Broadband noise for rotating blades: analysis of acceleration effects in the time and frequency domains

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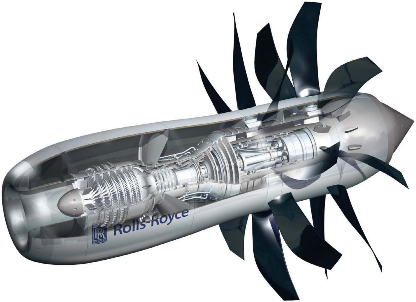
Outline

1. Open rotor broadband noise
   - Motivation
   - Amiet's theory for rotating blades
   - Review of acceleration effects
2. Time domain formulation
   - Review of time domain formulations
   - FW-H formulation 1C
   - Blade loading
3. Results
   - Rotor parameters
   - Stationary blade element
   - Rotating blade element
4. Conclusions

Outline

Motivation



- Broadband noise for Open Rotors or CRORS
- Need fast semi-analytical models for design

Amiet's theory for stationary aerofoils

Amiet 1974, 1975, 1976

Trailing edge noise

$$\Delta P = a \quad g_{TE}\ e^{i(k_y y - k_x U_c t)} \quad P_i$$

$$S_{pp} = A \quad |\Psi_{TE}|^2 \quad \phi_{pp}$$

Amiet's theory for stationary aerofoils

Amiet 1974, 1975, 1976

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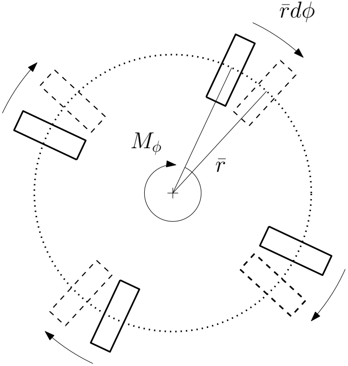
Leading edge noise

$$\Delta P = b \quad g_{LE}\ e^{i(k_y y - k_x U t)} \quad W_i$$

$$S_{pp} = B \quad |\Psi_{LE}|^2 \quad \phi_{ww}$$

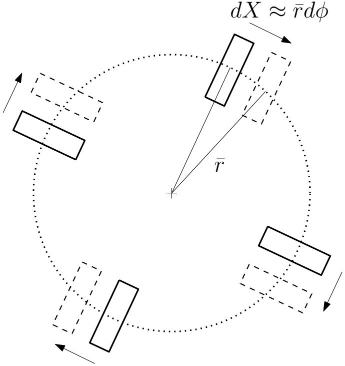
Amiet's theory for rotating aerofoils

Translations instead of rotations



Exact FW-H based model:

Predicts noise from rotating airfoils



Approximate model (Amiet):

Predicts noise from translating airfoil
+ correction for Doppler shift
+ average over all angles ϕ

Courtesy of Vincent Blandeau (2011)

Lowson (1965)

$$p \sim \dot{F} + aF\dot{M}$$

Amiet's theory for rotating aerofoils

Lowson's theory

Lowson (1965)

$$p \sim \dot{F} + aF\dot{M}$$

Amiet's idea

$$\dot{F} \sim \omega_S F \qquad \dot{M} \sim \Omega M$$

If $\omega_s \gg \Omega$,

$$p \sim \dot{F}$$

$\rightarrow$ Source in rectilinear motion.

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Amiet's idea

$$\dot{F} \sim \omega_S F \qquad \dot{M} \sim \Omega M$$

If $\omega_s \gg \Omega$,

$$p \sim \dot{F}$$

→ Source in rectilinear motion.

Question

Is $\omega_S \gg \Omega$ always necessary? Is Amiet's approach more widely applicable?

Acceleration effects: previous studies

Frequency domain formulation

S. Sinayoko, M. Kingan, A. Agarwal.
Trailing edge noise for rotating blades.
Proceedings of the Royal Society A, 2014.

- Frequency Domain formulation including acceleration effects
- Reviewed and validated Amiet's theory for rotating blades.

Acceleration effects: previous studies

Acceleration effects on TEN

S. Sinayoko, M. Kingan, A. Agarwal.
On the effect of acceleration on trailing edge noise radiation from rotating blades.
AIAA-2013-2287, 2013.

Findings

- Amiet's method found to work for $\omega \gtrsim \Omega/10$.
- Reason: error on instant PSD is averaged out over one cycle.

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Issues

1. Source frequency becomes very low at certain azimuthal angles
2. Hard to distinguish acceleration effect in exact formulation

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2. Hard to distinguish acceleration effect in exact formulation

$\rightarrow$ Use Leading Edge Noise instead of Trailing Edge Noise
$\rightarrow$ Use Time Domain formulation instead

Outline

Broadband noise formulations in the time domain

Casper and Farassat (IJA 2002, JSV 2004)

First trailing edge noise prediction for *stationary* blade in the time domain using FW-H.

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Trailing edge noise prediction for *rotating* blade in the time domain using FW-H.

Glegg, Devenport and Alexander (JSV 2015)

- Broadband rotor noise predictions using a time domain approach
- Predicts PSD rather than pressure field.

FW-H equations in uniform flow: formulation 1C

Far field formulation

Najafi-Yazdi, Bres, Mongeau (PRS A 2010)

$$4\pi c_0 p \approx \boxed{\int_{f=0} \left[\frac{\Delta \dot{p} n_i \tilde{R}_i}{R^*(1-M_R)^2}\right] d\eta} + \boxed{\int_{f=0} \left[\frac{\Delta p \dot{n}_i \tilde{R}_i}{R^*(1-M_R)^2}\right] d\eta - \int_{f=0} \left[\frac{\dot{M}_R \Delta p n_i \tilde{R}_i}{R^*(1-M_R)^3}\right] d\eta}$$

FW-H equations in uniform flow: formulation 1C
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- Unsteady loading term ($\Delta\dot{p}$)

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Far field formulation

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Blade element loading

Stationary blade element

Time domain fluctuations from wavenumber spectrum

$$\Delta p(x, y, t) = \mathrm{Re}\left\{ W_0(k_x, k_y) g_{LE}(x, k_x, k_y) e^{i[k_x(x-Ut)+k_y y+\phi]} \right\}$$

$$W_0(k_x, k_y) = \sqrt{8\Phi_{ww}(k_x, k_y)\Delta k_x \Delta k_y}.$$

$$k_x = \omega_s/U, \qquad \Delta k_x = 2\pi/U, \qquad \Delta k_y = 2\pi/\text{span}$$

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$\rightarrow$ New factor $\sqrt{8}$ compared to π in Casper and Farassat (2004).

Proof:

$$\text{Incident Power} = \frac{1}{2} W_0(k_x, k_y)^2 = 4\Phi_{ww}(k_x, k_y)\Delta k_x \Delta k_y.$$

Blade element loading

Rotating blade element

Objective: avoid calculating the instantaneous spectrum

PSD computation for rotating blade element

1. Select observer position and frequency.
2. Compute source frequency $\omega_S(\tau)$ from Doppler shift.
3. Compute pressure jump $\Delta p(x, y, \tau)$ over 4 periods.
4. Compute far field pressure $p(t)$ using FW-H.
5. Compute power by time averaging $p^2(t)$.

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Note on period:

- Period is $T_\Omega = 2\pi/\Omega$ for $\omega > \Omega$
- Period is $T_\omega = 2\pi/\omega$ for $\omega < \Omega$

Outline

Open propeller blade element

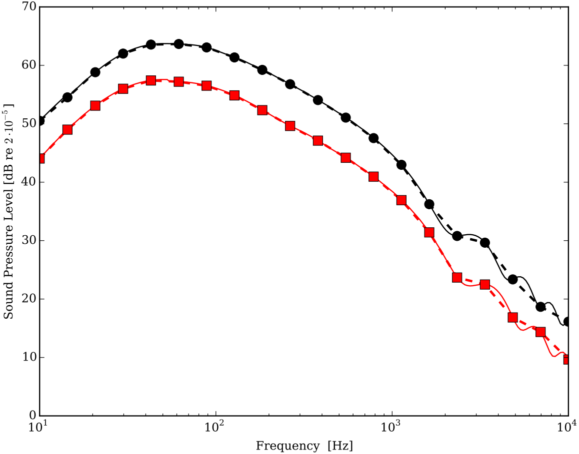
- Blade parameters

	radius	chord	M_{BO}	Pitch	M_{FO}	M_{FB}
Take-off	1.80	0.31 m	0.748	38 deg	0.228	0.782
Cruise	1.80	0.31 m	0.748	13 deg	0.584	0.949

- Turbulence intensity: 5% of inflow velocity
- Turbulence length scale: $r/2 = 0.9$
- Observer location: distance 100λ, elevation angle $\pi/4$.

Stationary blade element

take-off cruise

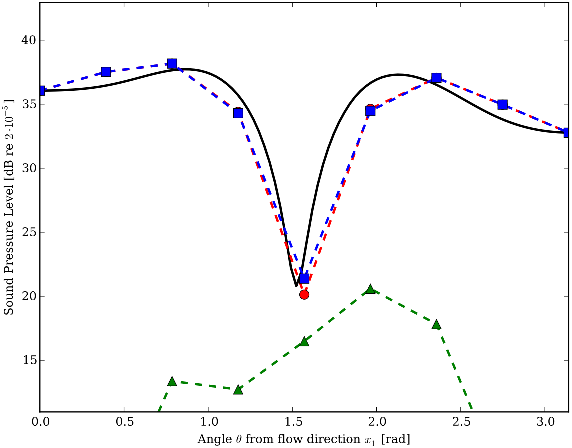


Rotating blade element: high frequency directivity

SPL directivity for take-off blade element

High frequency: $\omega = 10\Omega$

Amiet Unsteady loading Acceleration effects Total

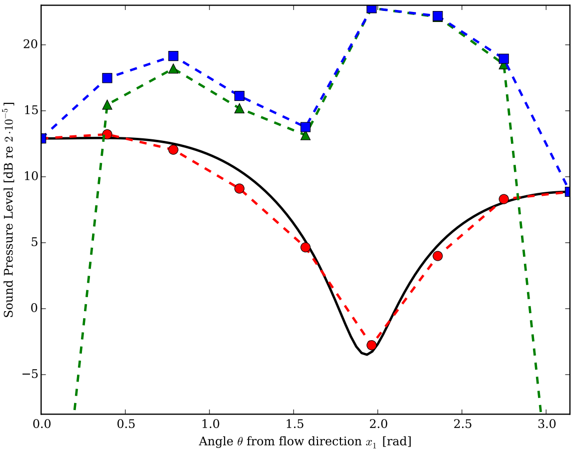


Rotating blade element: low frequency directivity

SPL directivity for take-off blade element

Low frequency: $\omega = 0.1\Omega$

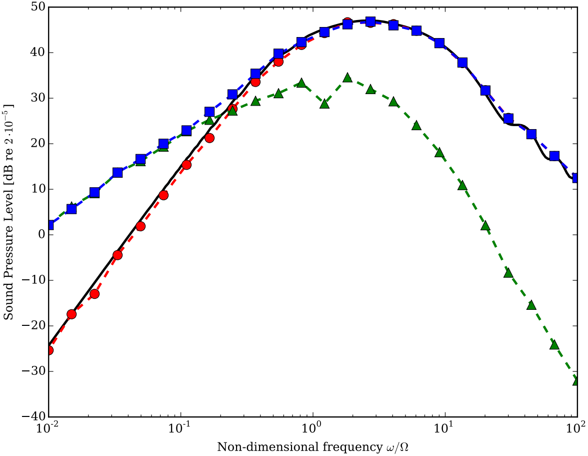
Amiet Unsteady loading Acceleration effects Total



Rotating blade element

SPL spectrum for take-off blade element

Amiet Unsteady loading Acceleration effects Total



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Conclusions

Achievements

1. Predicted leading edge noise in the time domain with FW-H
2. Acceleration term can be switched on and off
3. Compared predictions to Amiet's formulation for model propeller blade elements

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Achievements

1. Predicted leading edge noise in the time domain with FW-H
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3. Compared predictions to Amiet's formulation for model propeller blade elements

Conclusions

- Acceleration effects can be neglected for time averaged PSD for $\omega \geqslant 0.5\Omega$.
- Much better than $\omega \gg \Omega$.
- Amiet's formulation can be used even at low frequencies.

Acknowledgements

Acknowledgements

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Further information

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Thank you!