Helicopter Rotor Noise Prediction: 
*Background, Current Status, and Future Direction*

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Introduction

- Helicopter noise prediction is increasingly important
  - certification
  - detection

- A great deal of progress has been made since the mid 1980’s

- Purpose of this talk
  - Put into perspective the recent progress
  - Outline current prediction capabilities
  - Forecast direction of future prediction research
  - Identify rotorcraft noise prediction needs
Outline of Talk

- Introduction and Historical perspective
- Description of governing equations
- Current status of source noise prediction
- Future directions
- Summary
Rotor Source Noise

- Thickness and High-speed impulsive noise
- Blade-vortex interaction noise
- Loading and Broadband noise
- Blade-vortex interaction noise
### Historical Perspective

#### History of Helicopter Noise Prediction

<table>
<thead>
<tr>
<th>Event</th>
<th>Year</th>
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<tbody>
<tr>
<td>Propeller noise theory developed</td>
<td>1940</td>
</tr>
<tr>
<td>(steady loading, thickness)</td>
<td></td>
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<tr>
<td>Importance of unsteady loading recognized</td>
<td>1950</td>
</tr>
<tr>
<td>Rotor noise theory development</td>
<td>1960</td>
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<tr>
<td>Helicopter rotor noise mechanisms proposed</td>
<td>1970</td>
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<tr>
<td>Ffowcs Williams–Hawkings equation</td>
<td>1980</td>
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<tr>
<td>– computer power limited</td>
<td></td>
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<tr>
<td>– inadequate blade loading available</td>
<td></td>
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<tr>
<td>(NR)$^2$ program</td>
<td>1990</td>
</tr>
<tr>
<td>Kirchhoff formulation / quadrupole noise prediction / new application of FW–H equation</td>
<td>2000</td>
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Available Methods for Rotor Noise Prediction

- Acoustic Analogy
  - treats real flow effects by fictitious sources; exact in principle
  - for rotor blades: Ffowcs Williams–Hawkings equation (1969)
  - most developed, widely used in the helicopter industry

- Kirchhoff Formula
  - originally suggested by Hawkings (1979); (Farassat and Myers 1988)
  - method currently under development (development has been very rapid)
  - depends upon high resolution aerodynamics input data from CFD.

- CFD based Computational Aeroacoustics (CAA)
  - least mature
  - most computationally demanding
  - advances in CAA will help other methods
Lighthill Acoustic Analogy

- Treats real flow effects by fictitious sources
- A mathematical device which is exact in principle
- Capable of supplying good qualitative and quantitative results
- For rotating blades
  - Aerodynamic and acoustic problems separated
  - Powerful methods of linear analysis can be used
  - Inclusion of nonlinear effects feasible now
- Acoustic analogy is and will remain a very useful tool in aeroacoustics
Lighthill Acoustic Analogy Derivation

- Idea: rearrange governing equation into a wave equation

\[
\frac{\partial}{\partial t} \left\{ \frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} \right\} = 0 \quad \text{continuity}
\]

\[
- \frac{\partial}{\partial x_i} \left\{ \frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j + P_{ij}) \right\} = 0 \quad \text{momentum (N-S)}
\]

\[
\frac{\partial^2 \rho}{\partial t^2} = \frac{\partial^2}{\partial x_i \partial x_j} (\rho u_i u_j + P_{ij})
\]

form wave equation

\[
\frac{\partial^2 \rho}{\partial t^2} - c_o \frac{\partial^2 \rho}{\partial x_i \partial x_i} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}
\]

where \( T_{ij} = \rho u_i u_j + P_{ij} - c_o \rho \delta_{ij} \)
Ffowcs Williams–Hawkings Equation Derivation Procedure

- **Embed exterior flow problem in unbounded space**
  - define generalized functions valid throughout entire space
  - interpret derivatives as generalized differentiation

\[
\tilde{\rho} = \begin{cases} 
\rho & f > 0 \\
\rho_0 & f < 0 
\end{cases}
\]
\[
\rho\tilde{u}_i = \begin{cases} 
\rho u_i & f > 0 \\
0 & f < 0 
\end{cases}
\]
\[
\tilde{P}_{ij} = \begin{cases} 
P_{ij} & f > 0 \\
0 & f < 0 
\end{cases}
\]

- **Generalized conservation equations:**

  \[
  \frac{\partial \tilde{\rho}}{\partial t} + \frac{\partial \rho \tilde{u}_i}{\partial x_i} = \left( \rho \frac{\partial \tilde{f}}{\partial t} + \rho u_i \frac{\partial \tilde{f}}{\partial x_i} \right) \delta(f) \quad \text{continuity}
  \]

  \[
  \frac{\partial \rho \tilde{u}_i}{\partial t} + \frac{\partial \rho \tilde{u}_i \tilde{u}_j}{\partial x_j} + \frac{\partial \tilde{P}_{ij}}{\partial x_j} = \left( \rho u_i \frac{\partial \tilde{f}}{\partial t} + (\rho u_i u_j + P_{ij}) \frac{\partial \tilde{f}}{\partial x_i} \right) \delta(f) \quad \text{momentum}
  \]
FW – H Equation

■ Numerical solution of the FW–H equation

\[ p'(\vec{x}, t) = \frac{\partial}{\partial t} \left[ \rho_0 \nu_\delta(f) \right] - \frac{\partial}{\partial x_i} \left[ l \delta(f) \right] + \frac{\partial^2}{\partial x_i \partial x_j} [T_{ij} H(f)] \]

■ Three source terms
  ➤ thickness source (monopole)
    – requires blade geometry and kinematics
  ➤ loading source (dipole)
    – requires blade geometry, kinematics, and surface loading
  ➤ quadrupole source
    – requires flow field (i.e., \( T_{ij} \)) around the blade (volume integration)

■ WOPWOP+ implements all three of these source terms
Kirchhoff Derivation Procedure

- Use embedding procedure on wave equation
  > define generalized pressure perturbation:

\[
\tilde{p}' = \begin{cases} 
p' & f > 0 \\
0 & f < 0 
\end{cases}
\]

- use generalized derivatives
- generalized wave equation is Kirchhoff governing equation:

\[
\Box^2 p'(\tilde{x}, t) = -\left( \frac{\partial p'}{\partial t} \frac{M_n}{c} + \frac{\partial p'}{\partial n} \right) \delta(f) - \frac{\partial}{\partial t} \left( p' \frac{M_n}{c} \delta(f) \right) - \frac{\partial}{\partial x_i} \left( p' \hat{n}_i \delta(f) \right)
\]

\[\equiv Q_{kir}\]
Formulation Development

■ **Model wave equation to solve** (valid in entire unbounded space)
  \[ \Box^2 \phi(\vec{x}, t) = Q(\vec{x}, t) \delta(f) \]

■ **Integral representation of solution** (Green’s function \( \frac{\delta(g)}{4\pi r} \))
  \[ 4\pi \phi(\vec{x}, t) = \int_{-\infty}^{t} \int_{-\infty}^{\infty} \frac{Q(\vec{y}, \tau) \delta(f) \delta(g)}{r} d\vec{y} d\tau \]

■ **Three potential formulations:**
  \[ 4\pi \phi(\vec{x}, t) = \int_{-\infty}^{t} \int_{-\infty}^{\infty} \frac{Q(\vec{y}, \tau)}{r \sin \theta} cd\Gamma d\tau = \int_{F=0}^{\infty} \int_{g=0}^{\infty} \frac{1}{r} \left[ \frac{Q(\vec{y}, \tau)}{\Lambda} \right]_{ret} d\Sigma = \int_{F=0}^{\infty} \int_{g=0}^{\infty} \left[ \frac{Q(\vec{y}, \tau)}{r|1 - M_r|} \right]_{ret} dS \]
  
  collapsing sphere formulation  
  emission surface formulation  
  retarded time formulation
Integral Formulation of FW – H

- **Retarded-time solution to FW–H equation** (neglecting quadrupole)

\[ 4\pi p' (\vec{x}, t) = \frac{\partial}{\partial t} \left[ \int_{f=0}^{\infty} \frac{Q}{r(1 - M_r)} \right]_{\text{ret}} dS + \frac{\partial}{\partial x_i} \left[ \int_{f=0}^{\infty} \frac{L_i}{r(1 - M_r)} \right]_{\text{ret}} dS \]

where \( Q = \rho v_n \) and \( L_i = P_{ij} \hat{n}_j \)

- **Take derivatives inside integrals analytically (formulation 1A)**

\[ 4\pi p' (\vec{x}, t) = \int_{f=0}^{\infty} \left[ \dot{Q} + \frac{\dot{L}_r}{c} \frac{1}{r(1 - M_r)^2} \right]_{\text{ret}} dS + \int_{f=0}^{\infty} \left[ \frac{L_r - L_M}{r^2 (1 - M_r)^2} \right]_{\text{ret}} dS + \int_{f=0}^{\infty} \left[ \frac{(Q + L_r/c)(\dot{r}M_r + c(M_r - M^2))}{r^2 (1 - M_r)^3} \right]_{\text{ret}} dS \]
NASA Rotor Noise Prediction Codes

■ WOPWOP
  ➤ Uses FW–H equation, Farassat’s formulation 1A
  ➤ Used for discrete-frequency noise prediction
  ➤ Representative of time-domain prediction codes (Primary U. S. code)
  ➤ Code features
    – Near and far-field acoustics
    – Forward flight and hover
    – Stationary and moving observers
    – Unsteady and impulsive loading allowed as input
    – Loading input may be analytical, computational, or experimental
    – Transportable, efficient, and robust

■ WOPWOP+
  ➤ includes a far-field quadrupole computation
NASA Rotor Noise Prediction Codes

- **RKIR**
  - original code from Purdue University; modified by Sikorsky and NASA Langley to include all WOPWOP blade motions
  - utilizes Farassat and Myers’ Kirchhoff formulation for moving surfaces
  - requires $p$, $\frac{\partial p}{\partial t}$, and $\nabla p$ on the Kirchhoff surface

- **FW–H/RKIR** (prototype code)
  - based on RKIR (Rotating Kirchhoff code)
  - utilizes Farassat’s formulation 1A (FW)
  - quadrupole source neglected; could be included

- **Tiltrotor Aeroacoustic Codes (TRAC)**
  - collection of codes to predict the airloads, flow-field, and noise
  - utilizes any of these codes to predict rotor noise
Examine Current Prediction Capability

- Thickness and Loading Noise
- Blade Vortex Interaction Noise
- High-Speed Impulsive Noise
- New Prediction Tools
  - Kirchhoff Predictions
  - FW-H Equation applied off the body (i.e. like a Kirchhoff formula)
- Broadband Noise
Thickness and Loading Noise

- Predictions accurately reflect design changes

\[ V_\infty = 110 \text{ kts} \]
upstream mic in TPP on advancing side

ref: Brentner 1987

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Thickness and Loading Noise

- Predictions distinguish between small differences in input parameters
- Computations are efficient (29 CPU sec/observer on 22 MFLOPS workstation)

ref: Brentner et al. 1994

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Blade-Vortex Interaction (BVI)

Tip vortex

Air flow

Noise Directivity

Blade-vortex interaction

$\psi = 0^\circ$

$\psi = 90^\circ$
BVI Noise Prediction: *with measured airloads*

- Amplitude, waveform, and spectra predicted well
- High temporal and spatial resolution of blade loads essential

- microphone located upstream of rotor on advancing side, 25 deg. below TPP
  \[ \mu = 0.152, \quad C_T / \sigma = 0.07, \quad \text{decent condition} \]

Ref: Brentner et al. 1994, Visintainer et al. 1993

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BVI Noise Prediction: *with calculated airloads*

- Near first principles prediction
- Representative of state-of-the-art

ref: Tadghighi et al. 1990

![Diagram showing the relationship between Comprehensive Code, CFD Flow Solver, and Acoustic Prediction with measured and predicted acoustic pressure over time.](image-url)
High-Speed Impulsive Noise

- High-speed impulsive (HSI) noise
  - particularly intense and annoying
  - occurs in high-speed forward flight
  - onset usually very rapid
  - primarily in-plane directivity

- HSI noise prediction
  - requires knowledge of 3D, nonlinear flow field
  - computationally intensive
  - modeled by FW–H quadrupole source
Quadrupole Noise Prediction History

Importance of quadrupole source recognized
Yu, Caradonna, and Schmitz (1978)
- simplified source strength
- far-field assumption / preintegration in z direction
- relatively immature flow field calculation

Recent efforts
- Prieur (1986) - frequency domain, hover only
- Schultz and Splettstoesser (1987) - followed Yu et al.
- Schultz et al (1994) - approx. source strength, both volume integration and preintegration
- Ianniello and De Bernardis (1994) - full volume integration

NO readily available quadrupole prediction code in U.S.
High-Speed Impulsive Noise

- Prediction by approximate quadrupole calculation
  - Measured blade pressures and computed flow field used in prediction

\[ M_H = 0.9 \]

hovering rotor
mic in TPP

ref: Schultz and Splettstoesser 1987

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High-Speed Impulsive Noise

- Prediction by direct CFD computation
  - Nonlifting, symmetric rotor in hover

Ref: Baeder 1991

\[ M_h = 0.92 \]

Acoustic pressure

Time, msec

Exp.

Euler

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Why Use the Acoustic Analogy?

- FW–H source contributions linearly superimpose
  \[ p'(\bar{x},t) = p'_t(\bar{x},t) + p'_\ell(\bar{x},t) + p'_Q(\bar{x},t) \]
  - develop quadrupole source prediction independently
  - can identify contributions from each source
- Current prediction codes based on FW–H equation
  - significant knowledge base
  - thickness & loading noise predictions very efficient
- Less demanding CFD computation
  - only compute the source region
  - don’t need to capture long-distance wave propagation
- Easy to study role of complicated rotor kinematics
Quadrupole Development Considerations

FW-H: \[ \square^2 p'(\bar{x},t) = \frac{\partial}{\partial t}[\rho o v n \delta(f)] - \frac{\partial}{\partial x_i}[\ell_i \delta(f)] + \frac{\partial^2}{\partial x_i \partial x_j}[T_{ij} H(f)] \]

- Source terms linearly superimpose
  \[ p'(\bar{x},t) = p_t'(\bar{x},t) + p_\ell'(\bar{x},t) + p_Q'(\bar{x},t) \]
- Quadrupole source region is a volume
  ➤ needs large amount of data – 3D time dependent
  ➤ naturally separate
- Current WOPWOP very efficient
  ➤ desirable to not change thickness and loading now
  ➤ want to benefit from knowledge gained in thickness and loading noise development
Collapsing Sphere Formulation

**Equation**

\[
4\pi p'_Q(\bar{x}, t) = \frac{1}{c} \frac{\partial^2}{\partial t^2} \int_{-\infty}^{t} \int_{r>0} \frac{T_{rr}}{r} d\Omega d\tau \\
+ \frac{\partial}{\partial t} \int_{-\infty}^{t} \int_{r>0} \frac{3T_{rr} - T_{ii}}{r^2} d\Omega d\tau \\
+ c \int_{-\infty}^{t} \int_{r>0} \frac{3T_{rr} - T_{ii}}{r^3} d\Omega d\tau
\]

**Interpretation**

- \( f > 0 \) - everywhere outside of blade surface
- \( d\Omega \) - element of collapsing sphere surface
- \( T_{ij} = \rho u_i u_j + (p' - \rho' c^2)\delta_{ij} \)

Collapsing sphere (\( g = 0 \))

Observer position \( \bar{x} \)

\( \Gamma \) curve
Far-Field Approximation

**Assumptions**
- Far-field observer
- In-plane observer

**Define new tensor**

\[ Q_{ij} = \int_{-\infty}^{\infty} T_{ij} dz \]

**Collapsing sphere approximated as a cylinder**

**Integration in \( z \) is independent of source time**
Far-Field Approximation

Contours of quadrupole source strength

approximation to collapsing sphere

collapsing sphere
WOPWOP+ Validation

Validation case
- UH-1H, 1/7th scale model rotor (untwisted)
- Experimental data available - Boxwell et al., Purcell
- Unique Euler calculation available (Baeder)
  - good resolution of flow field around blade
  - solution extends to microphone position at 3.09 R
  - symmetric solution

Operating conditions for comparison
- hover
- $M_H = \{0.88, 0.925\}$
- inplane microphone at 3.09 R
UH-1H Model Rotor Comparison

- Observer inplane at 3.09 R from rotor hub, $M_H = .85$

- Quadrupole contribution roughly one-third that of thickness and loading
- Good agreement with Euler calculation and experiment
UH-1H Model Rotor Comparison

- Observer inplane at 3.09 R from rotor hub, $M_H = .88$

- Good agreement with Euler calculation and experiment
Observer inplane at 3.09 R from rotor hub, $M_H = .90$

- Quadrupole contribution is larger than thickness and loading and has steepened
- Retarded-time formulation does not allow all contributing panels to be included
UH-1H Model Rotor Comparison

- Observer inplane at 3.09 R from rotor hub, $M_H = 0.925$

- Quadrupole negative peak pressure shifts at higher speed
- Quadrupole contribution nearly twice that of thickness and loading

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UH-1H Model Rotor Quadrupole Strength

- Contours of $Q_{ii}$

M_re=.85

M_re=.88

M_re=.90

M_re=.925

M_re=.95

UH-1H model rotor untwisted; no lift hover test

sonic circle

extent of quadrupole integration

WOPWOP+ preprocessor output

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Components of acoustic pressure

UH-1H Model Rotor Noise

UH-1H model rotor untwisted; no lift hover test

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UH-1H Model Rotor Comparison

- Observer inplane at 3.09 R from rotor hub, $M_H = .95$

- Quadrupole term dominates pressure time history
- Predicted signal amplitude overpredicted
- Complete signal widening not predicted, but shock-like feature captured

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Efficiency

■ Preprocessor
  ➤ nominal run time: 3-5 CPU seconds

■ Acoustic calculation
  ➤ thickness and loading noise: ~ 5 CPU seconds
  ➤ quadrupole noise: ~ 11-17 seconds*
  ➤ total: ~ 16-22 CPU seconds
* ~ 45 CPU seconds when code forced to use 20pts/panel on last two rows
  CPU times for HP 735-99 scientific workstation

■ Efficiency considerations
  ➤ quadrupole noise computation comparable to thickness and loading on a per panel basis
  ➤ adaptive quadrature enables use of a large number of quadrature points when needed
  ➤ reductions in CPU time possible
New Prediction Methods Compared

- FW-H applied off the blade surface (like a Kirchhoff method)
- Kirchhoff method for moving surfaces
FW–H for a penetrable surface

- Not necessary to assume integration surface $f=0$ is coincident with body

\[
\Box^2 p'(\bar{x}, t) = \frac{\partial^2}{\partial x_i \partial x_j} \left[ T_{ij} H(f) \right] \\
- \frac{\partial}{\partial x_i} \left[ (p_{ij} \hat{n}_j + \rho u_i ((u_n - v_n)) \delta(f) \right] \\
+ \frac{\partial}{\partial t} \left[ (\rho o u_n + \rho ((u_n - v_n)) \delta(f) \right]
\]

- FW–H can be used as a Kirchhoff formula
Identification of Noise Components

- Compare components from FW–H/RKIR with WOPWOP+
  - UH-1H rotor in hover
  - Hover solution from TURNS (Baeder)

- Two predictions necessary with FW–H/RKIR
  - thickness and loading from surface coincident with rotor blade
  - total signal (including quadrupole) from a surface approximately 1.5 chords away from blade.

- New application of FW–H equation retains advantage of predicting noise components
Comparison with Kirchhoff

- Manipulate FW–H source terms into form of Kirchhoff source terms (inviscid fluid)

\[ \Box^2 p'(\vec{x}, t) = Q_{kir} + \frac{\partial}{\partial x_i \partial x_j} \left[ T_{ij} H(f) \right] \]

- Extra source terms are 2nd order in perturbations quantities

- FW–H and Kirchhoff source terms
  - equivalent in linear region \( p' \approx c^2 \rho' \ u_i \ll 1 \)
  - NOT equivalent in nonlinear flow region

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Numerical Comparison: UH-1H hovering rotor

- UH-1H rotor
  - 1/7th scale model
  - untwisted blade
- Test setup (Purcell)
  - Hover, $M_H = 0.88$
  - inplane microphone, 3.09 R from hub
  - minimal rotor lift
- Flow-field computation
  - full potential flow solver used (FPRBVI)
  - 80 x 36 x 24 grid (somewhat coarse)
  - no rotor lift

$p', \text{ Pa}$ vs. time, msec

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Numerical Comparison: Sensitivity to Surface Placement

- Principal advantage of the FW–H approach is insensitivity to surface placement

Kirchhoff

(Note difference in pressure scales)

FW–H

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Numerical Comparison: Forward Flight Case

- Advancing-side acoustic pressure underpredicted
- Agreement with data is good
- All three codes agree with each other — non-lifting rotor
FW–H vs. Kirchhoff

- **FW–H method of choice for aeroacoustic problems**
  - conservation of mass and momentum built in
  - unified theory with thickness, loading, and quadrupole source terms
  - insensitive to integration surface placement

- **FW–H approach the “better” than linear Kirchhoff because:**
  - valid in linear and nonlinear flow regions
  - surface terms include quadrupole contribution enclosed
  - physical noise components can be identified with two surfaces

- **The Kirchhoff approach**
  - valid only in the linear flow region (not known a priori)
    - input data must satisfy the wave equation
    - wakes and potential flow field can cause major problems
  - solution can be sensitive to placement of Kirchhoff surface
Broadband Noise

■ Understanding
  ➤ Subjectively very important
  ➤ Many different mechanisms responsible – separate treatment for each
  ➤ Physical generation mechanisms well understood

■ Prediction status
  ➤ Unsteady blade loads calculation difficult – classical methods used
  ➤ Frequency domain methods only – turbulence data in frequency domain
  ➤ Good prediction where turbulence statistics are known
  ➤ Good prediction of self-noise with semi-empirical methods

■ Little explored approaches
  ➤ Application of FW–H equation
  ➤ Direct simulation of blade turbulence
Future Directions

■ Ffowcs Williams – Hawkings equation
  ➤ Maturity level high — first choice for discrete frequency noise
  ➤ Efficient and robust codes currently available
  ➤ Solutions to current challenges in hand (BVI and HSI noise)

■ Alternate approaches — feasible due to advances in CFD and computer technology
  ➤ FW–H equation used as Kirchhoff method
  ➤ Direct computation of acoustics

■ Relative importance of broadband noise increasing

■ Continued work needed
  ➤ wake prediction
  ➤ aeroelastic coupling
  ➤ full configuration aerodynamics/aeroacoustics
Summary

- Rotor noise prediction capability is advanced
  - Discrete frequency noise
    - Thickness and loading noise – prediction now routine
    - Blade-vortex interaction noise – good agreement demonstrated
    - High-speed impulsive noise – robust solutions available; depends upon CFD
  - Broadband noise
    - Semi-empirical predictions give good results for standard helicopter rotors

- Challenges for the future remain
  - Accurate prediction of high resolution airloads
  - Increased importance of broadband-noise prediction
  - Systems noise prediction – component interaction; scattering; reflection