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

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### 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 (steady loading, thickness)</td>
<td>- 1940 -</td>
</tr>
<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>
</tr>
<tr>
<td>– computer power limited</td>
<td>- 1990 -</td>
</tr>
<tr>
<td>– inadequate blade loading available</td>
<td>- 2000 -</td>
</tr>
<tr>
<td>(NR)^2 program</td>
<td></td>
</tr>
<tr>
<td>Kirchhoff formulation / quadrupole noise prediction / new application of FW–H equation</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

\[ \tilde{\rho} = \begin{cases} \rho & f > 0 \\ \rho_o & f < 0 \end{cases} \]

\[ \rho \tilde{u}_i = \begin{cases} \rho u_i & f > 0 \\ 0 & f < 0 \end{cases} \]

\[ \tilde{P}_{ij} = \begin{cases} P_{ij} & f > 0 \\ 0 & f < 0 \end{cases} \]

- Generalized conservation equations:

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

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

- Numerical solution of the FW–H equation

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

- 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:
    \[ \Box^2 p'(\bar{x},t) = -\left(\frac{\partial p'}{\partial t} \frac{M_n}{c} + \frac{\partial p'}{\partial n}\right)\delta(f) - \frac{\partial}{\partial t}\left( p' \frac{M_n}{c} \delta(f) \right) - \frac{\partial}{\partial x_i} \left( p' \hat{n}_i \delta(f) \right) \]
    \[ \equiv Q_{kir} \]
Formulation Development

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

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

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

- Retarded-time solution to FW–H equation (neglecting quadrupole)
  \[ 4\pi p'(\vec{x}, t) = \frac{\partial}{\partial t} \int_{f=0} \left[ \frac{Q}{r(1 - M_r)} \right]_{\text{ret}} dS + \frac{\partial}{\partial \vec{x}_i} \int_{f=0} \left[ \frac{L_i}{r(1 - M_r)} \right]_{\text{ret}} dS \]
  where \( Q = \rho v_n \) and \( L_i = P_{ij} \hat{n}_j \)

- Take derivatives inside integrals analytically (formulation 1A)
  \[ 4\pi p'(\vec{x}, t) = \int_{f=0} \left[ \frac{\dot{Q} + \dot{L}_r / c}{r(1 - M_r)^2} \right]_{\text{ret}} dS + \int_{f=0} \left[ \frac{L_r - L^M}{r^2(1 - M_r)^2} \right]_{\text{ret}} dS \]
  \[ + \int_{f=0} \left[ \frac{(Q + L_r / c)(r \dot{M}_r + c(M_r - M^2))}{r^2(1 - M_r)^3} \right]_{\text{ret}} dS \]
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
  ➤ require $p$, $\frac{\partial p}{\partial t}$, 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
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

Deviation from baseline

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Blade-Vortex Interaction (BVI)

- **Rotation**: $\psi = 0^\circ$
- **Tip vortex**
- **Air flow**
- **Blade-vortex interaction**
- **Noise Directivity**: $\psi = 90^\circ$
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

![Diagram showing the process from Comprehensive Code to CFD Flow Solver to Acoustic Prediction and comparing Measured and Predicted acoustic pressure over time.](image)

ref: Tadghighi et al. 1990
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

<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>Prediction</th>
</tr>
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<tbody>
<tr>
<td>Time</td>
<td>Acoustic pressure</td>
<td>Acoustic pressure</td>
</tr>
<tr>
<td>-600</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-400</td>
<td>-200</td>
<td>-200</td>
</tr>
<tr>
<td>-200</td>
<td>-400</td>
<td>-400</td>
</tr>
<tr>
<td>0</td>
<td>200</td>
<td>200</td>
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</tbody>
</table>

ref: Schultz and Splettstoesser 1987
High-Speed Impulsive Noise

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

Ref: Baeder 1991

![Graph showing acoustic pressure over time, with markers for experimental data and Euler predictions.](image)

- $M_H = 0.92$
- hover
- mic in TPP

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

- **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**

\[ 4\pi p'_Q(x, t) = \frac{1}{c} \frac{\partial^2}{\partial t^2} \int \int \frac{T_{rr}}{r} d\Omega d\tau \]

\[ + \frac{\partial}{\partial t} \int \int \frac{3T_{rr} - T_{ii}}{r^2} d\Omega d\tau \]

\[ + c \int \int \frac{3T_{rr} - T_{ii}}{r^3} d\Omega d\tau \]

**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

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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
UH-1H Model Rotor Comparison

- 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

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UH-1H Model Rotor Comparison

- Observer inplane at 3.09 R from rotor hub, $M_H = .925$

- Quadrupole negative peak pressure shifts at higher speed
- Quadrupole contribution nearly twice that of thickness and loading
UH-1H Model Rotor Quadrupole Strength

- Contours of $Q_{ii}$

- $M_n = .85$
- $M_n = .88$
- $M_n = .90$
- $M_n = .925$
- $M_n = .95$

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

SONIC CIRCLE

EXTENT OF QUADRUPOLE INTEGRATION

WOPWOP+ PREPROCESSOR OUTPUT
UH-1H Model Rotor Noise

Components of acoustic pressure

\[ M_h = 0.85, \quad M_h = 0.88, \quad M_h = 0.90, \quad M_h = 0.925, \quad M_h = 0.95 \]

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

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

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)

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

- Extra source terms are 2nd order in perturbations quantities

- FW–H and Kirchhoff source terms
  - equivalent in linear region \((p' \approx c^2 \rho' \quad u_i << 1)\)
  - NOT equivalent in nonlinear flow region
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
Numerical Comparison: Sensitivity to Surface Placement

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

Kirchhoff

FW–H

(Note difference in pressure scales)
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

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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