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

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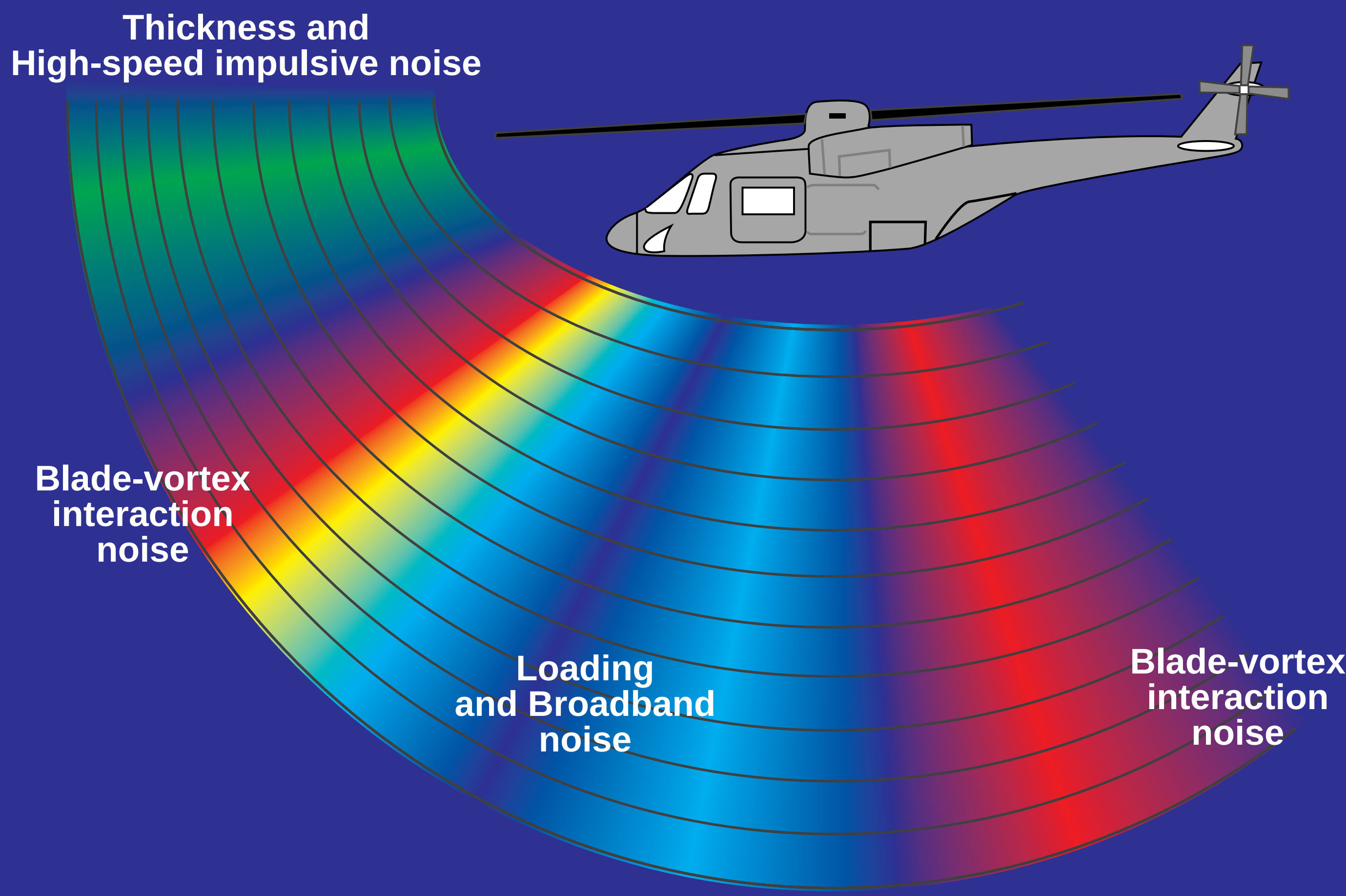
Introduction

- 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



K. S. Brentner

Historical Perspective

History of Helicopter Noise Prediction

Propeller noise theory developed (steady loading, thickness)

Importance of unsteady loading recognized

Rotor noise theory development

Helicopter rotor noise code development

– excellent validation data available
– large increase in computation power

- 1940 -
- 1950 -
- 1960 -
- 1970 -
- 1980 -
- 1990 -
- 2000 -

Helicopter rotor noise mechanisms proposed

Ffowcs Williams–Hawkings equation

– computer power limited
– inadequate blade loading available

$(NR)^2$ program

Kirchhoff formulation /
quadrupole noise prediction /
new application of FW–H equation

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)

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

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**

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

- **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 ∇p on the Kirchhoff surface**

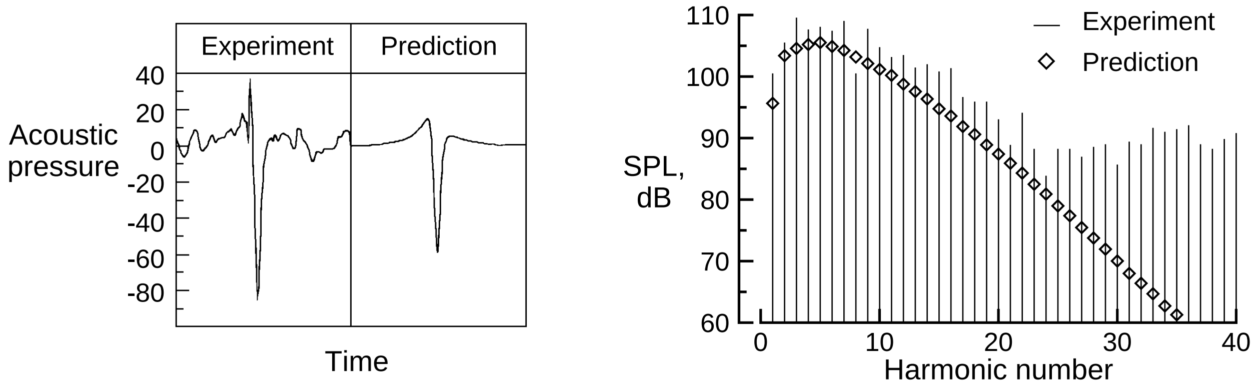
- **FW–H/RKIR (prototype code)**
  - ➤ **based on RKIR (Rotating Kirchhoff code)**
  - ➤ **utilizes Farassat's formulation 1A (FW**
  - ➤ **quadrupole source neglected; could be included**
- **Tiltrotor Aeroacoustic Codes (TRAC)**
  - ➤ **collection of codes to predict the airloads, flow-field, and noise**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

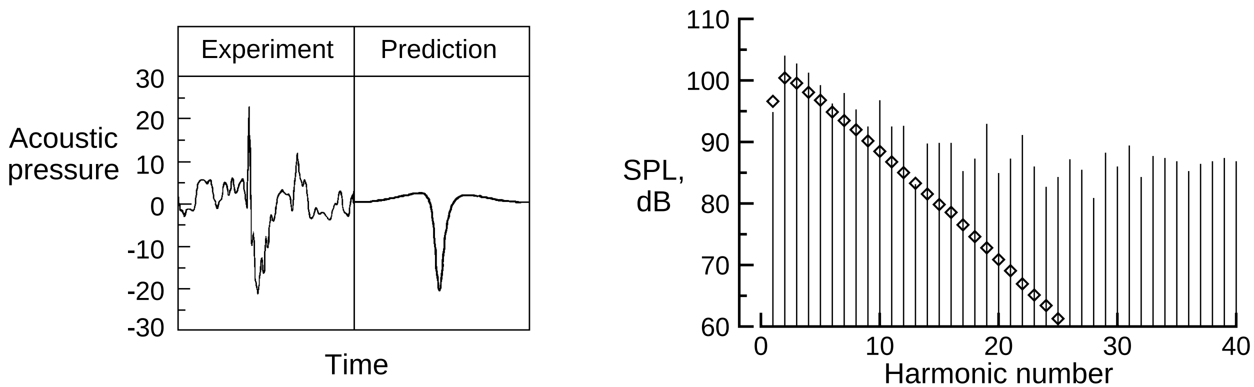
Thickness and Loading Noise

- **Predictions accurately reflect design changes**



a) Rectangular planform

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

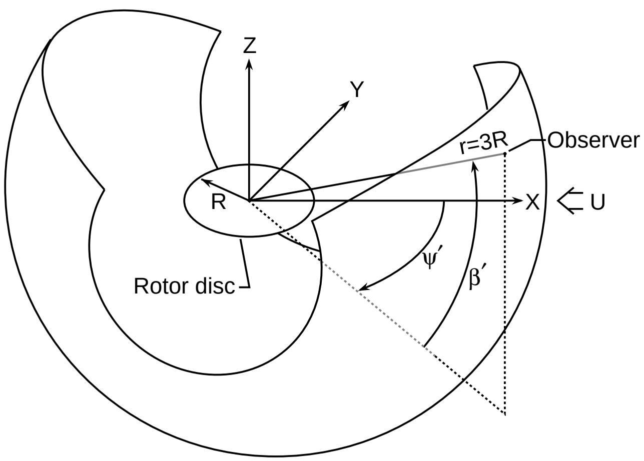


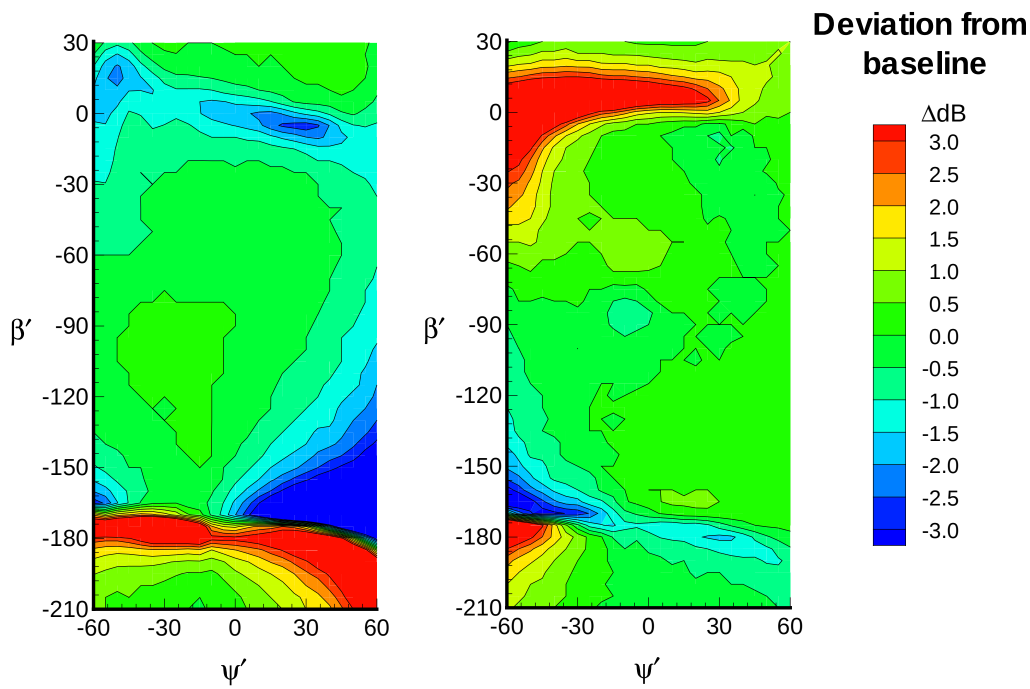
b) Tapered planform

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)

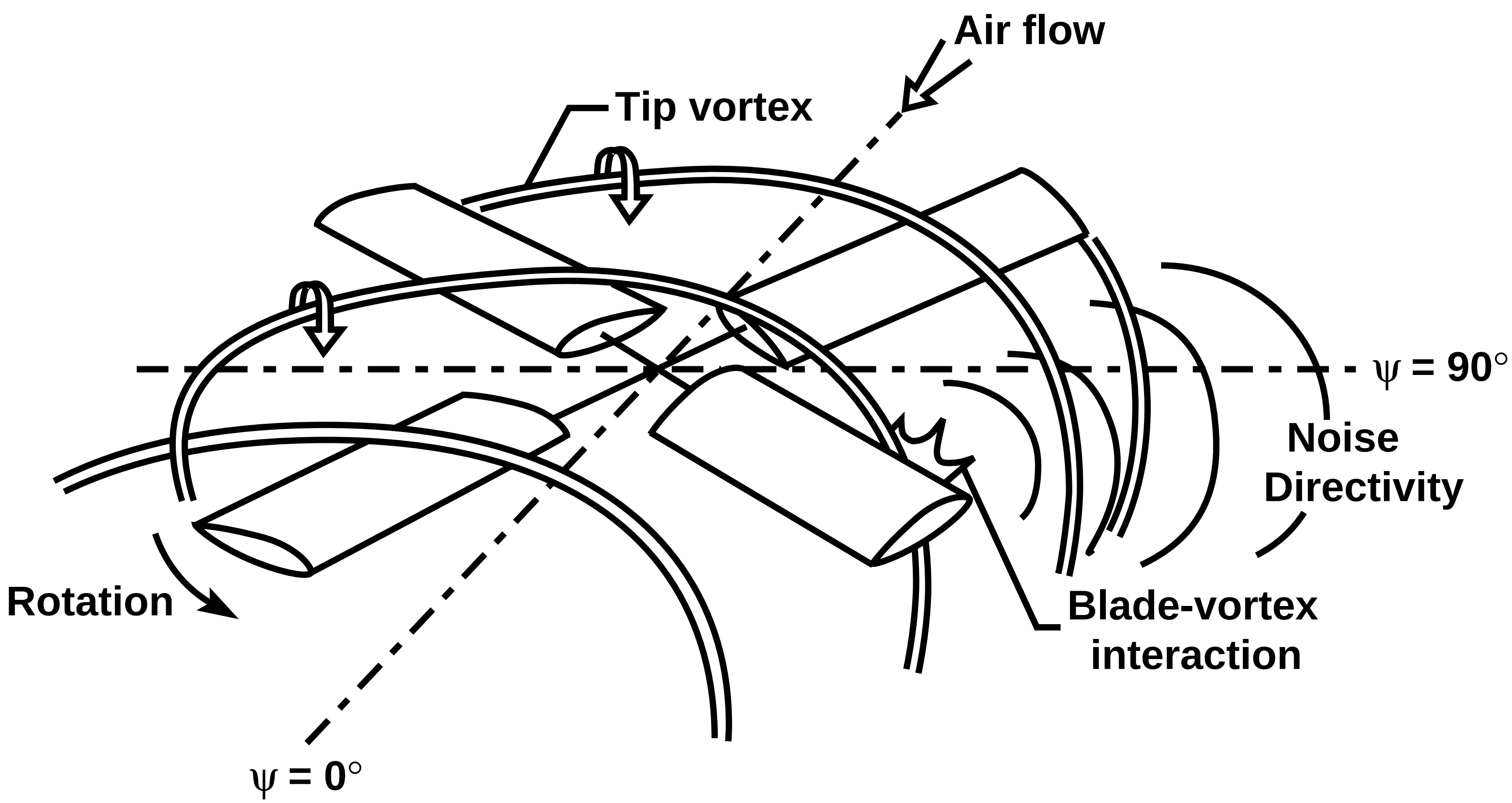




effect of pitching **effect of flapping**

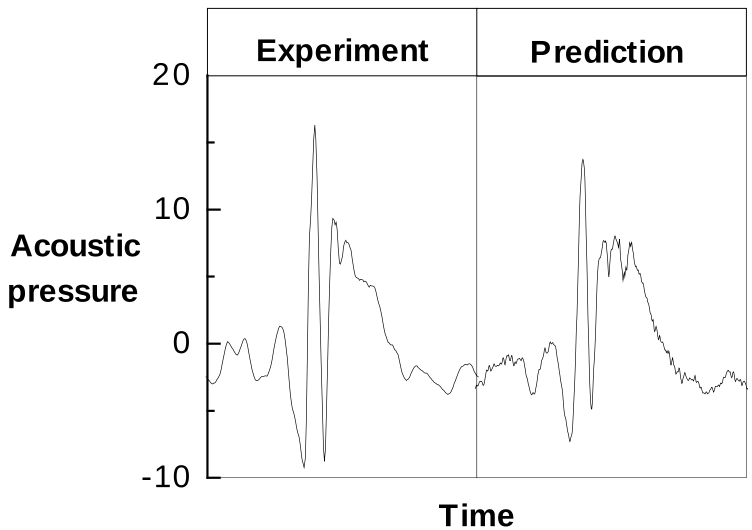
ref: Brentner et al. 1994

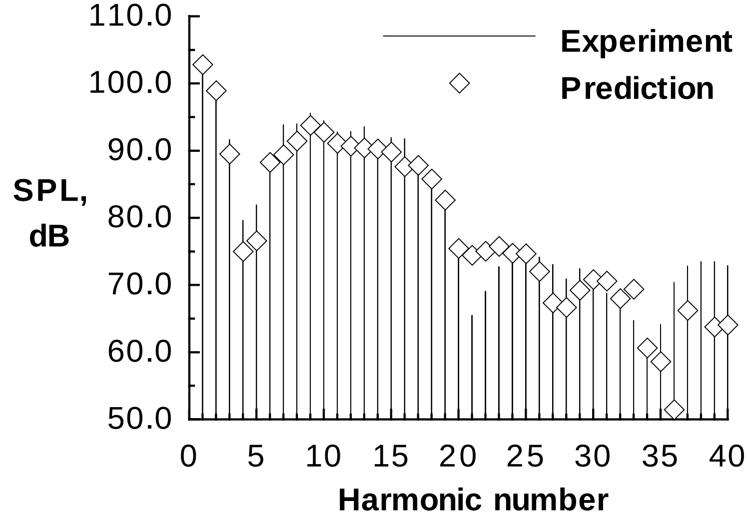
Blade-Vortex Interaction (BVI)



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**

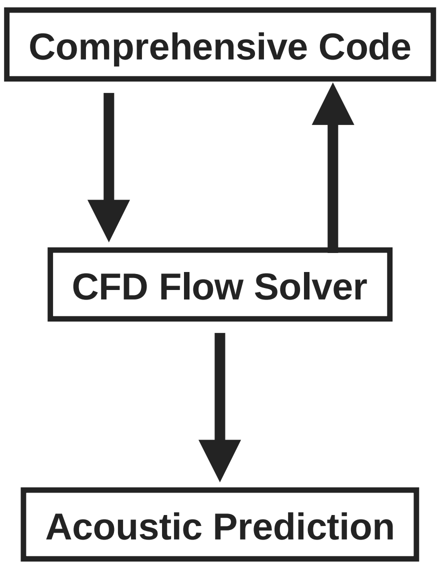
$\mu = 0.152, \quad C_T / \sigma = 0.07,$ decent condition

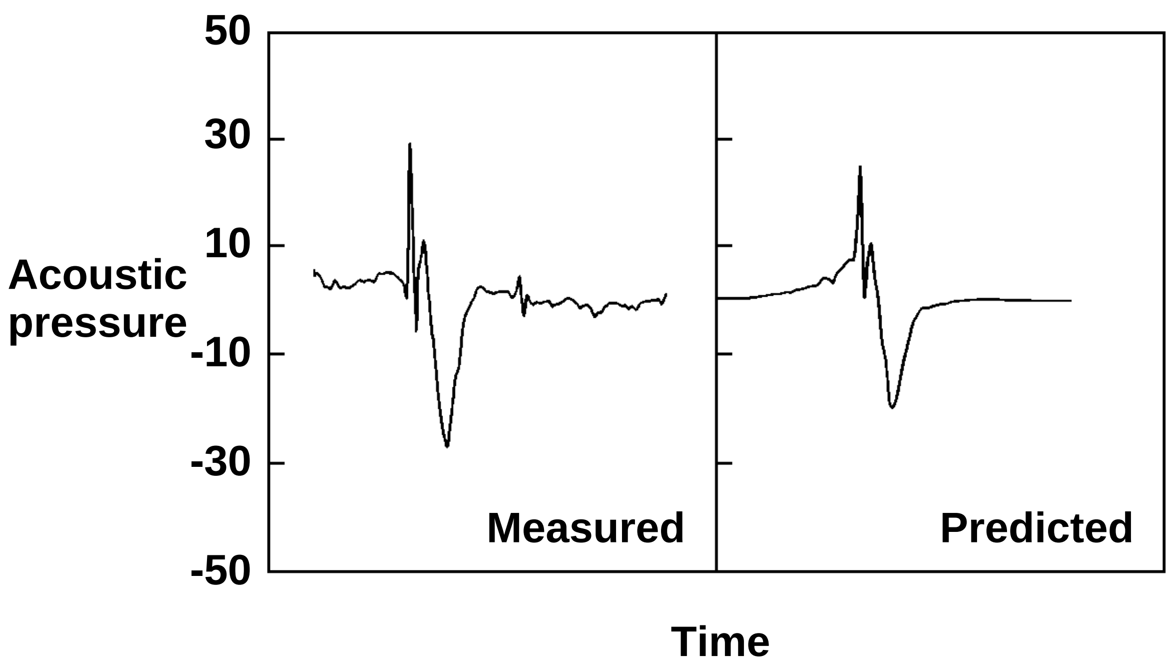
Ref: Brentner et al. 1994, Visintainer et al. 1993

BVI Noise Prediction: *with calculated airloads*

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

ref: Tadghighi et al. 1990





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**

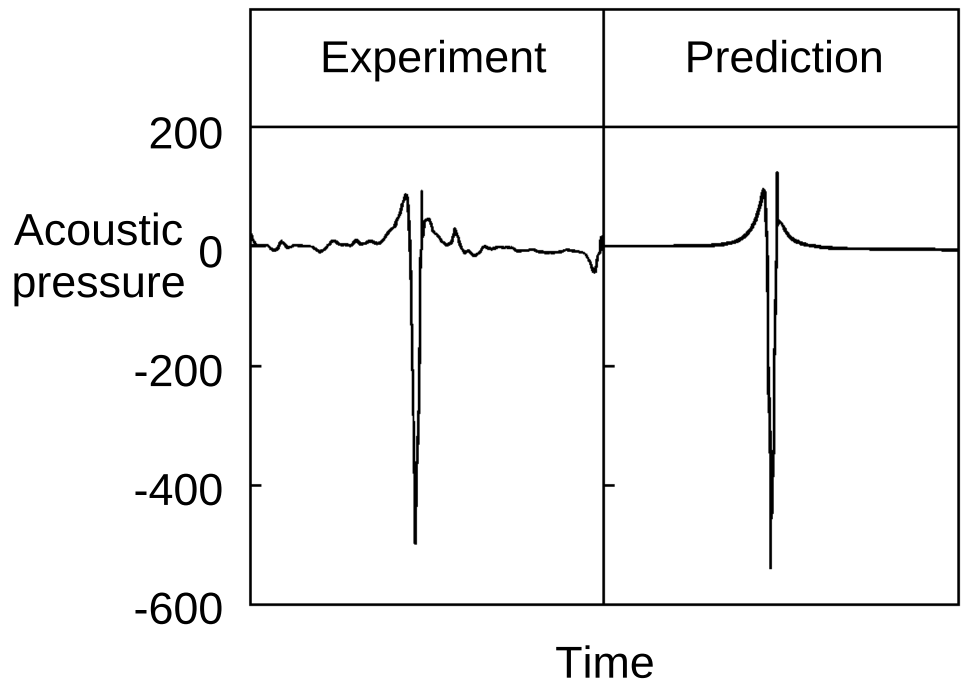
  Yu, Caradonna, and Schmitz (1978)
  - **simplified source strength**
  - **far-field assumption / preintegration in *z* direction**
  - **relatively immature flow field calculation**
- **Recent efforts**
  - **Prieur (1986) - frequency domain, hover only**
  - **Schultz and Splettstoesser (1987) - followed 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



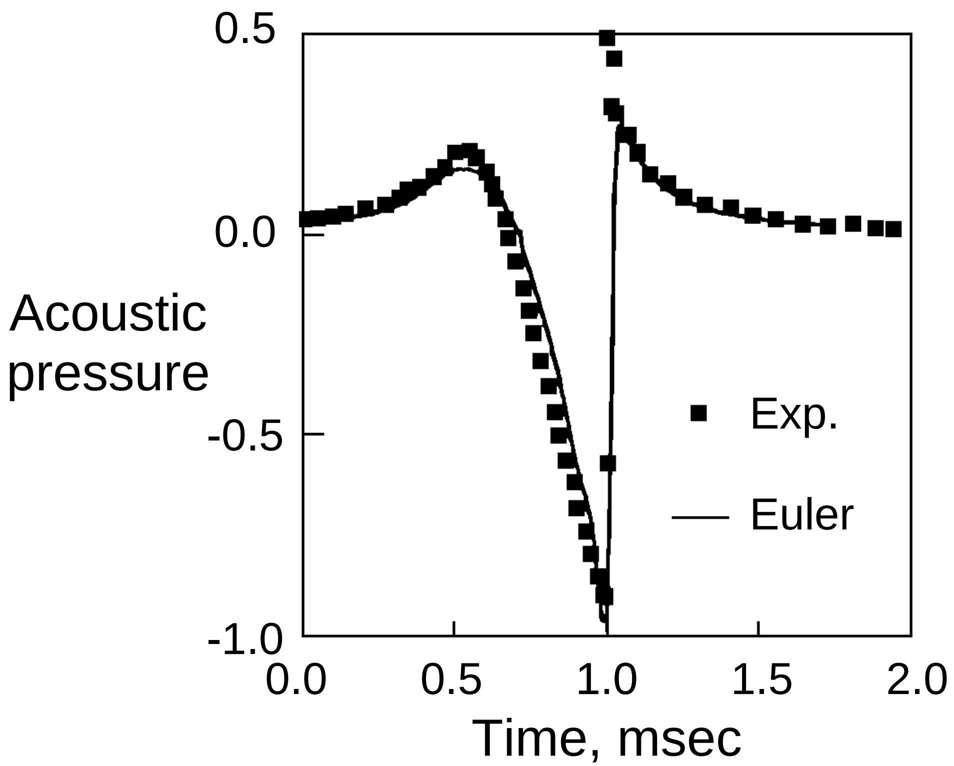
ref: Schultz and Splettstoesser 1987

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



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**

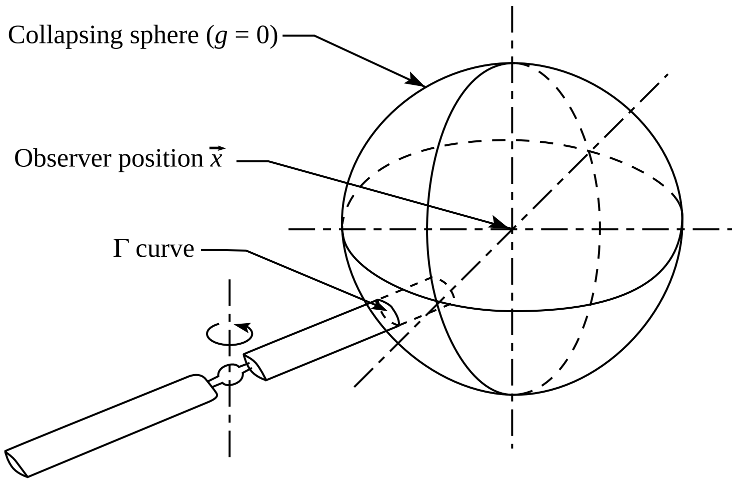
Collapsing Sphere Formulation

■ 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

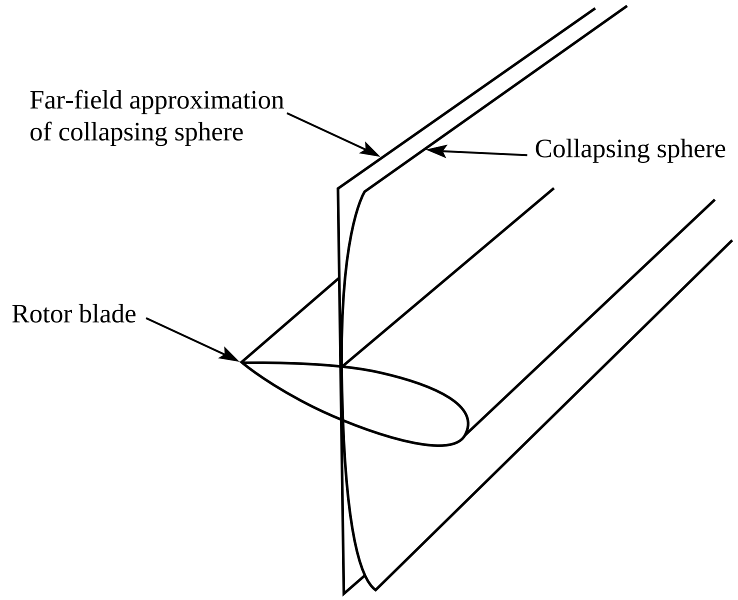
- ➤ ***f*>0** - everywhere outside of blade surface
- ➤ ***dΩ*** - element of collapsing sphere surface

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

Far-Field Approximation

- **Assumptions**
  - ➤ **Far-field observer**
  - ➤ **In-plane observer**
- **Define new tensor**

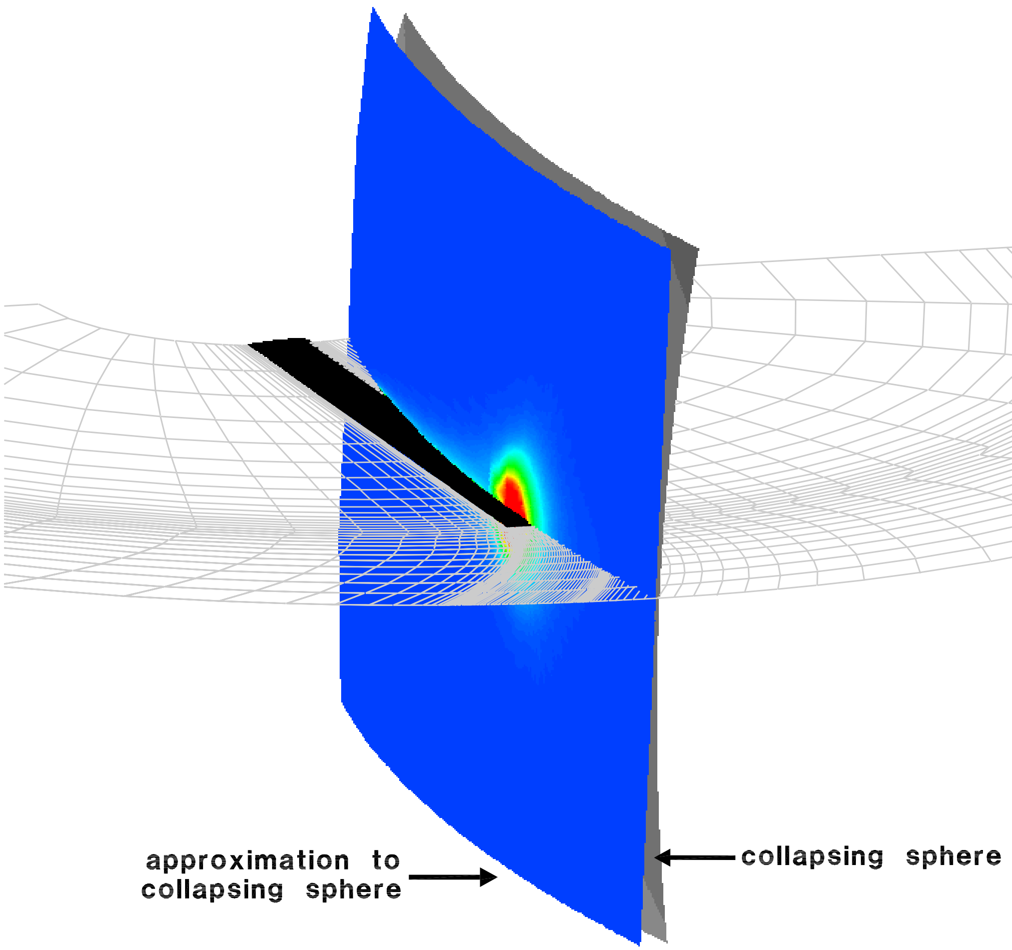
$$Q_{ij} = \int_{-\infty}^{\infty} T_{ij}\,dz$$



- **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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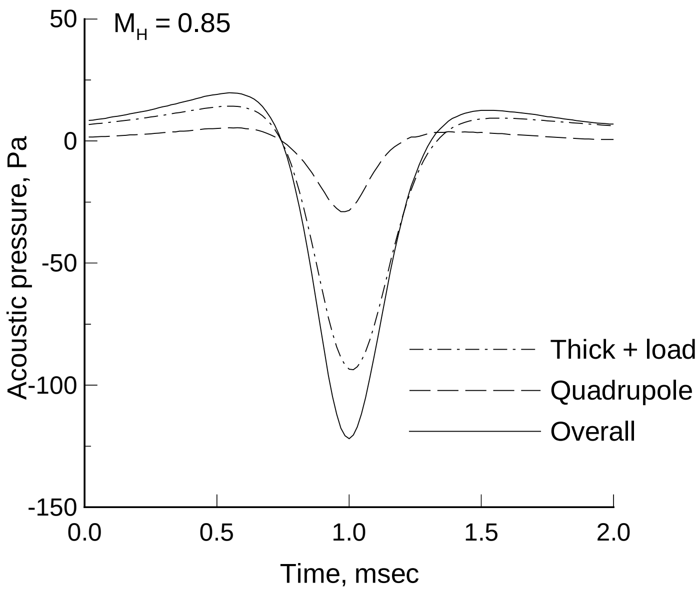
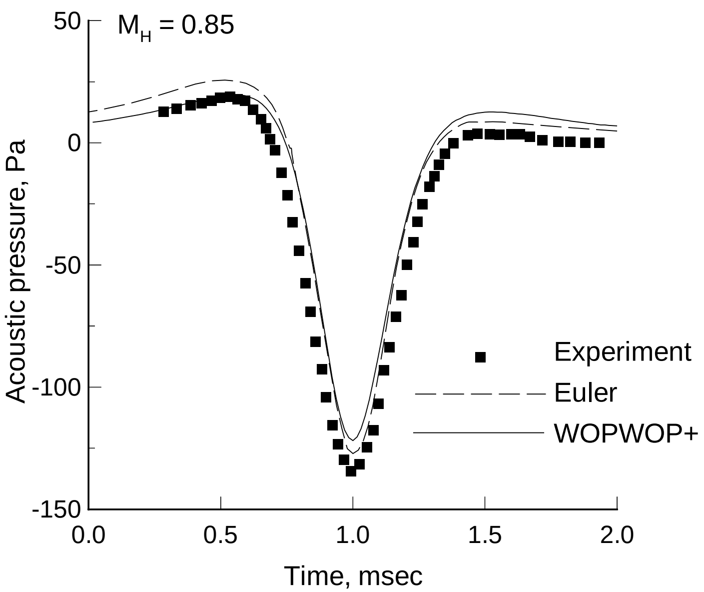
WOPWOP+ Validation

- **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, $M_H = .85$

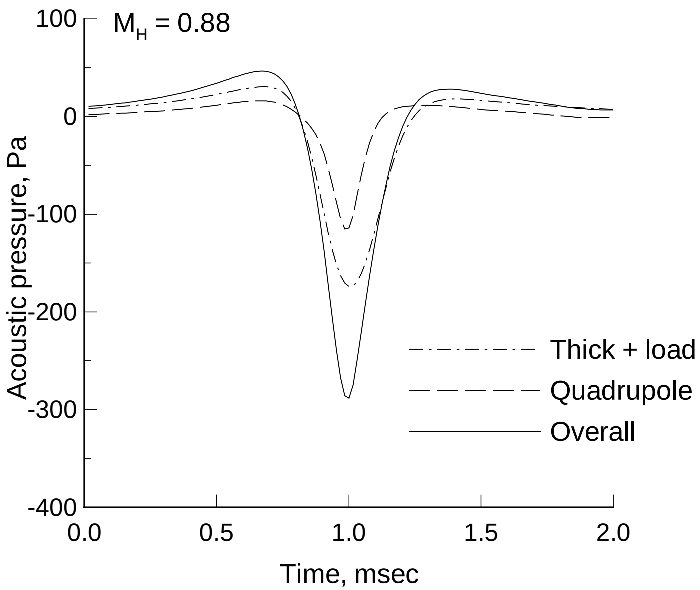


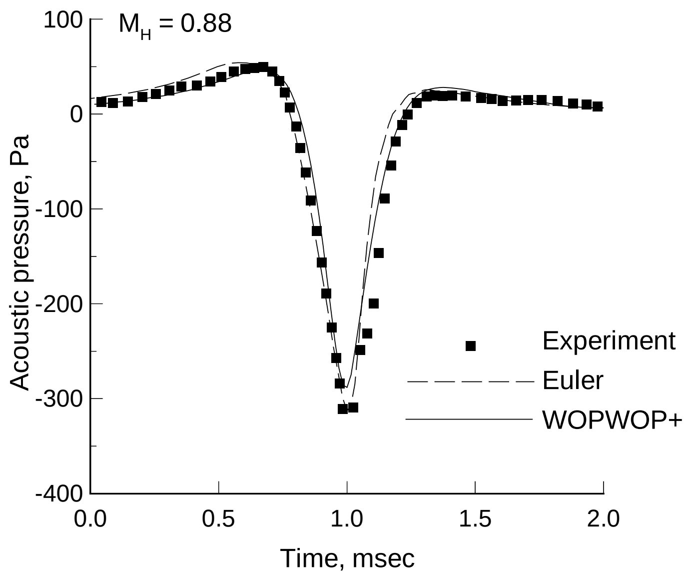


- Quadrupole contribution roughly one-third that of thickness and loading
- Good agreement with Euler calculation and experiment

UH-1H Model Rotor Comparison

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

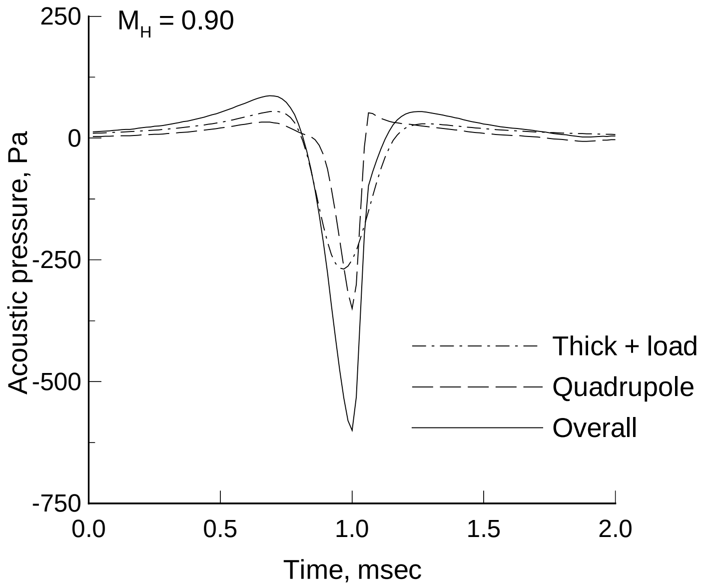


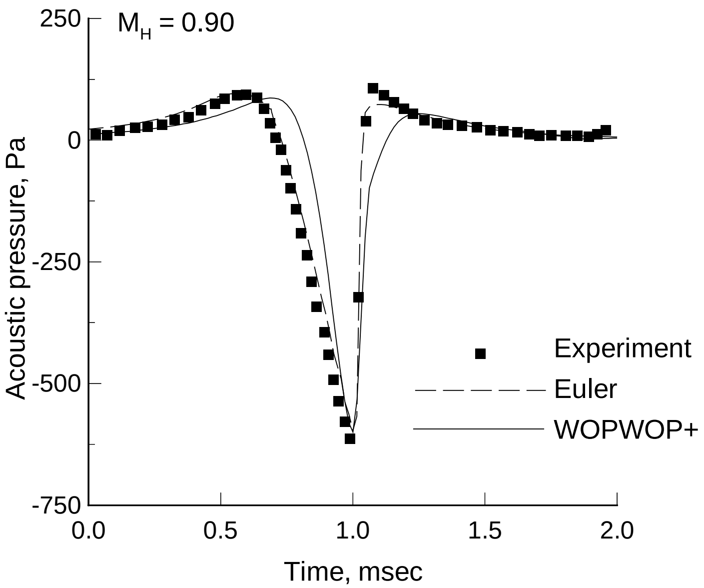


- Good agreement with Euler calculation and experiment

UH-1H Model Rotor Comparison

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

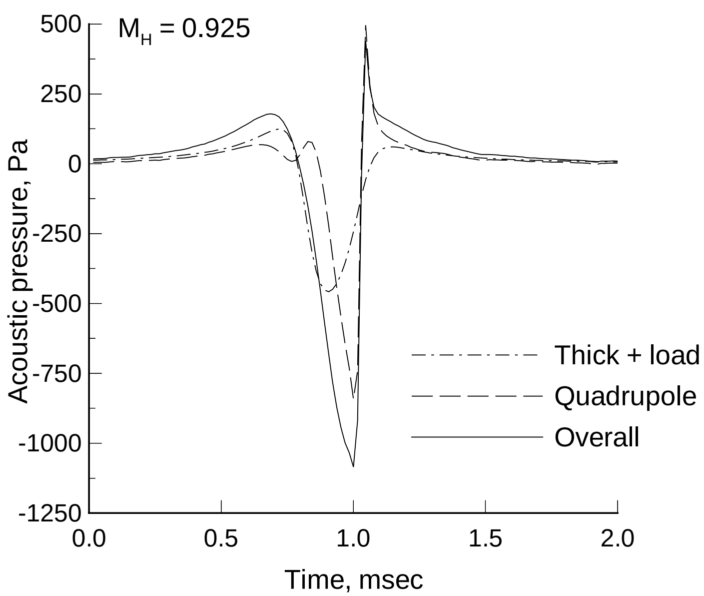


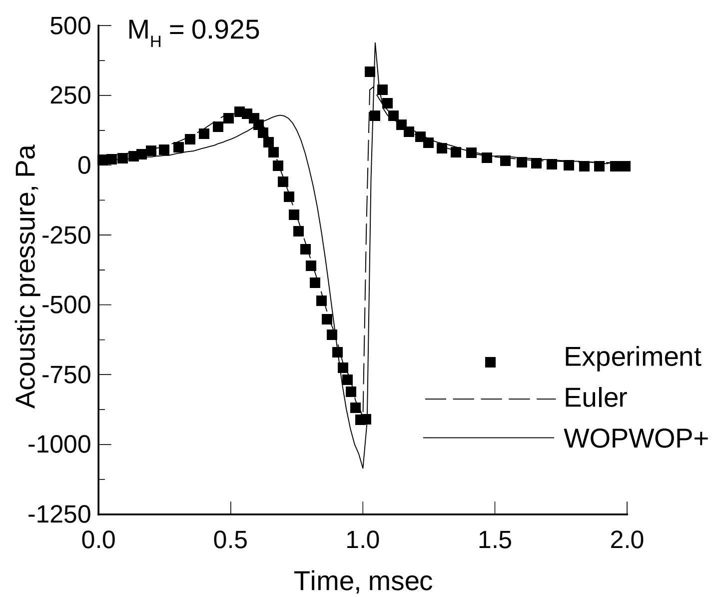


- Quadrupole contribution is larger than thickness and loading and has steepened
- Retarded-time formulation does not allow all contributing panels to be included

UH-1H Model Rotor Comparison

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

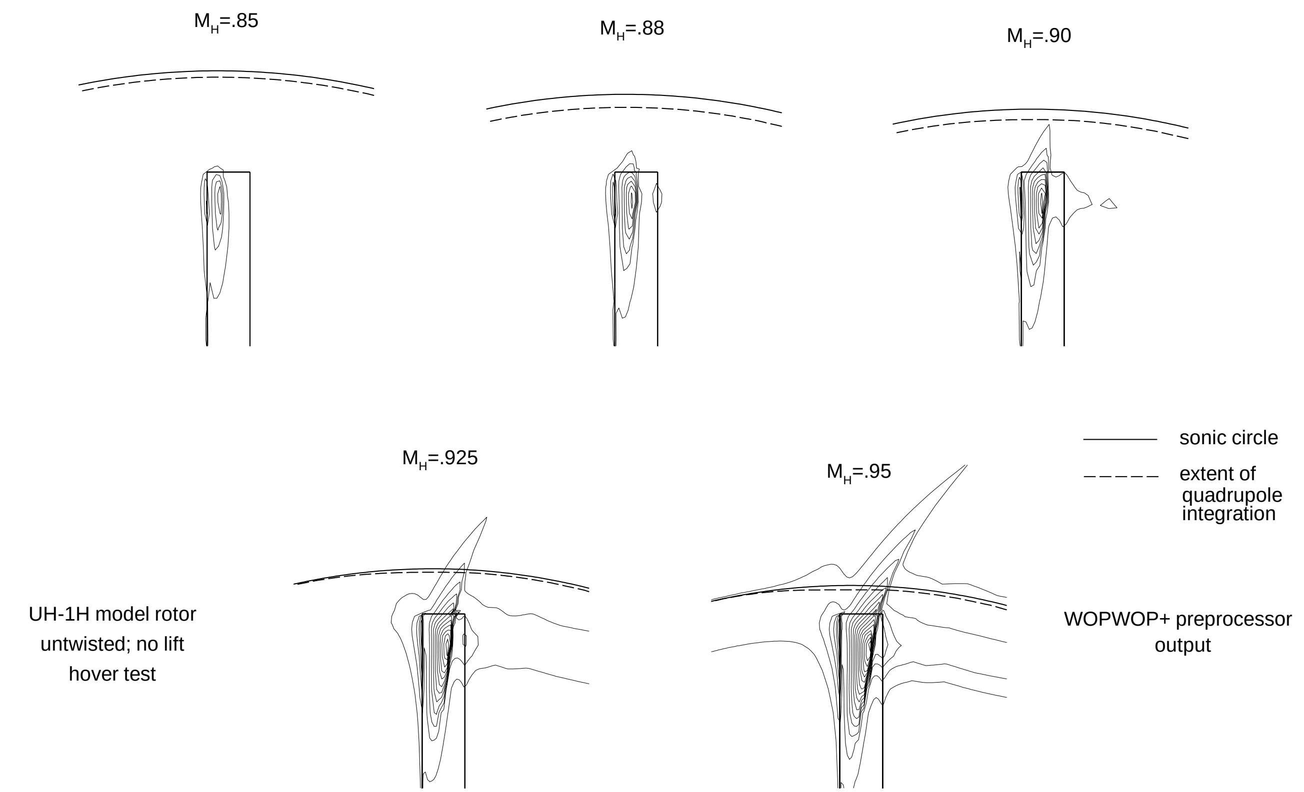




- Quadrupole negative peak pressure shifts at higher speed
- Quadrupole contribution nearly twice that of thickness and loading

UH-1H Model Rotor Quadrupole Strength

- **Contours of Q_{ii}**



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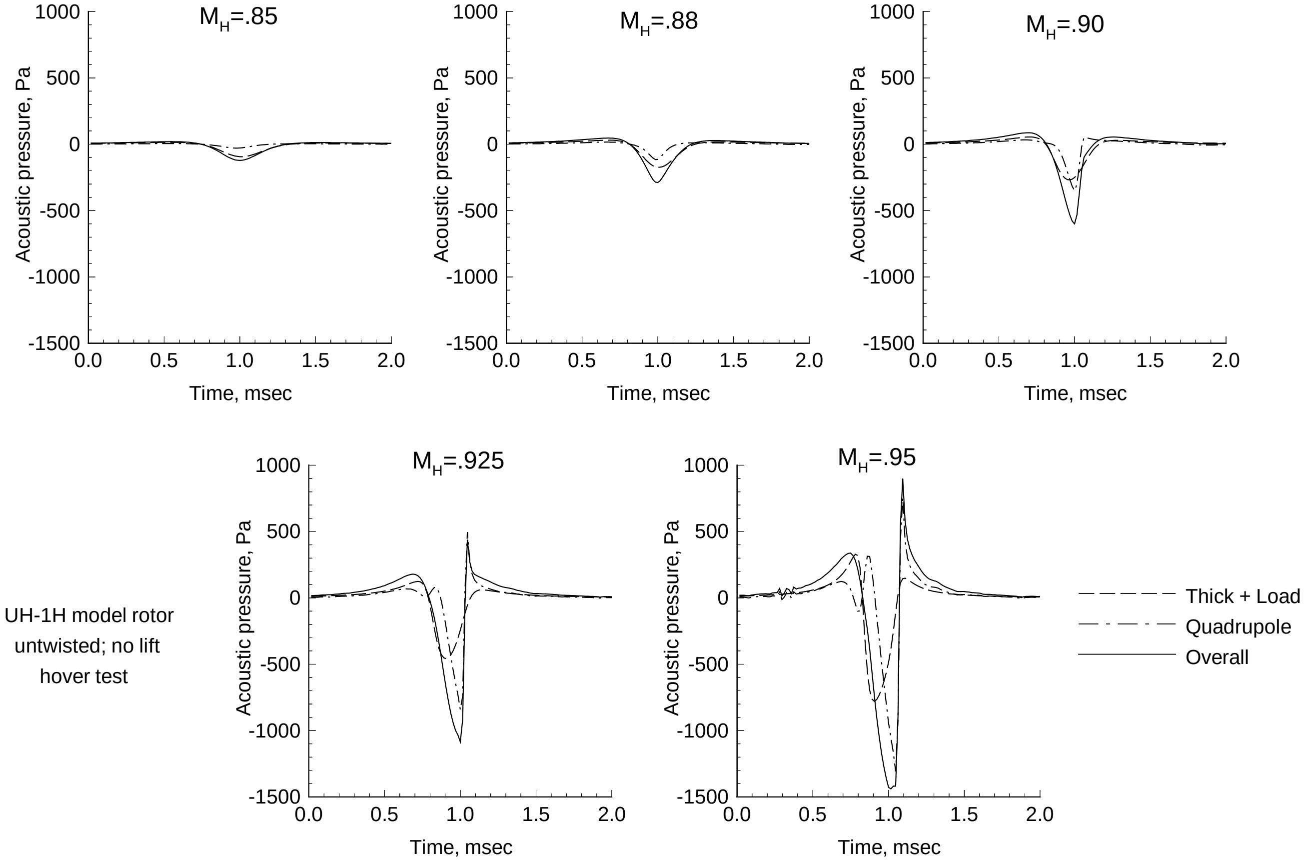
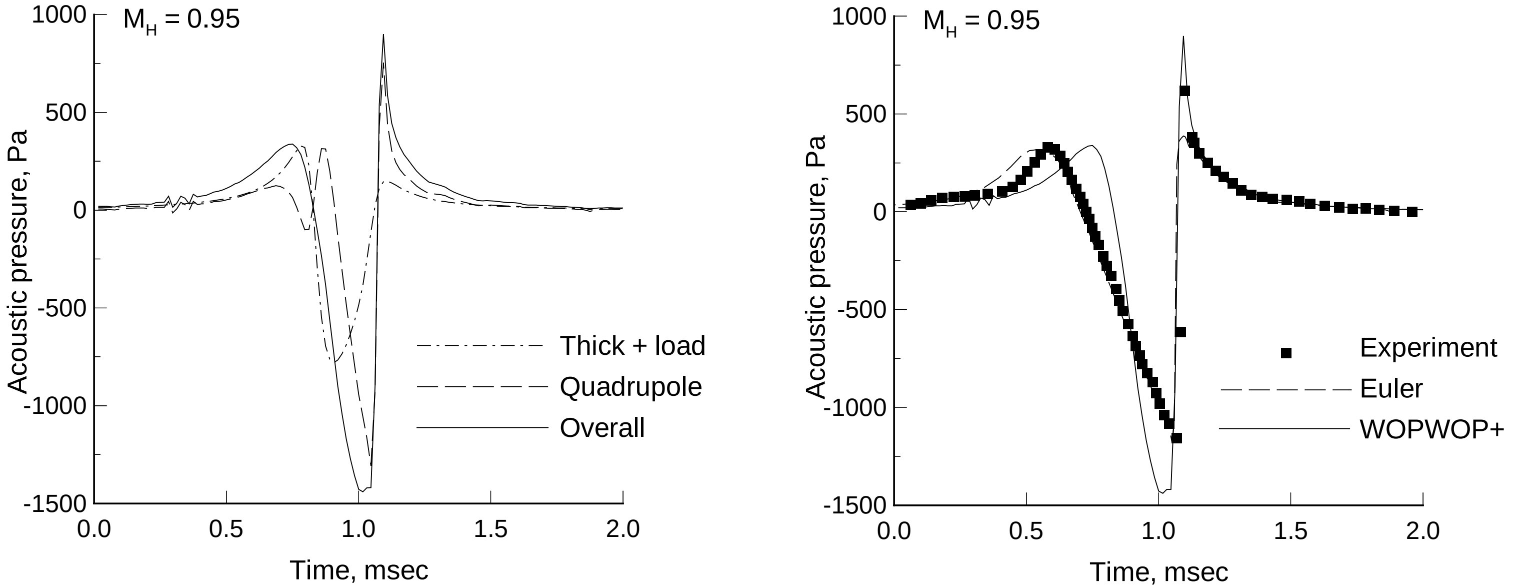
UH-1H Model Rotor Noise

- **Components of acoustic pressure**



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**

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**

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

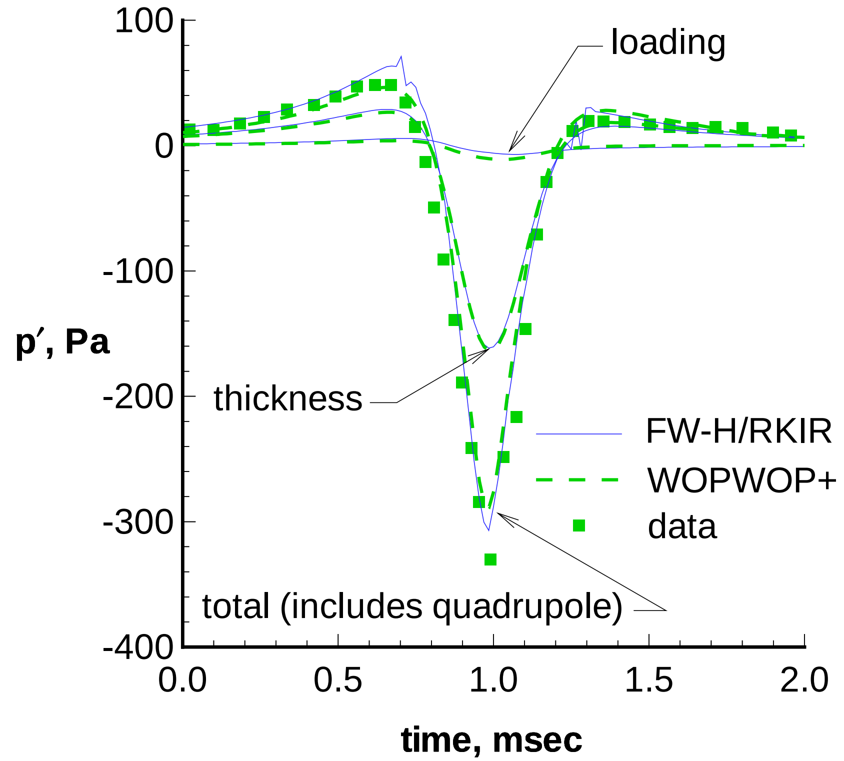
$$\frac{\partial f}{\partial t} = -v_n$$

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

- **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)**

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

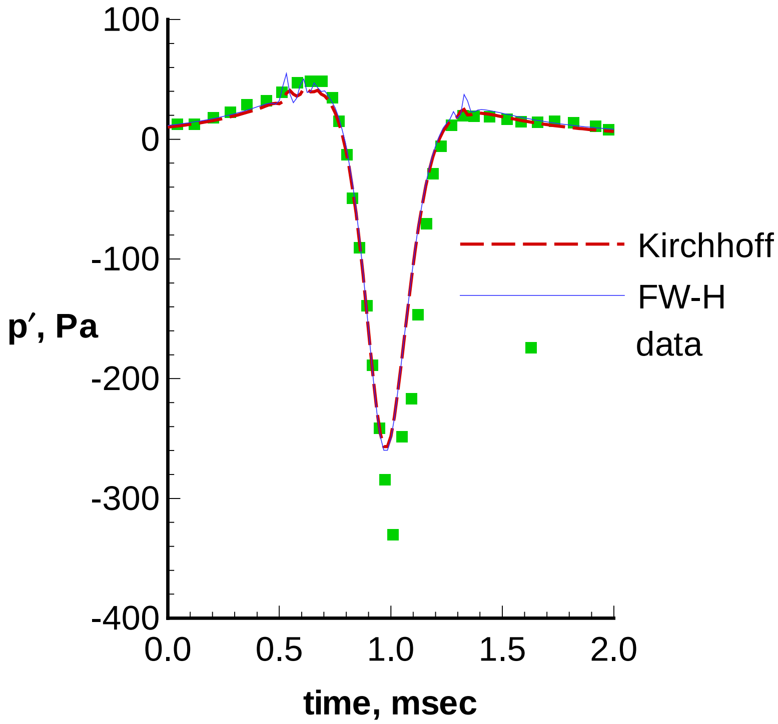
$$-\frac{\partial}{\partial x_j}\left[\rho u_i u_j\right]\hat{n}_i \delta(f) - \frac{\partial}{\partial x_j}\left[\rho u_i u_n \delta(f)\right]$$

$$+\frac{\partial}{\partial t}\left[p' - c^2\rho'\right]\frac{M_n}{c}\delta(f) + \frac{\partial}{\partial t}\left[\left(p' - c^2\rho'\right)\frac{M_n}{c}\delta(f)\right]$$

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

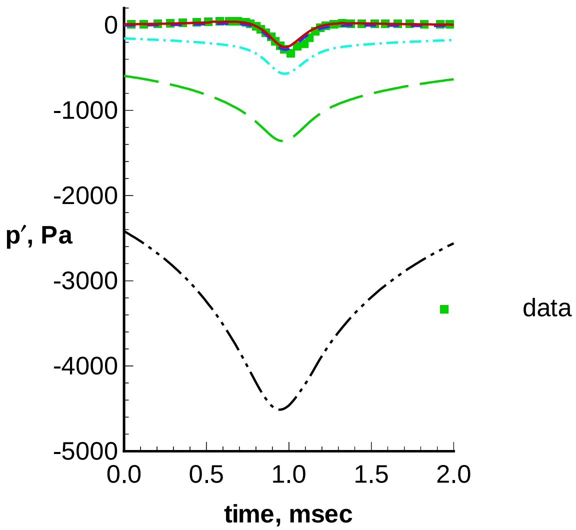
Numerical Comparison: UH-1H hovering rotor

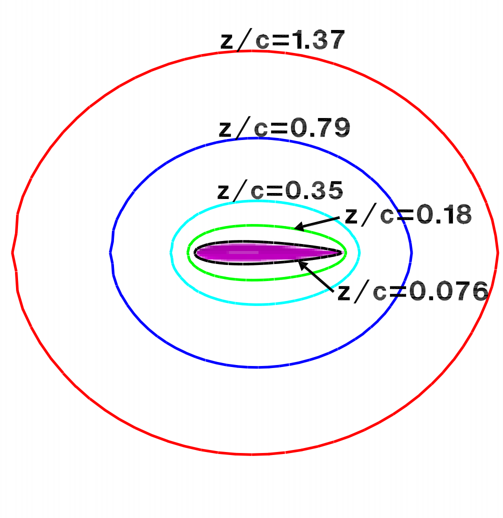
- **UH-1H rotor**
  - **1/7th scale model**
  - **untwisted blade**
- **Test setup** (Purcell)
  - **Hover, $M_H = 0.88$**
  - **inplane microphone, 3.09 R from hub**
  - **minimal rotor lift**
- **Flow-field computation**
  - **full potential flow solver used (FPRBVI)**
  - **80 x 36 x 24 grid (somewhat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

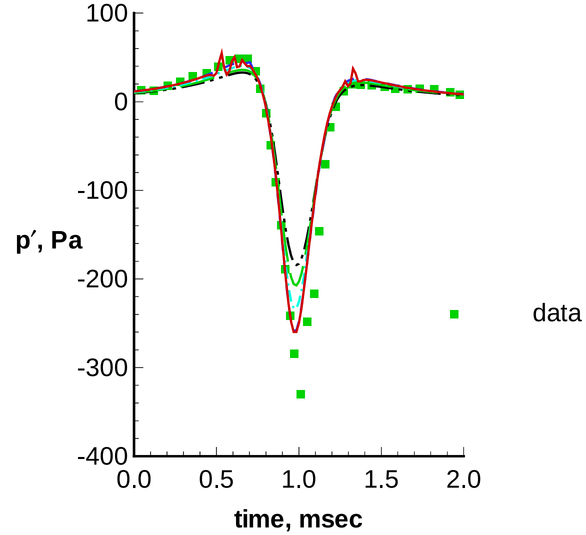


Numerical Comparison:
Sensitivity to Surface Placement

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





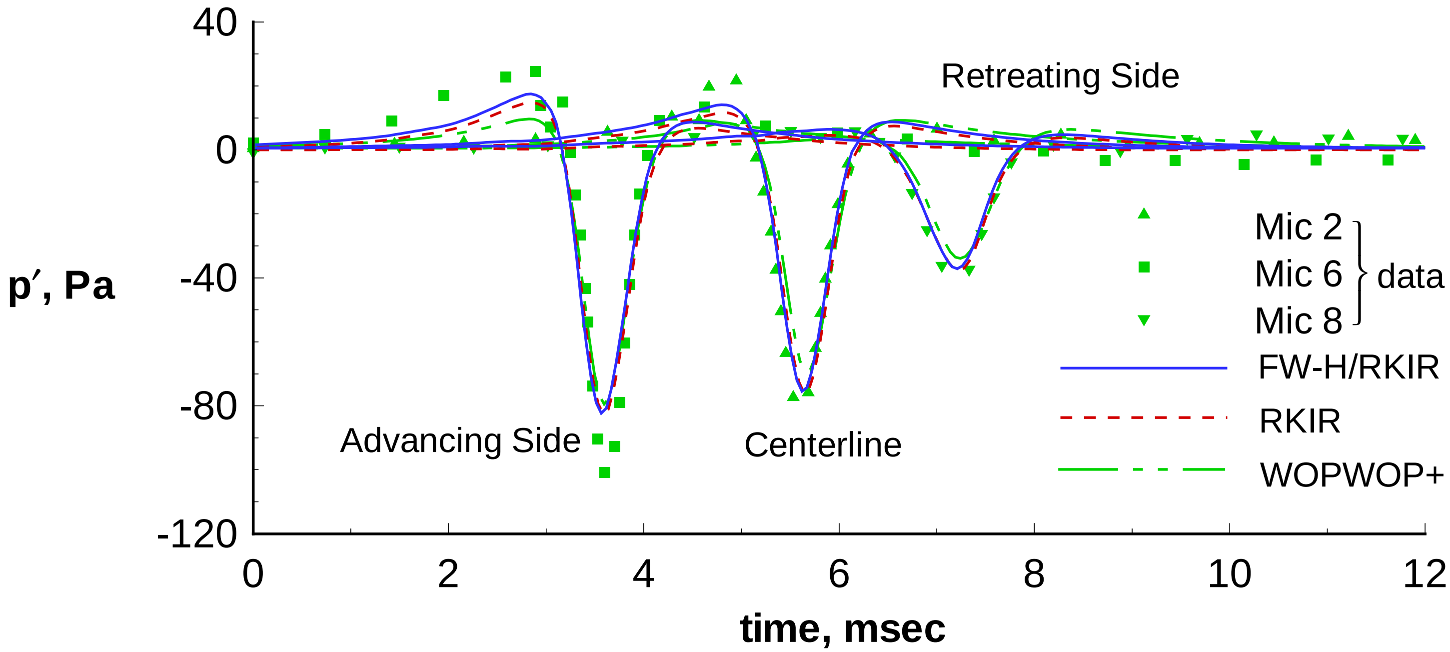


Kirchhoff

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