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

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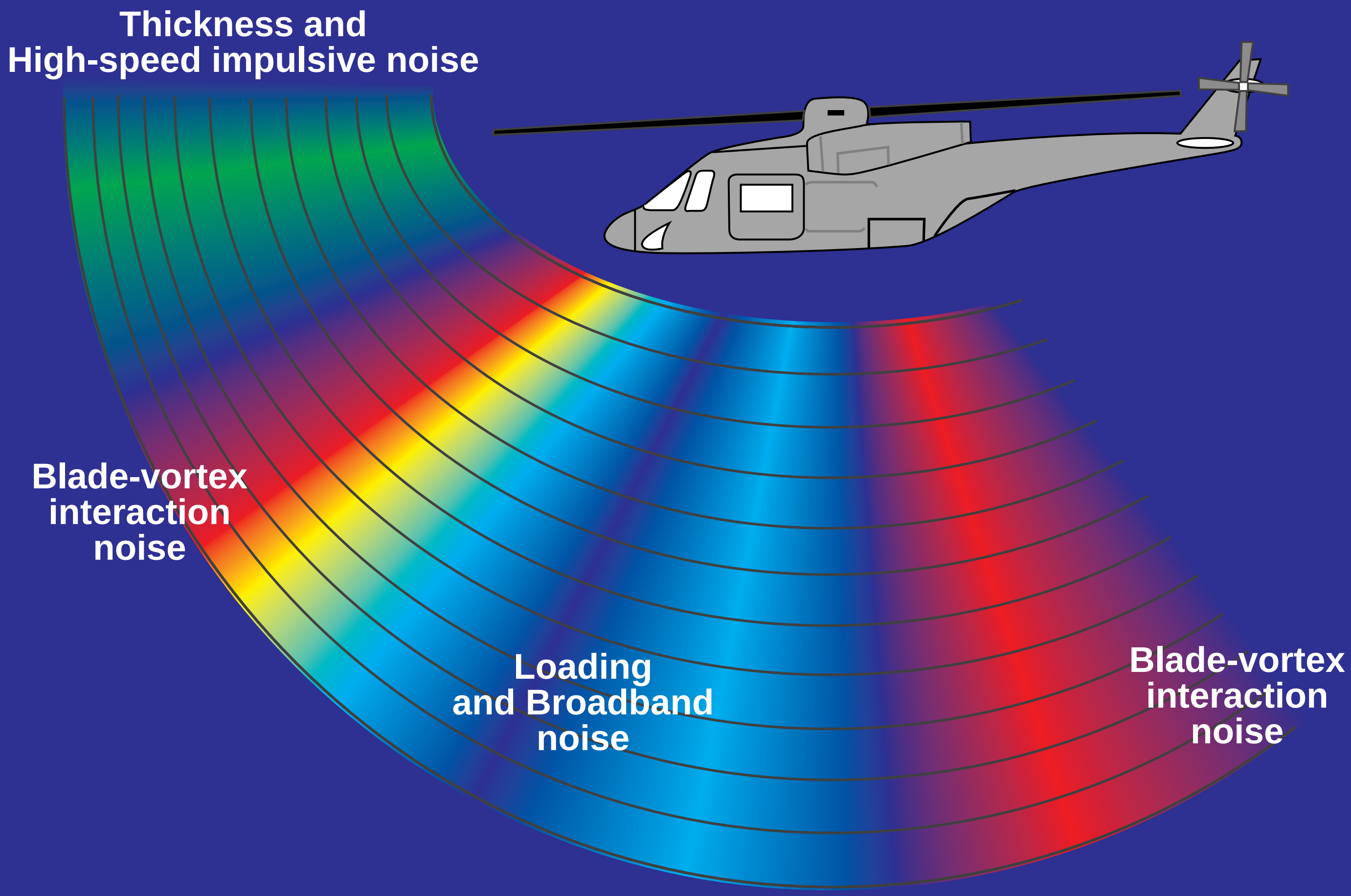
# Introduction

- 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

| | | |
|---|---|---|
| Propeller noise theory developed (steady loading, thickness) | - 1940 - | |
| | - 1950 - | Helicopter rotor noise mechanisms proposed |
| Importance of unsteady loading recognized | - 1960 - | |
| | - 1970 - | Ffowcs Williams–Hawkings equation |
| Rotor noise theory development | | – computer power limited<br>– inadequate blade loading available |
| Helicopter rotor noise code development | - 1980 - | $(NR)^2$ program |
| – excellent validation data available<br>– large increase in computation power | - 1990 - | Kirchhoff formulation /<br>quadrupole noise prediction /<br>new application of FW–H equation |
| | - 2000 - | |

# 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**

$$\frac{\partial}{\partial t}\left\{\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}\right\}=0$$

continuity

$$-\quad\frac{\partial}{\partial x_i}\left\{\frac{\partial\, \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i u_j+P_{ij})\right\}=0$$

momentum (N-S)

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$$\frac{\partial^2 \rho}{\partial t^2}=\frac{\partial^2}{\partial x_i \partial x_j}\left(\rho u_i u_j+P_{ij}\right)$$

form wave equation

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

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:

$$\frac{\bar{\partial}\tilde{\rho}}{\partial t} + \frac{\bar{\partial}\rho\tilde{u}_i}{\partial x_i} = (\rho' \frac{\bar{\partial} f}{\partial t} + \rho u_i \frac{\bar{\partial} f}{\partial x_i})\delta(f) \qquad \text{continuity}$$

$$\frac{\bar{\partial}\rho\tilde{u}_i}{\partial t} + \frac{\bar{\partial}\rho\tilde{u}_i\tilde{u}_j}{\partial x_j} + \frac{\bar{\partial}\tilde{P}_{ij}}{\partial x_j} = (\rho u_i \frac{\partial f}{\partial t} + (\rho u_i u_j + P_{ij})\frac{\partial f}{\partial x_i})\delta(f) \qquad \text{momentum}$$

# FW – H Equation

- **Numerical solution of the FW–H equation**

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

- **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:

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

$$\equiv Q_{kir}$$

# 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 $\dfrac{\delta(g)}{4\pi r}$ )

$$4\pi\phi(\vec{x},t) = \int_{-\infty}^{t}\int_{-\infty}^{\infty}\frac{Q(\vec{y},\tau)\delta(f)\delta(g)}{r}\,d\vec{y}\,d\tau$$

- **Three potential formulations:**

$$4\pi\phi(\vec{x},t) = \int_{-\infty}^{t}\int_{\substack{f=0\\ g=0}}\frac{Q(\vec{y},\tau)}{r\sin\theta}\,c\,d\Gamma\,d\tau = \int_{F=0}\frac{1}{r}\left[\frac{Q(\vec{y},\tau)}{\Lambda}\right]_{ret}d\Sigma = \int_{f=0}\left[\frac{Q(\vec{y},\tau)}{r\left|1-M_r\right|}\right]_{ret}dS$$

| collapsing sphere formulation | emission surface formulation | retarded time formulation |
|---|---|---|

# Integral Formulation of FW – H

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

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

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

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

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

$$+\int_{f=0}\left[\frac{(Q+L_r/c)\left(r\dot{M}_r + c\left(M_r - M^2\right)\right)}{r^2(1-M_r)^3}\right]_{ret} dS$$

# 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

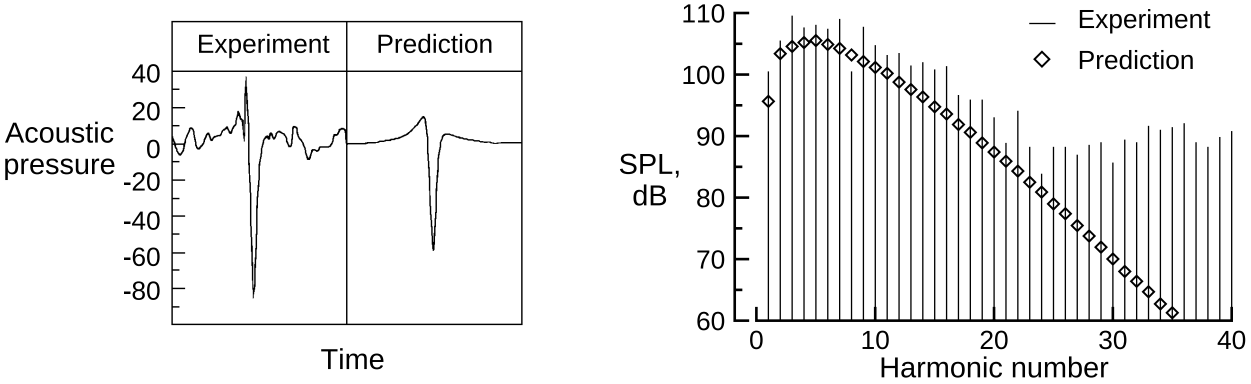
- FW–H/RKIR (prototype code)
  - ➤ based on RKIR (Rotating Kirchhoff code)
  - ➤ utilizes Farassat's formulation 1A (FW
  - ➤ quadrupole source neglected; could be included
- Tiltrotor Aeroacoustic Codes (TRAC)
  - ➤ collection of codes to predict the airloads, flow-field, and noise
  - ➤ utilizes any 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

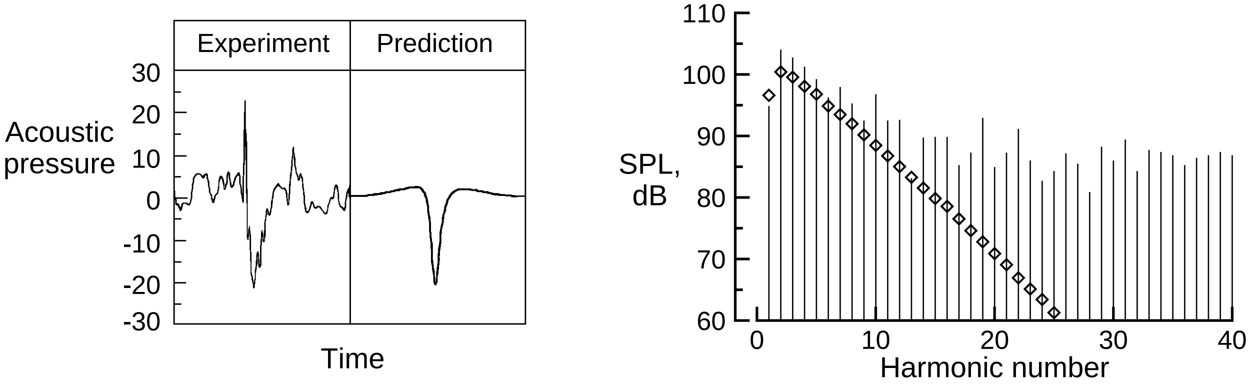
# Thickness and Loading Noise

- **Predictions accurately reflect design changes**



**a) Rectangular planform**

$V_\infty = 110$ kts
upstream mic in TPP
on advancing side

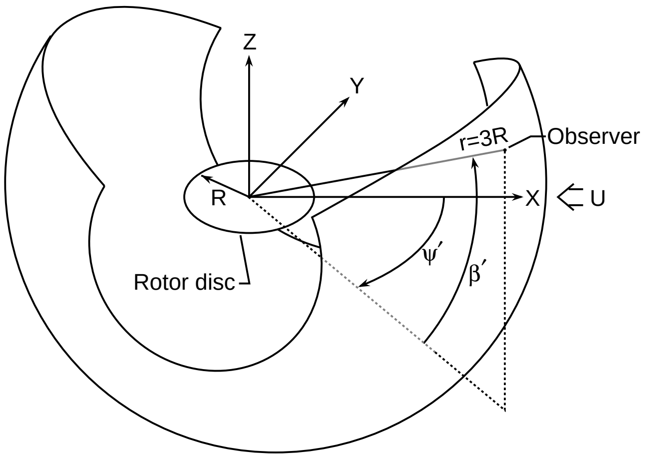


**b) Tapered planform**

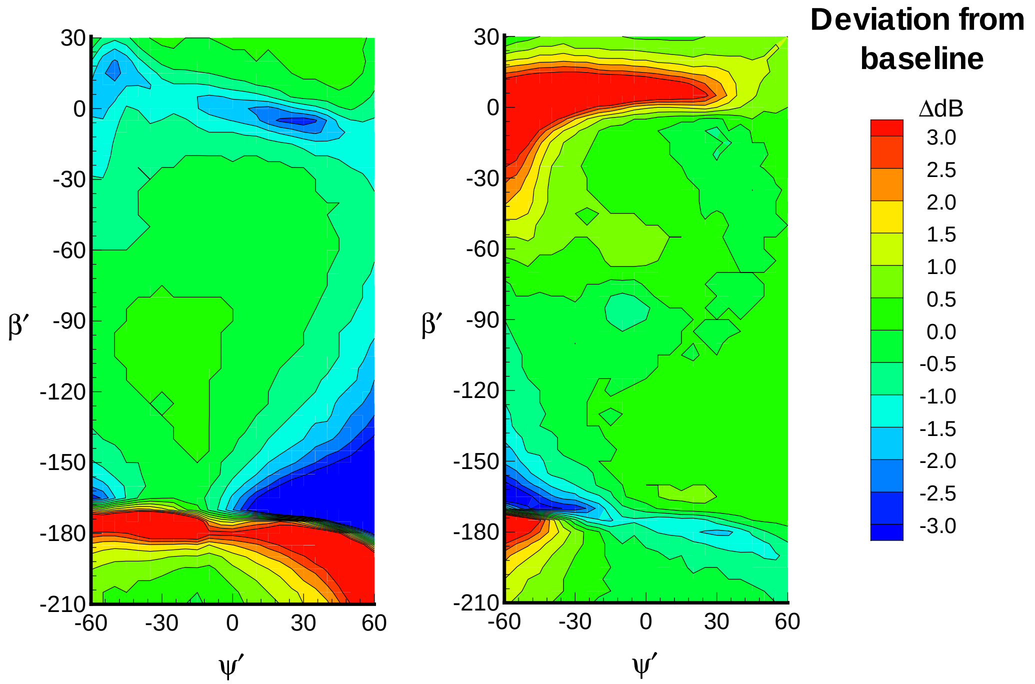
ref: Brentner 1987

# Thickness and Loading Noise

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



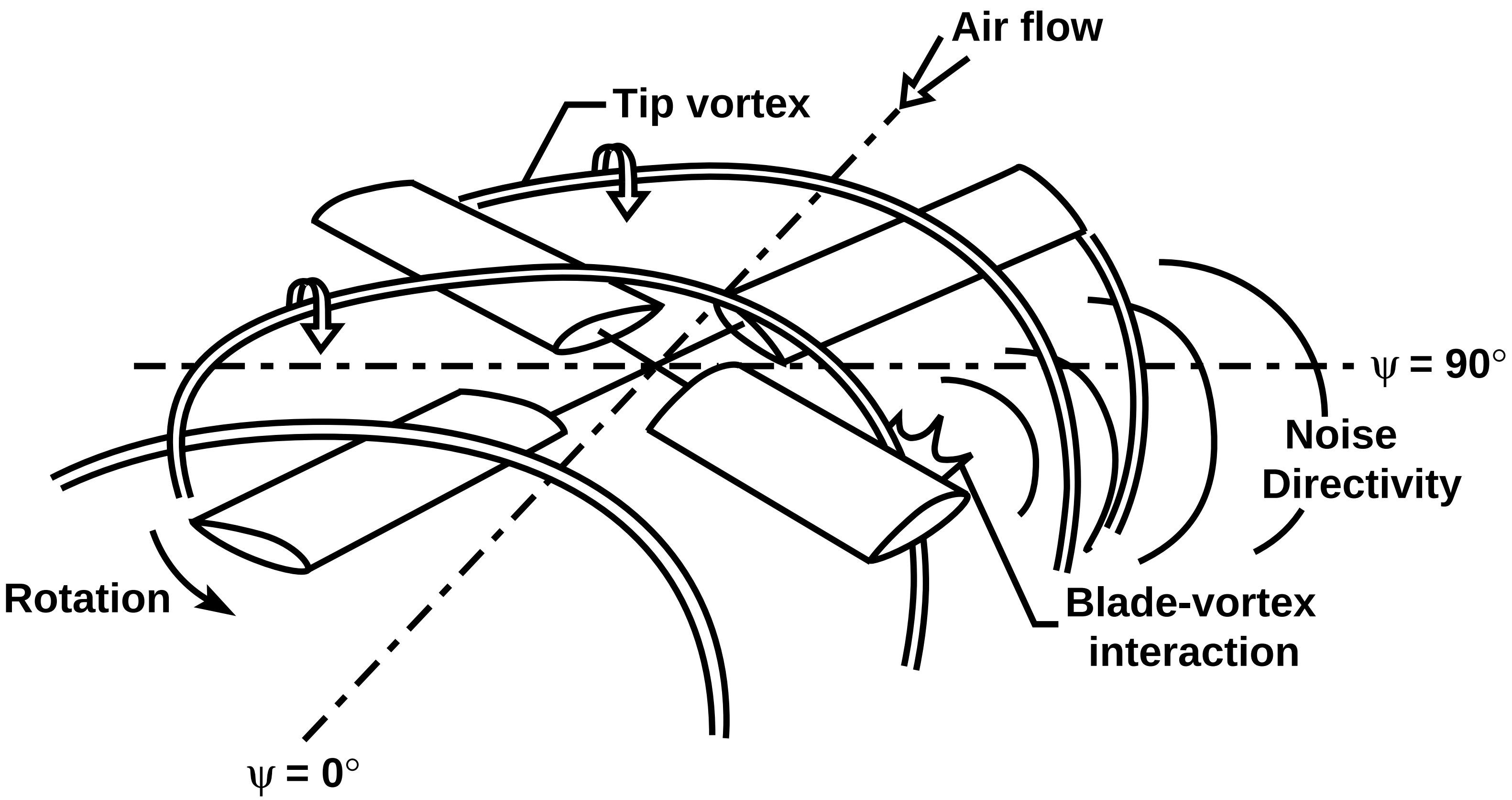
ref: Brentner et al. 1994



**effect of pitching**

**effect of flapping**

# Blade-Vortex Interaction (BVI)



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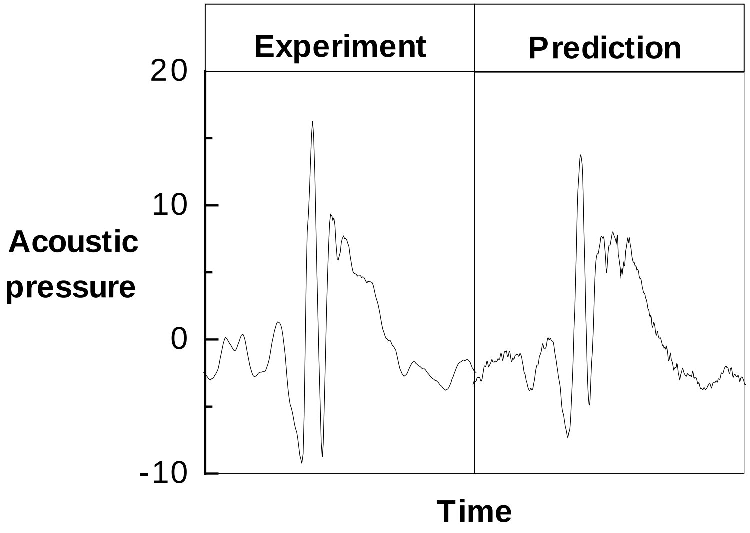
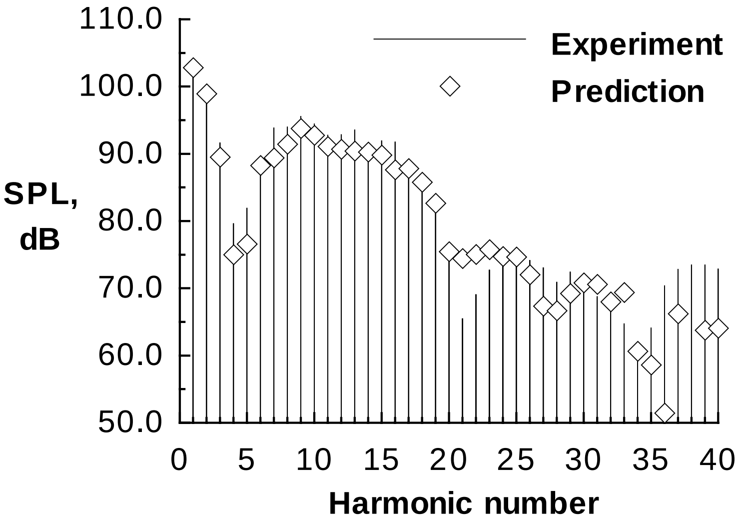
# BVI Noise Prediction: *with measured airloads*

- **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**

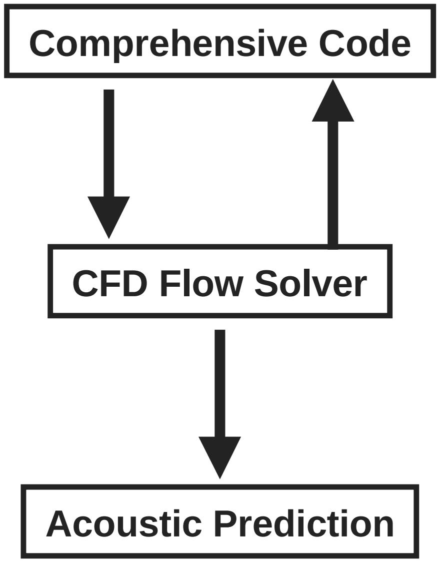
$\mu = 0.152, \quad C_T / \sigma = 0.07,$ decent condition

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

# BVI Noise Prediction: *with calculated airloads*

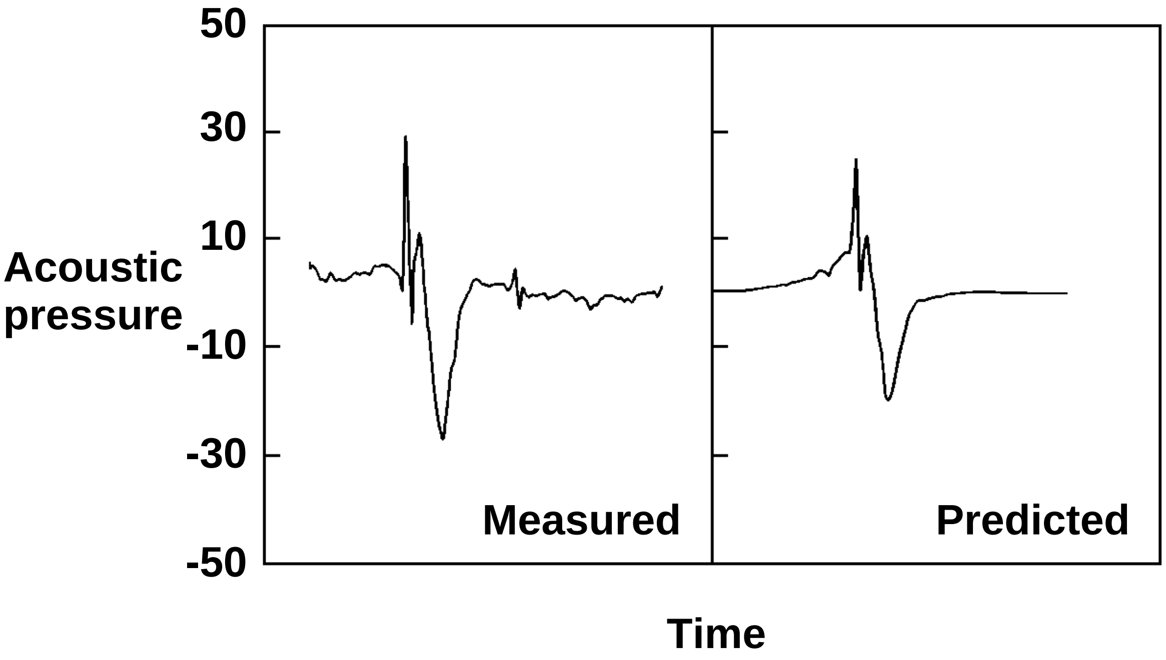
- **Near first principles prediction**
- **Representative of state-of-the-art**

ref: Tadghighi et al. 1990


Comprehensive Code

CFD Flow Solver

Acoustic Prediction



# 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**

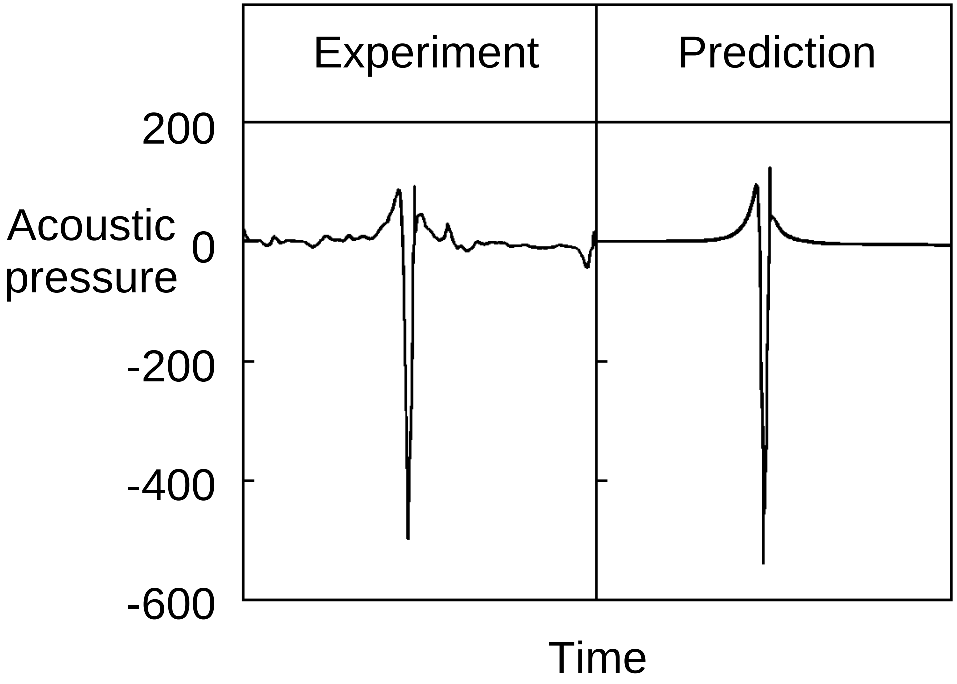
  **Yu, Caradonna, and Schmitz (1978)**
  - **simplified source strength**
  - **far-field assumption / preintegration in *z* direction**
  - **relatively immature flow field calculation**
- **Recent efforts**
  - **Prieur (1986) - frequency domain, hover only**
  - **Schultz and Splettstoesser (1987) - followed Yu et al.**
  - **Farassat (1987-1991) - shock noise theory**
  - **Schultz et al (1994) - approx. source strength, both volume integration and preintegration**
  - **Ianniello and De Bernardis (1994) - full volume integration**
- **<u>NO readily available quadrupole prediction code in U.S.</u>**

*rotorcraft

# 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**



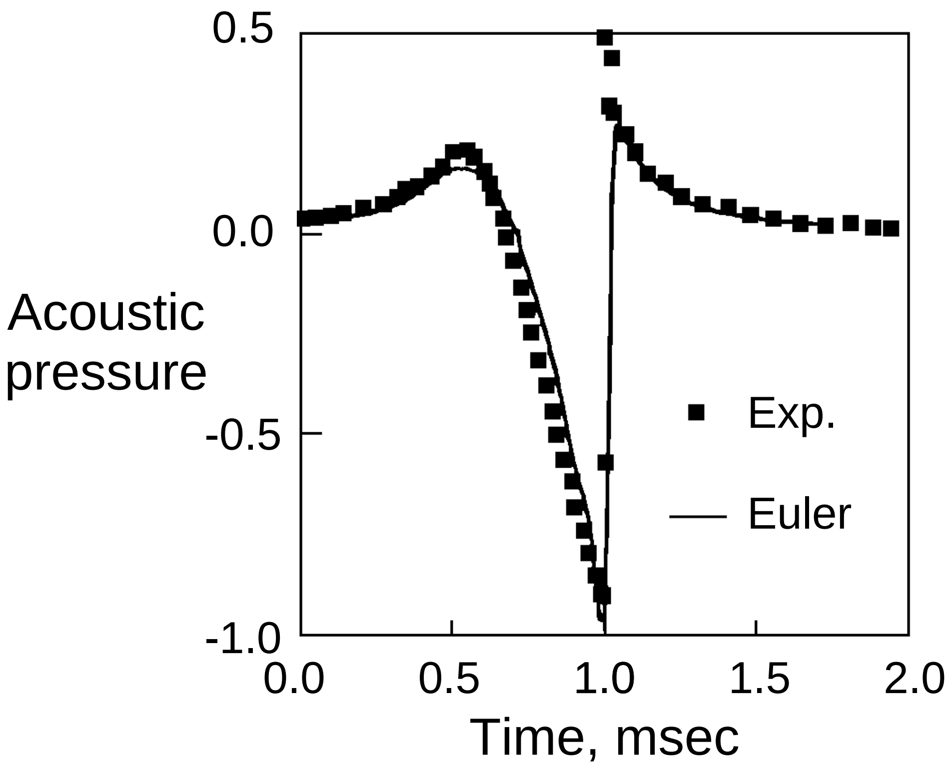
ref: Schultz and Splettstoesser 1987

# High-Speed Impulsive Noise

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

Ref: Baeder 1991

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



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# Why Use the Acoustic Analogy?

- FW–H source contributions linearly superimpose

$$p'(\vec{x},t) = p'_t(\vec{x},t) + p'_\ell(\vec{x},t) + p'_Q(\vec{x},t)$$

  - ➤ 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:** $$\Box^2 p'(\vec{x},t) = \frac{\partial}{\partial t}\left[\rho_o v_n \delta(f)\right] - \frac{\partial}{\partial x_i}\left[\ell_i \delta(f)\right] + \frac{\partial^2}{\partial x_i \partial x_j}\left[T_{ij} H(f)\right]$$

- **Source terms linearly superimpose**

  $$p'(\vec{x},t) = p'_t(\vec{x},t) + p'_\ell(\vec{x},t) + p'_Q(\vec{x},t)$$

- **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**

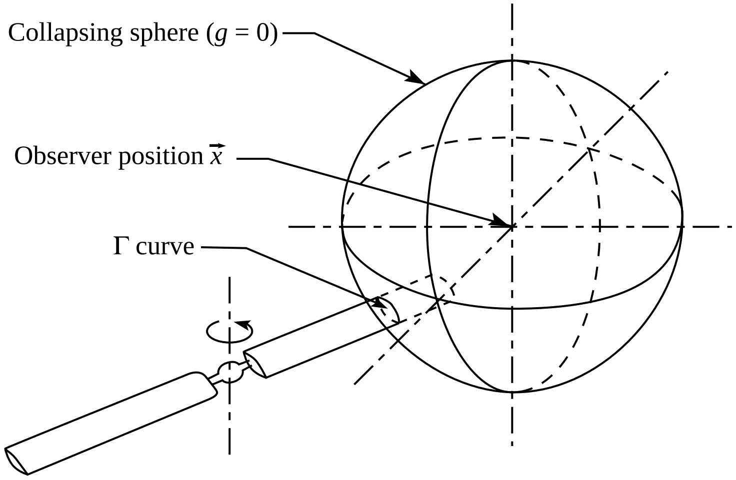
# Collapsing Sphere Formulation

- **Equation**

$$4\pi p'_Q(\vec{x},t) = \frac{1}{c}\frac{\partial^2}{\partial t^2}\int_{-\infty}^{t}\int_{f>0}\frac{T_{rr}}{r}\,d\Omega d\tau$$

$$+\frac{\partial}{\partial t}\int_{-\infty}^{t}\int_{f>0}\frac{3T_{rr}-T_{ii}}{r^2}\,d\Omega d\tau$$

$$+c\int_{-\infty}^{t}\int_{f>0}\frac{3T_{rr}-T_{ii}}{r^3}\,d\Omega d\tau$$



- **Interpretation**
  - ➤ ***f*>0** **- everywhere outside of blade surface**
  - ➤ ***d*Ω** **- element of collapsing sphere surface**

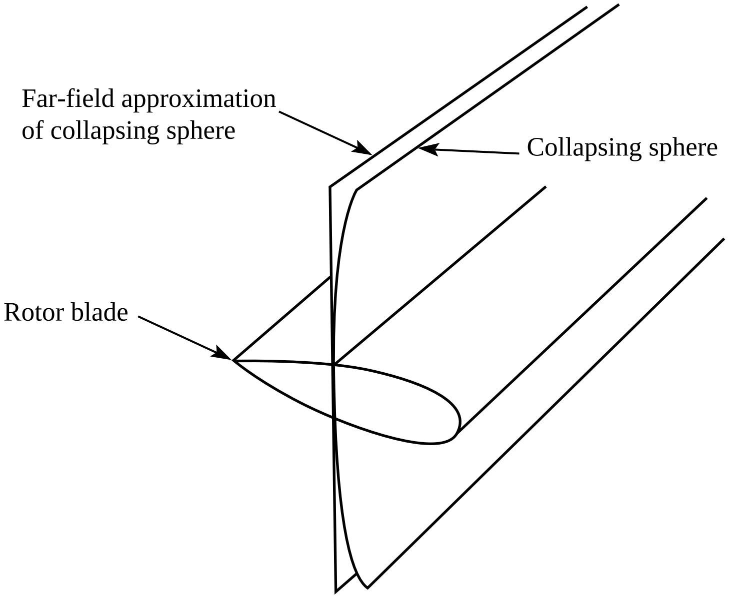
$$T_{ij} = \rho u_i u_j + (p' - \rho' c^2)\delta_{ij}$$

# Far-Field Approximation

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

- **Define new tensor**

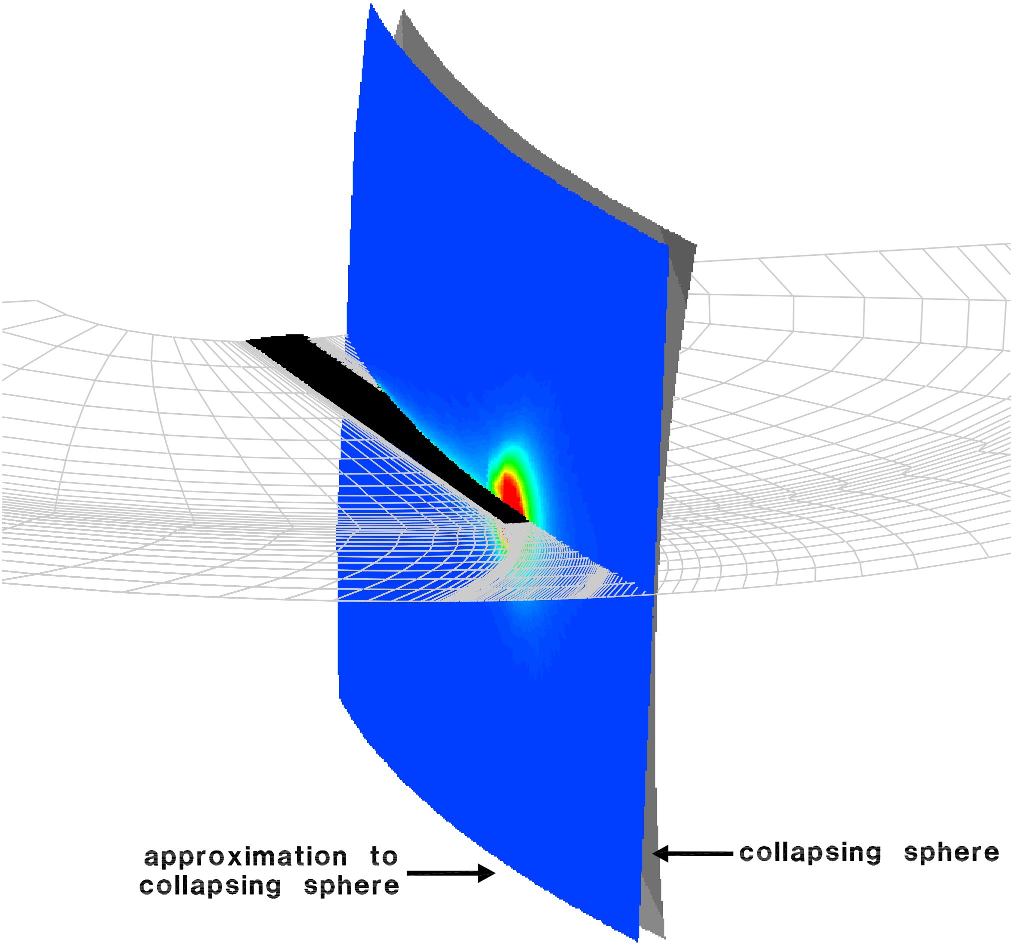
$$Q_{ij} = \int_{-\infty}^{\infty} T_{ij}\,dz$$



- **Collapsing sphere approximated as a cylinder**
- **Integration in *z* is independent of source time**

# Far-Field Approximation

Contours of
quadrupole
source strength



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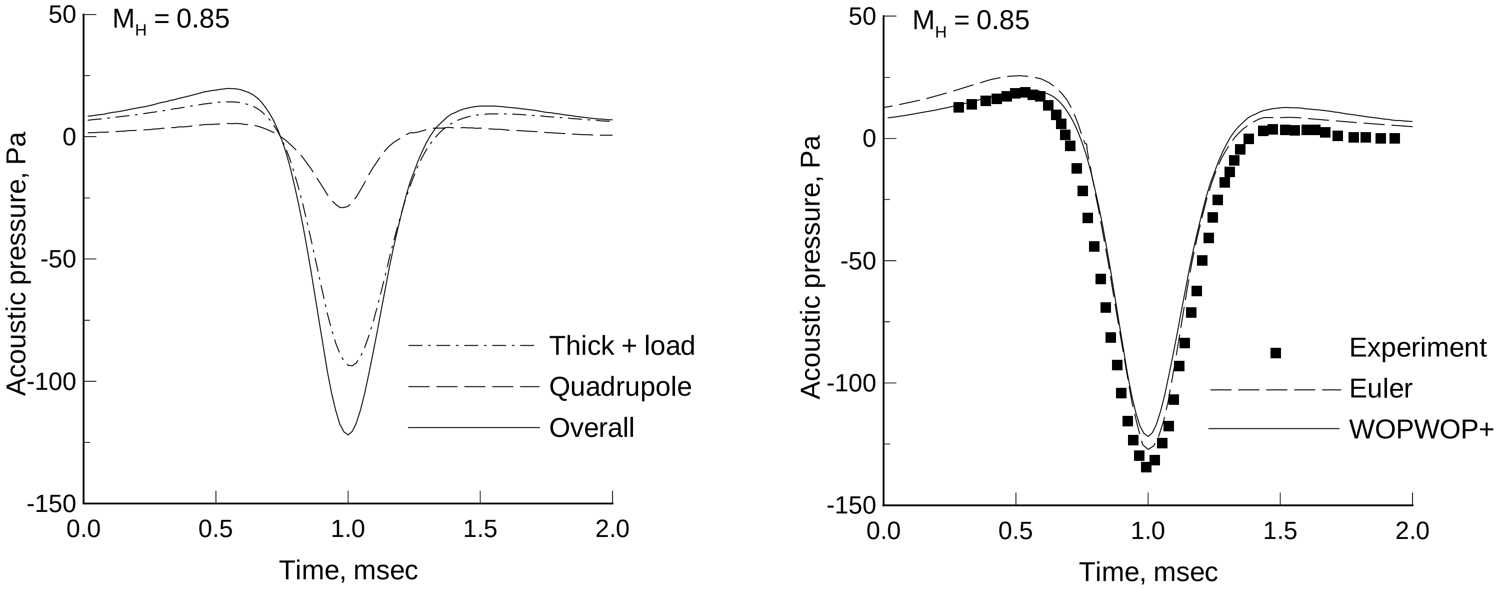
# WOPWOP+ Validation

- 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

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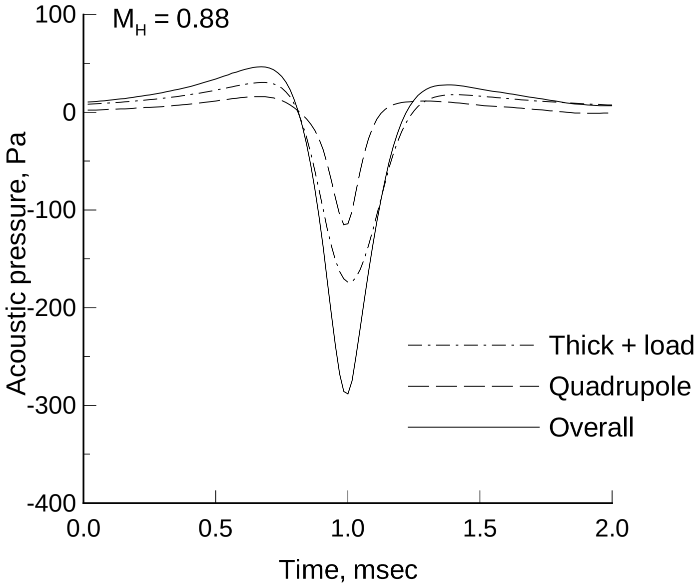
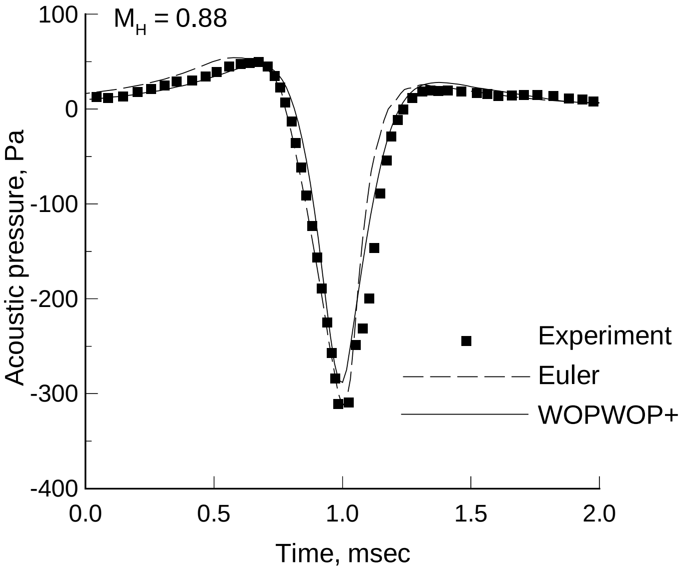
# UH-1H Model Rotor Comparison

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

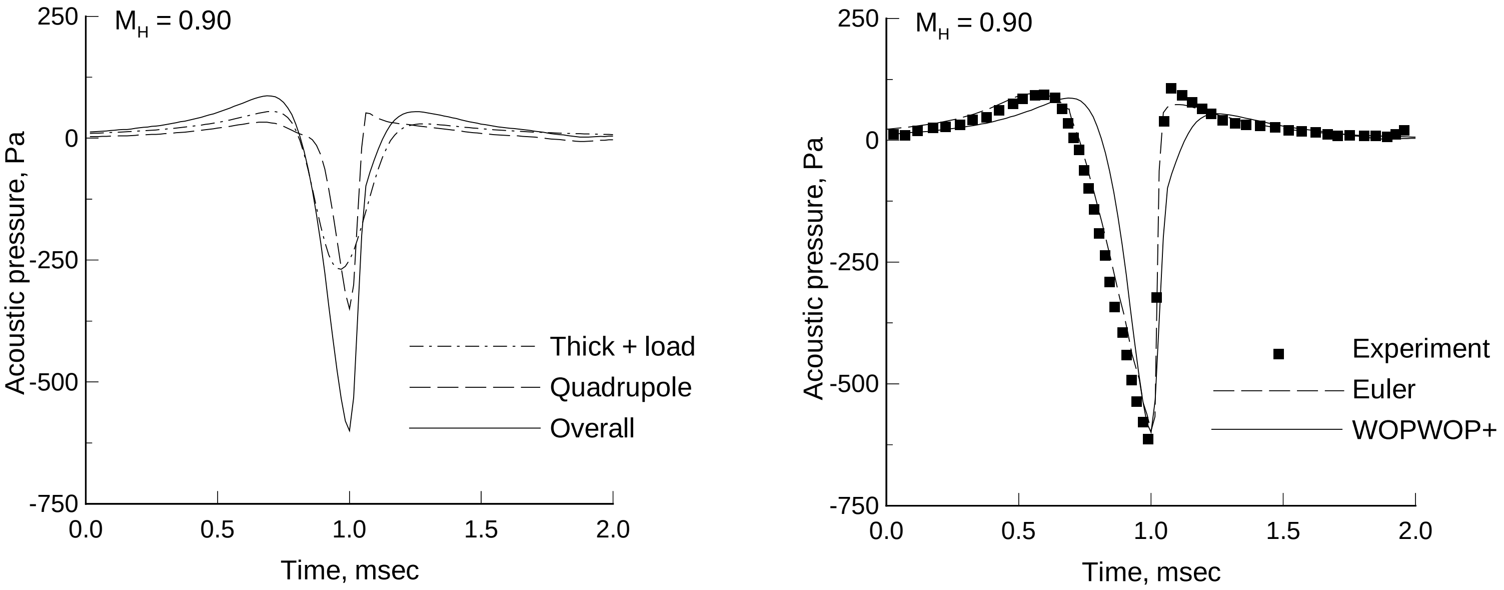




- Good agreement with Euler calculation and experiment

# UH-1H Model Rotor Comparison

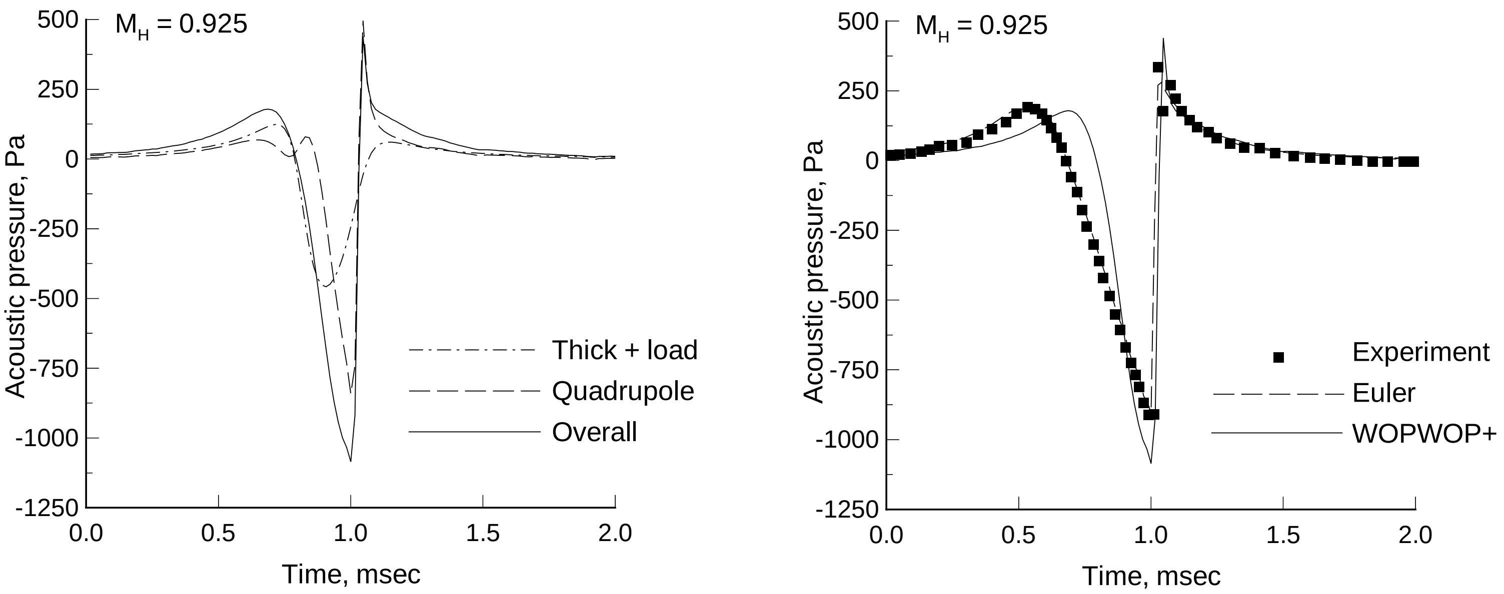
- Observer inplane at 3.09 R from rotor hub, $M_H = .90$



- Quadrupole contribution is larger than thickness and loading and has steepened
- Retarded-time formulation does not allow all contributing panels to be included

# UH-1H Model Rotor Comparison

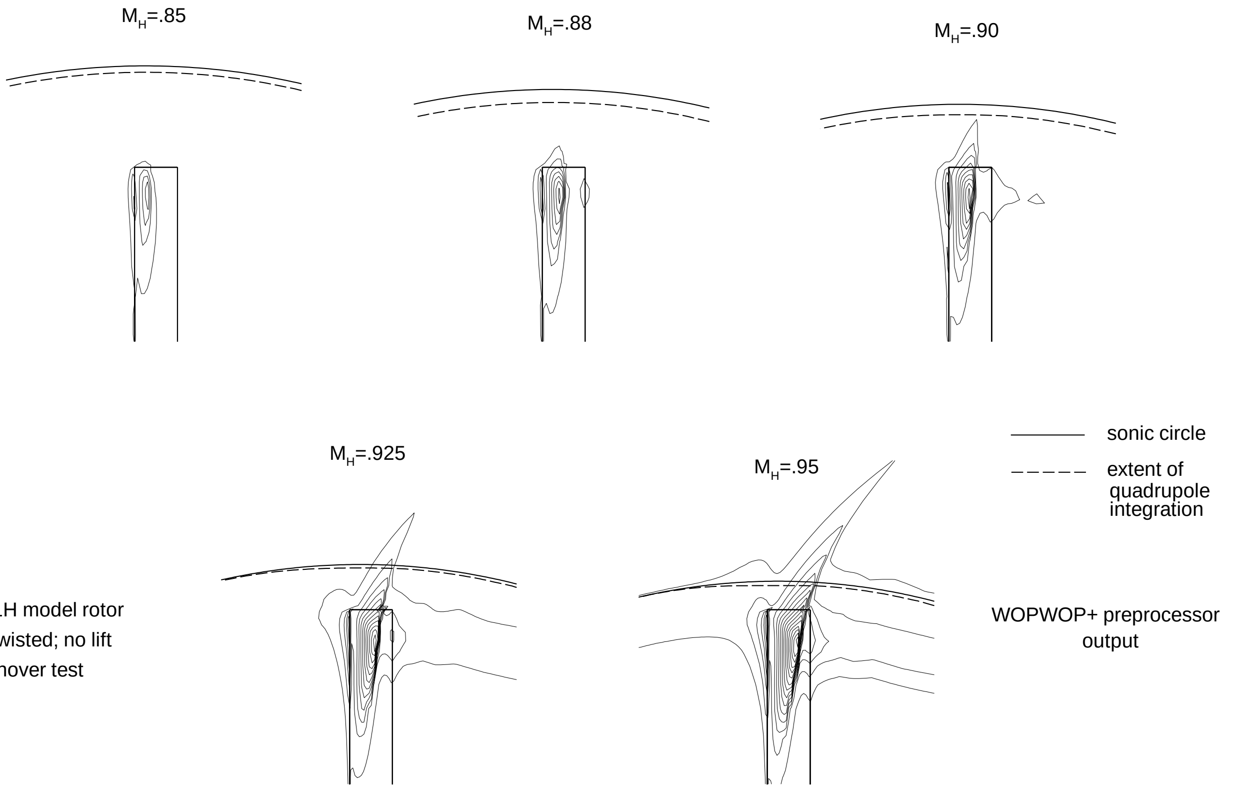
- **Observer inplane at 3.09 R from rotor hub, $M_H$ = .925**



- **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 $Q_{ii}$**



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

WOPWOP+ preprocessor
output

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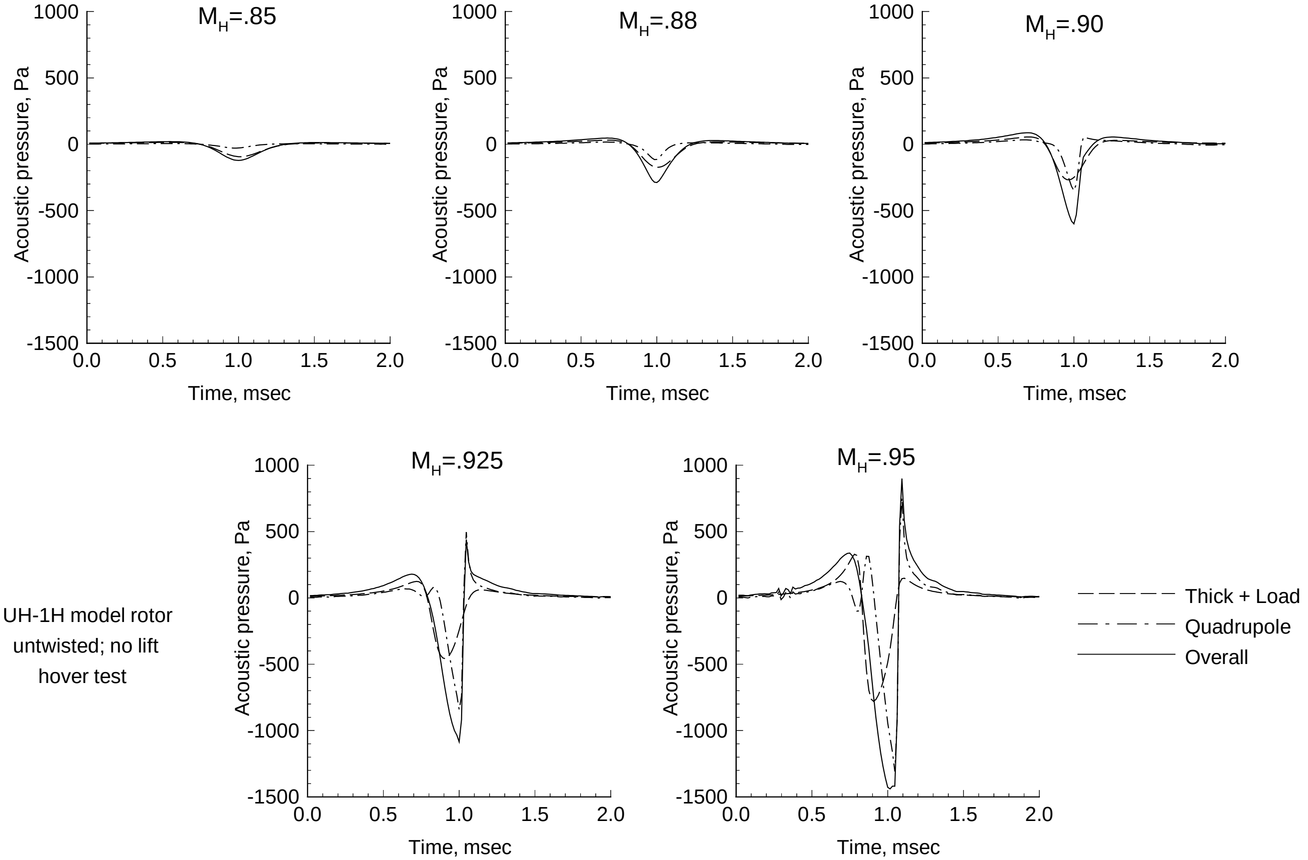
# UH-1H Model Rotor Noise

- **Components of acoustic pressure**



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

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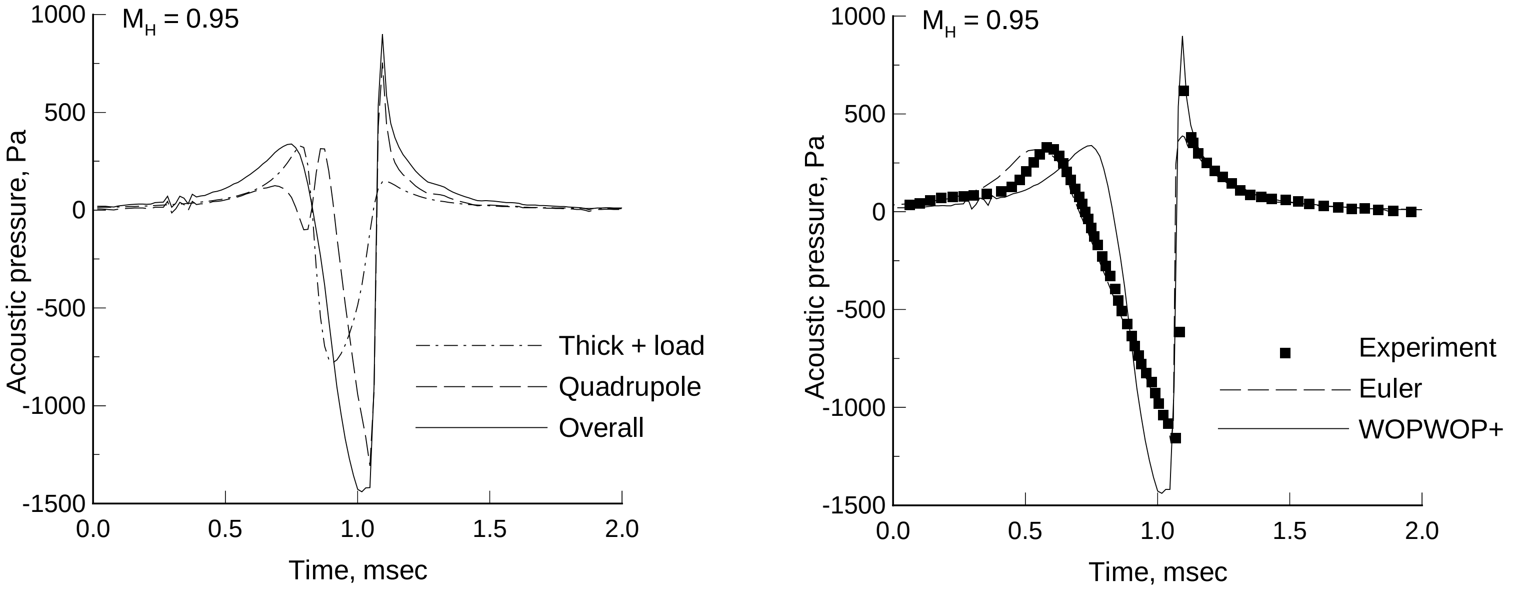
# UH-1H Model Rotor Comparison

- 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**

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

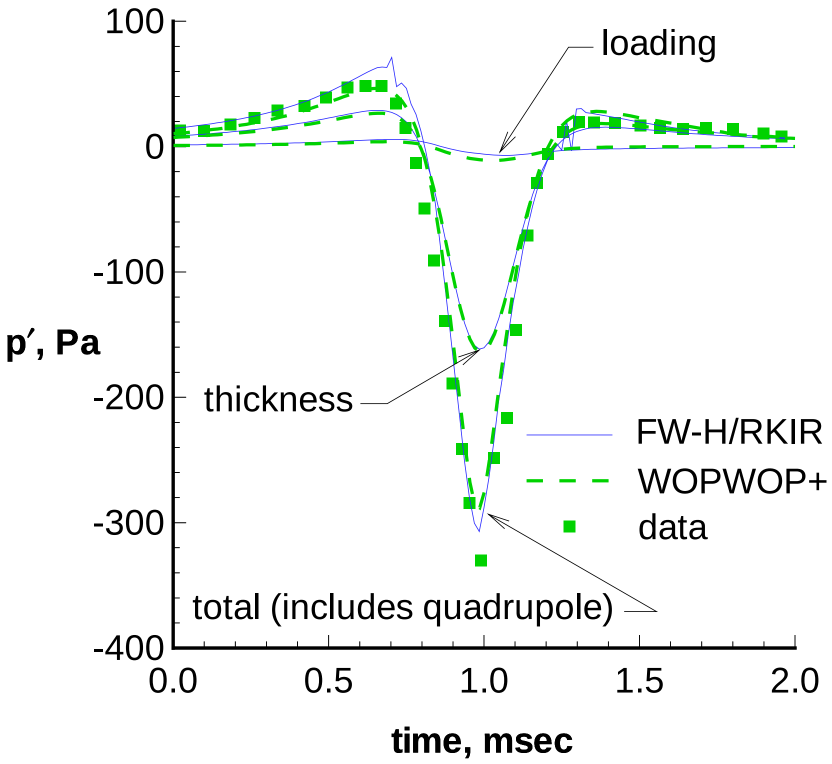
$$\frac{\partial f}{\partial t} = -v_n$$

$$\frac{\partial f}{\partial x_i} = \hat{n}_i$$

- **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

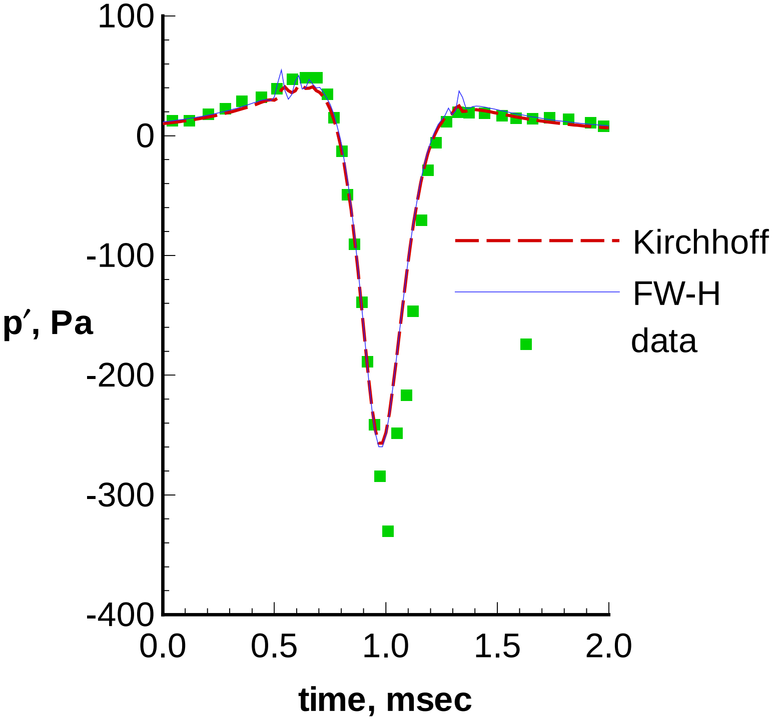
- Manipulate FW–H source terms into form of Kirchhoff source terms (inviscid fluid)

$$\Box^2 p'(\vec{x},t) = Q_{kir} + \frac{\bar{\partial}^2}{\partial x_i \partial x_j}\left[T_{ij} H(f)\right]$$
$$- \frac{\partial}{\partial x_j}\left[\rho u_i u_j\right]\hat{n}_i \delta(f) - \frac{\partial}{\partial x_j}\left[\rho u_i u_n \delta(f)\right]$$
$$+ \frac{\partial}{\partial t}\left[p' - c^2\rho'\right]\frac{M_n}{c}\delta(f) + \frac{\partial}{\partial t}\left[\left(p' - c^2\rho'\right)\frac{M_n}{c}\delta(f)\right]$$

- Extra source terms are 2nd order in perturbations quantities
- FW–H and Kirchhoff source terms
  - equivalent in linear region $(p' \approx c^2 \rho' \quad u_i << 1)$
  - <u>NOT</u> 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**



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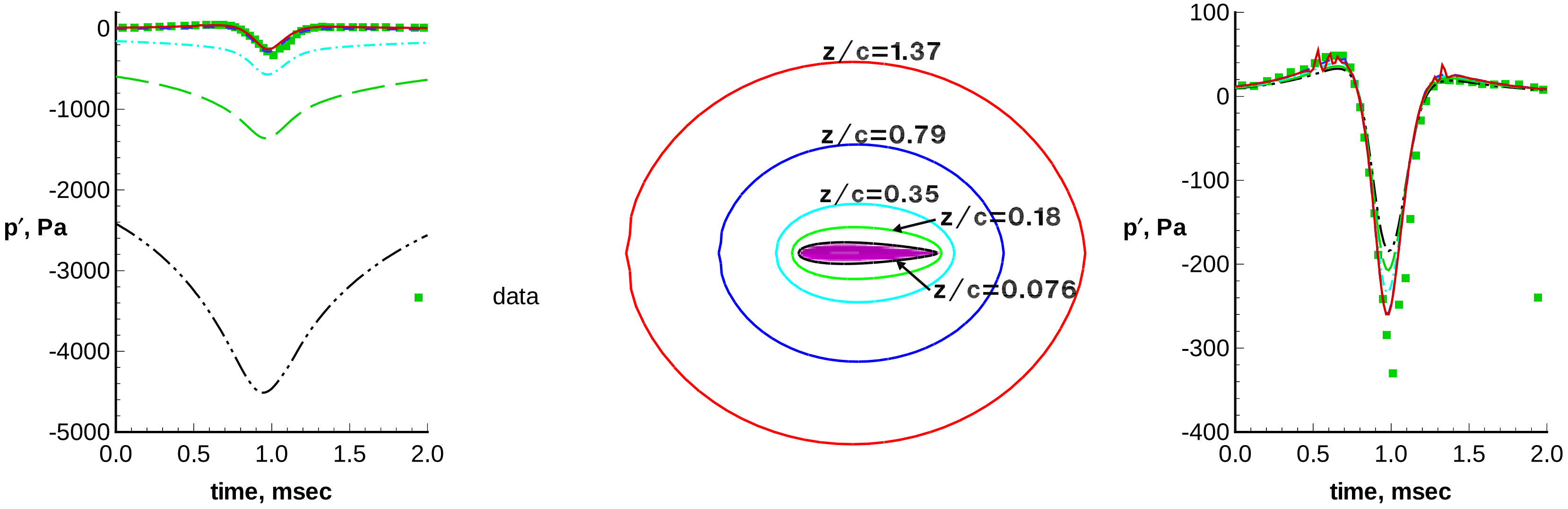
# Numerical Comparison:
# Sensitivity to Surface Placement

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

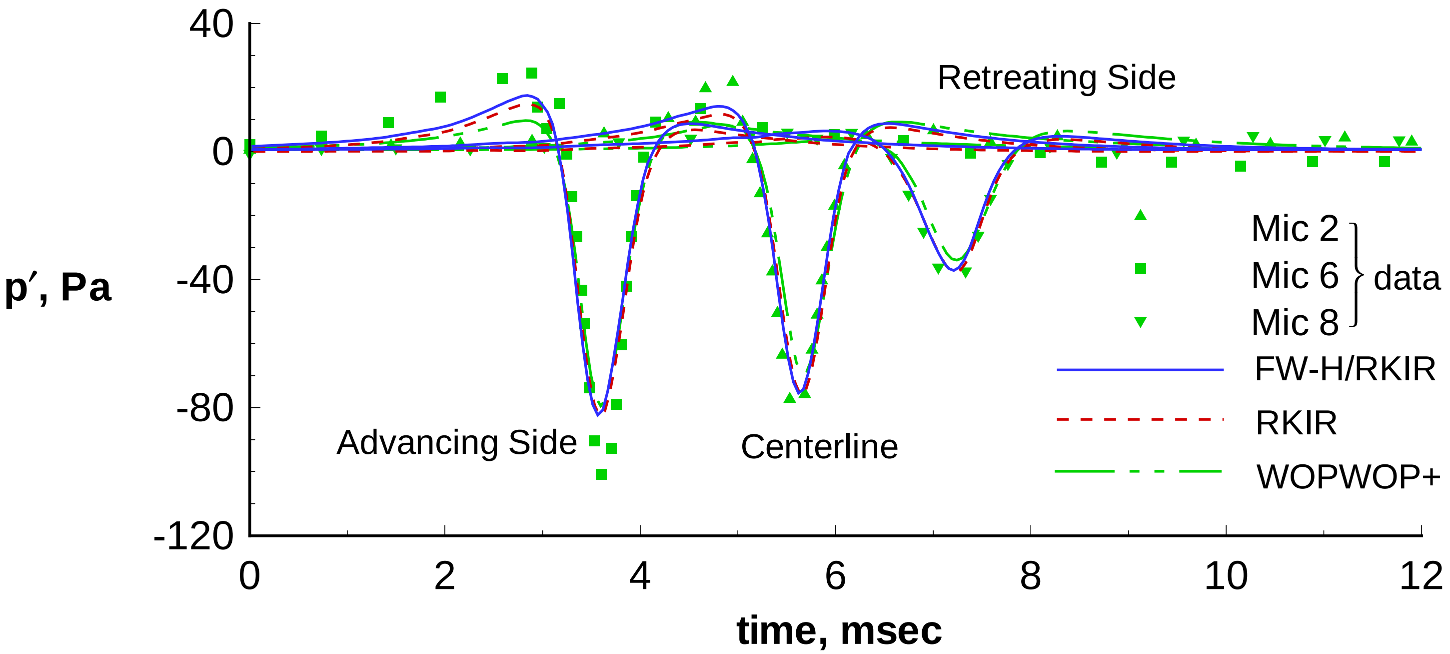


Kirchhoff

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

# 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