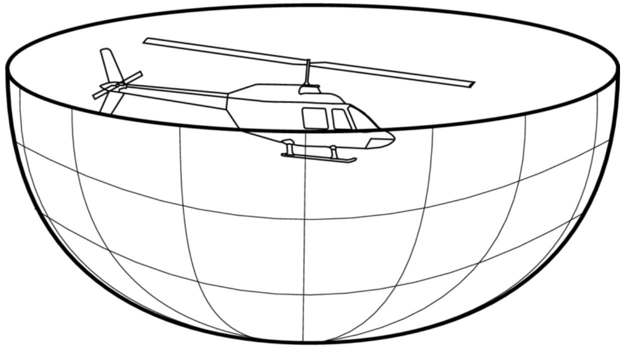
Computational Contributions

- **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)

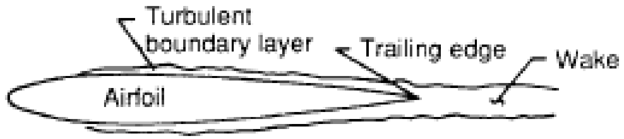


Greenwood (2011)

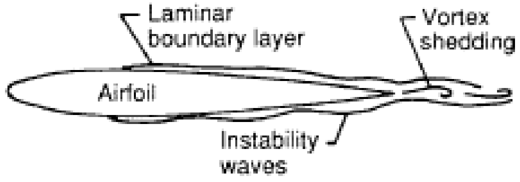
Computational Contributions: Empirical Models

- **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_{Tip}) to the power of 5.5

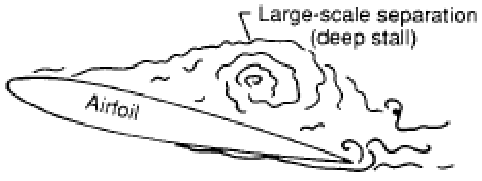
- **1989:** Brooks, Pope, and Marcolini (BPM) developed semi-empirical prediction method for self noise. BPM used within acoustic prediction tools



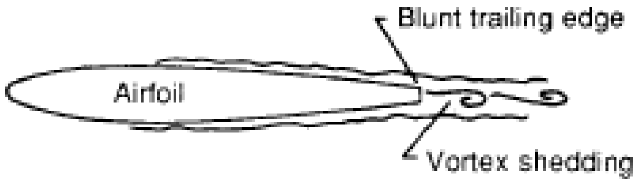
Turbulent-boundary-layer—trailing-edge noise



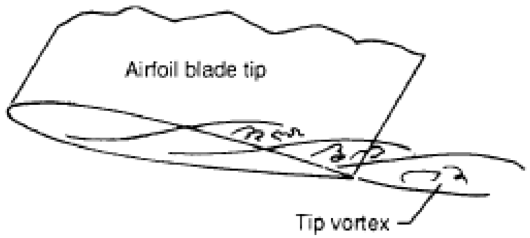
Laminar-boundary-layer—vortex-shedding noise



Separation-stall noise



Trailing-edge-bluntness—vortex-shedding noise



Tip vortex formation noise

Computational Contributions

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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  - **Flight testing**
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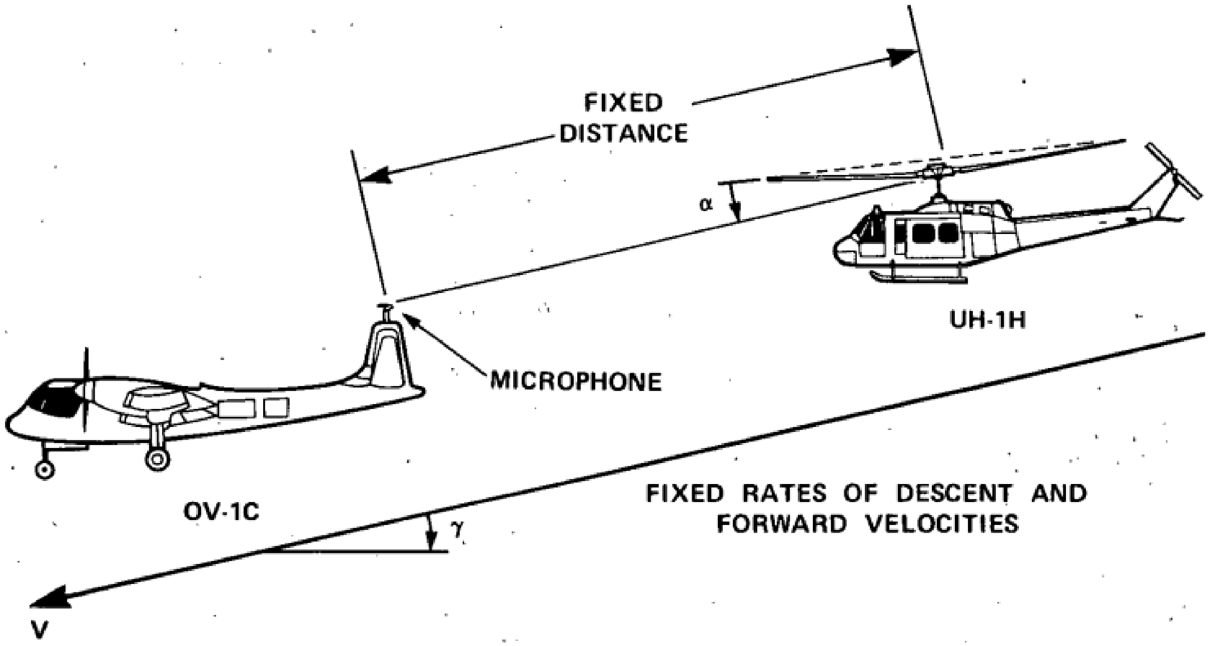
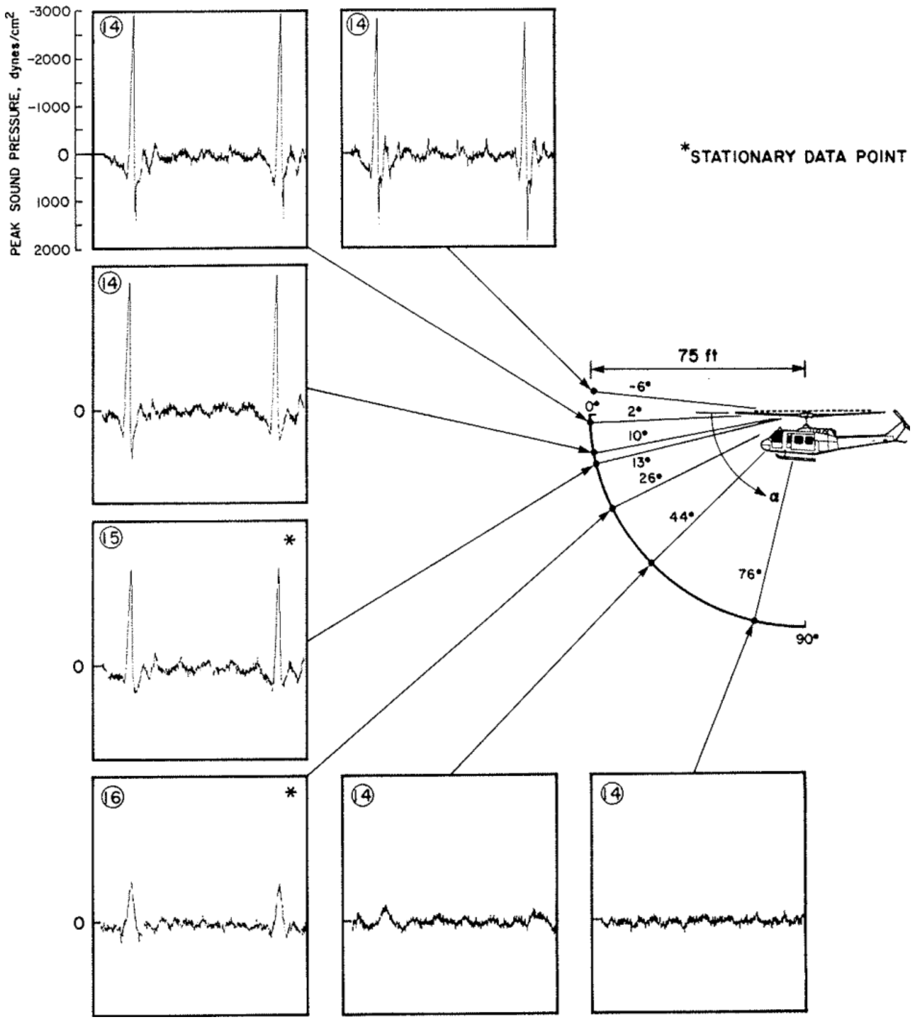
Experimental Contributions: Flight Testing

- **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:
  - S-76C (1991 - 1992)
  - BO 105 (1993)
  - UH-60A (1993 - 1994)
  - XV-15 (1995)

NASA-AMES
YO-3A
IN-FLIGHT ROTORCRAFT ACOUSTICS PROGRAM


S-76C


BO 105


UH-60A


XV-15

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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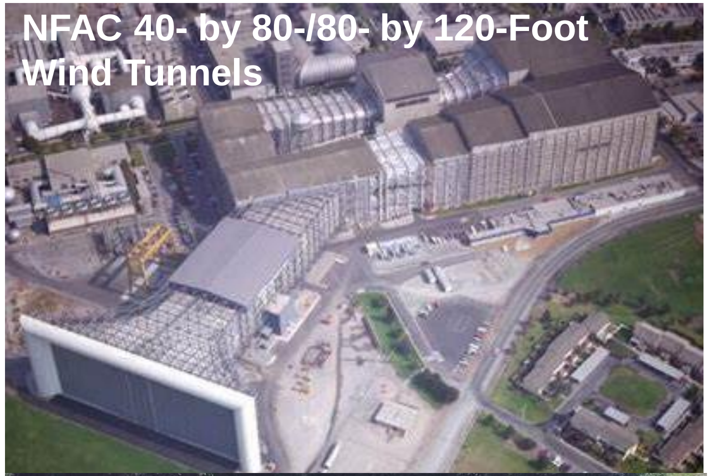
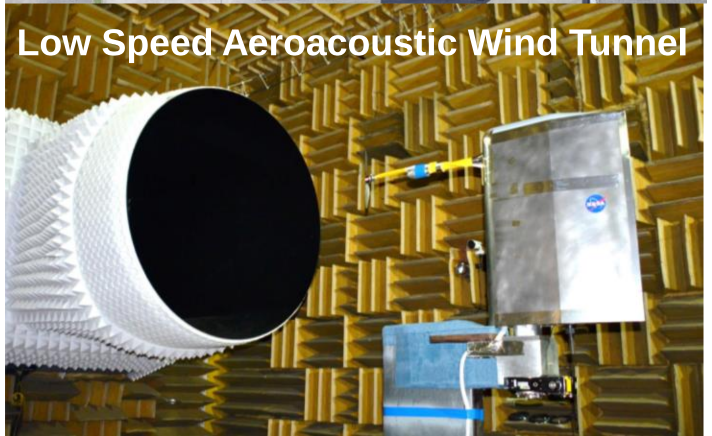
Wind Tunnels Used for Rotor Testing

- **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)



NFAC 40- by 80-/80- by 120-Foot Wind Tunnels

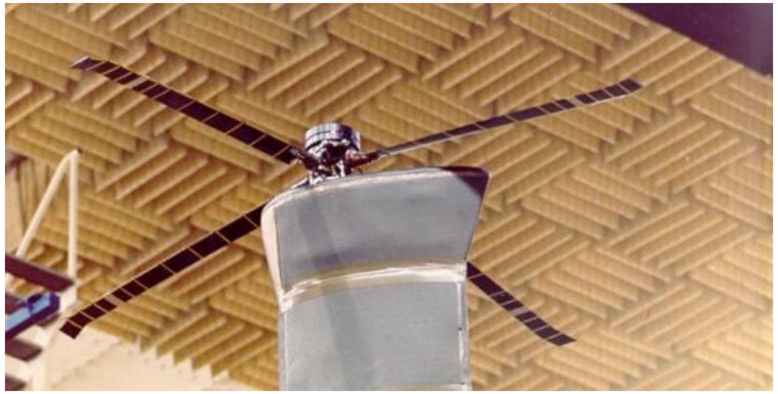
German-Dutch Wind Tunnel (DNW)



Low Speed Aeroacoustic Wind Tunnel

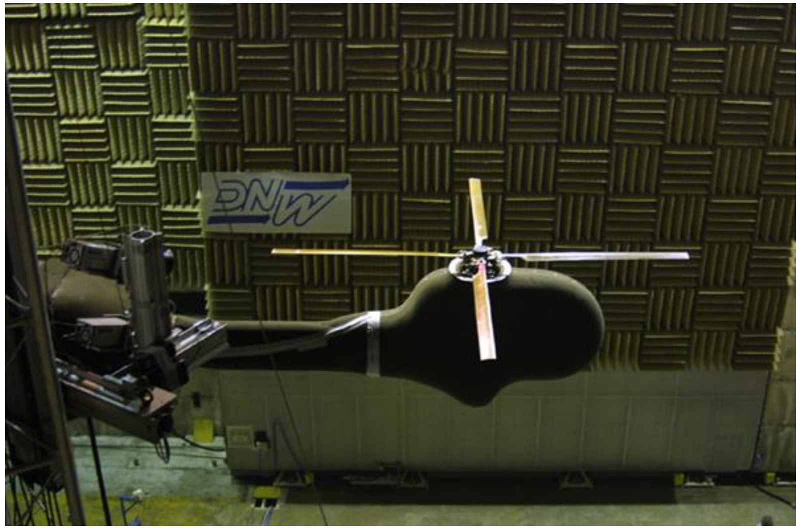
Experimental Contributions: Wind Tunnel Testing

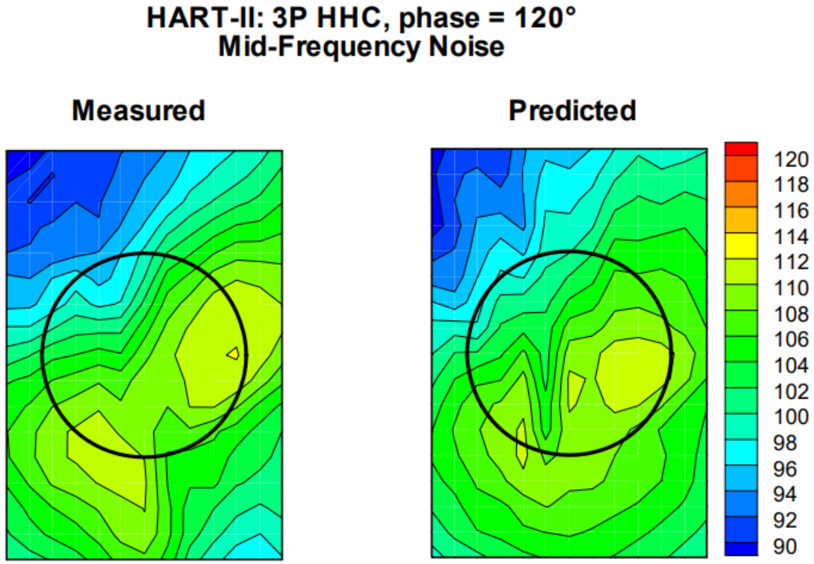
- **1989 - 2009:** NASA/Army UH-60A Airloads Program
  - **1989:** Model-scale rotor tested in DNW wind tunnel
  - **1993 - 1994:** Flight test
  - **2009:** Full-scale rotor tested in NFAC 40- by 80-Foot Wind Tunnel (same rotor used from flight vehicle)
  - Led to long running workshop (for analysis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



Experimental Contributions: Wind Tunnel Testing

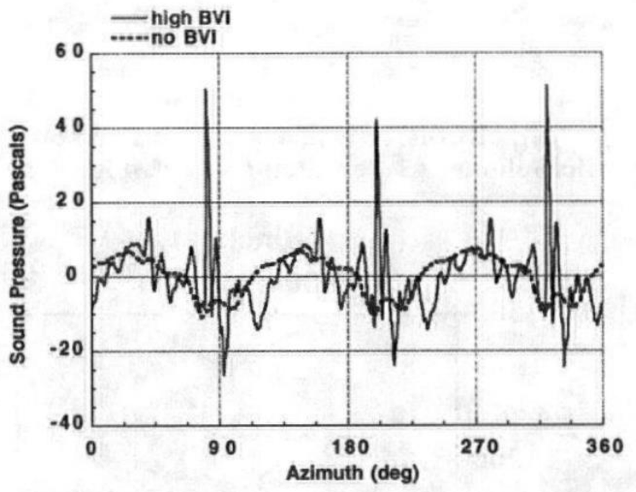
- **1994/2001**: Higher Harmonic Control Acoustic Rotor Test (HART I and HART II) test in DNW International program
  - Objective to understand rotor BVI noise generation/reduction mechanisms with higher-harmonic blade-pitch control inputs of a scaled BO 105 rotor
  - Extensive acoustic and wake flow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



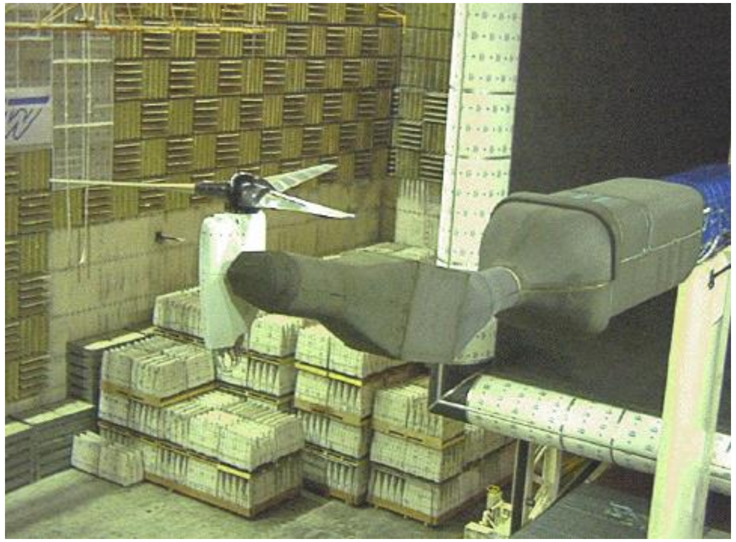


Experimental Contributions: Wind Tunnel Testing

- **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

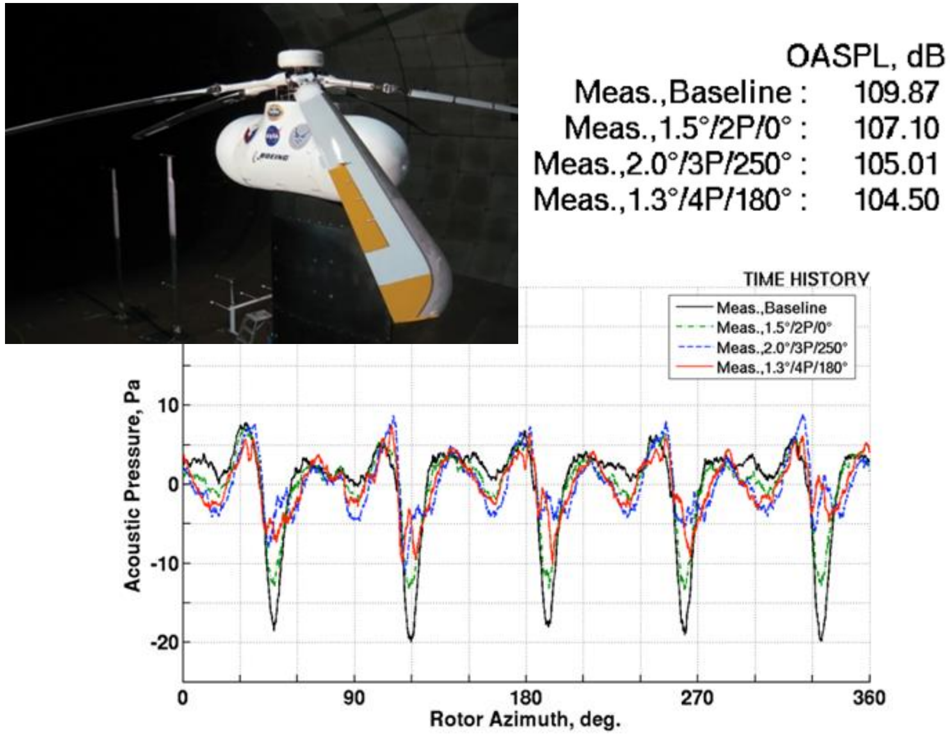


- **1998:** Tilt Rotor Aeroacoustic Model (TRAM) test in the DNW for a single ¼-scale tiltrotor in hover, helicopter flight, and low speed axial flight
  - Performance, airloads, structural loads, acoustics

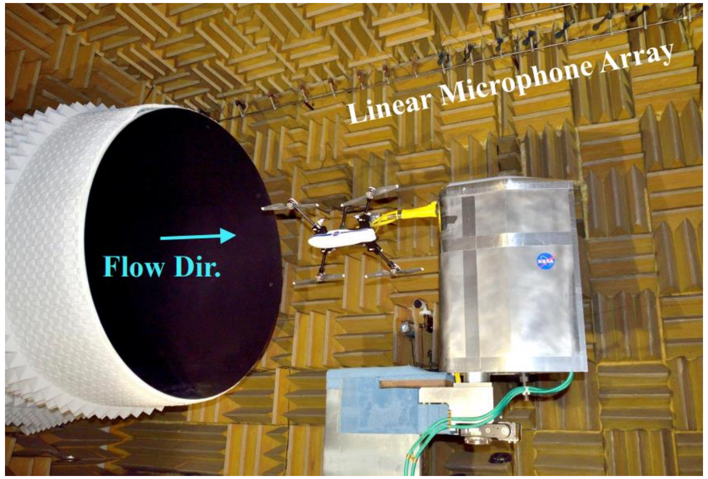


Experimental Contributions: Wind Tunnel Testing

- **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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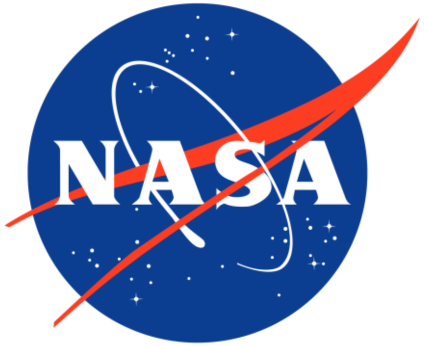
Looking Forward

- **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

Acknowledgements

- VFS acoustics committee
- NASA Ames Aeromechanics Office and interns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