From noise in jets & wind turbines to relativity

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ROYAL COMMISSION EXHIBITION OF 1851

Imperial College, 16 May 2014

Objectives

- Two applications
  - Jet noise sources
  - Wind turbine noise

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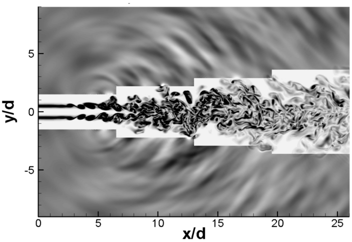
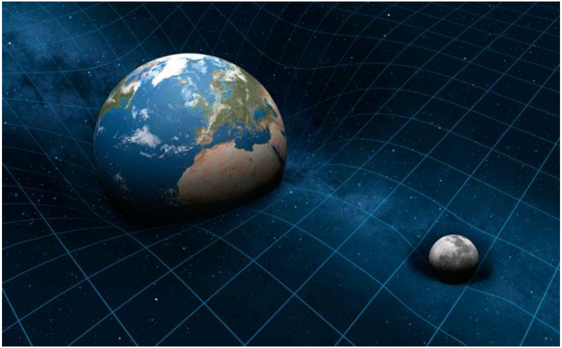
- Two applications
  - Jet noise sources
  - Wind turbine noise
- Two major problems
  - Noise sources / fluctuations are hidden in the flow.
  - Existing mathematical tools are limited: confusing and error prone.
- Possible solutions
  - silent base flow analogy
  - acoustic space-time

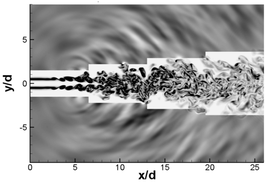
Outline





Outline

True sources of jet noise



EPSRC
Engineering and Physical Sciences Research Council

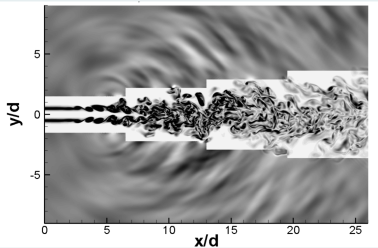
Rolls-Royce

University of Southampton
Institute of Sound and Vibration Research

Acknowledgements

- Anurag Agarwal
- Chris Morfey
- Zhiwei Hu
- Victoria Suponitsky
- Neil Sandham
- Peter Jordan
- Richard Sandberg

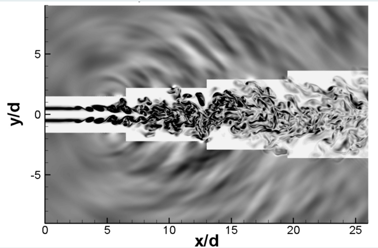
Complex turbulent flow



Source definition

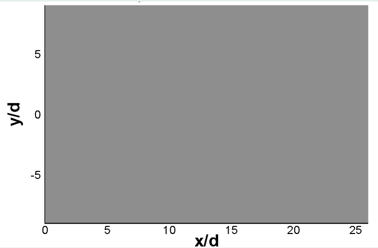
Lighthill's acoustic analogy

Turbulent flow



Complex propagation

Quiescent medium



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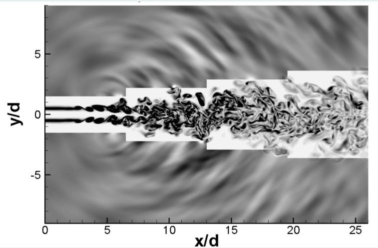

Complex propagation

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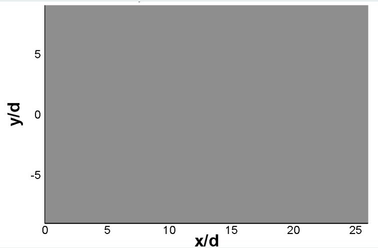
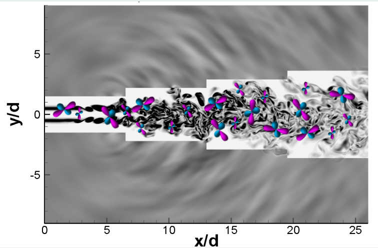


Simple propagation

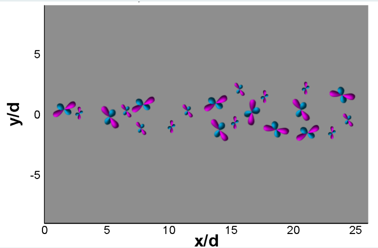
$\Rightarrow$ What are the equivalent sound sources?

Lighthill's acoustic analogy

Complex turbulent flow



Simple quiescent medium



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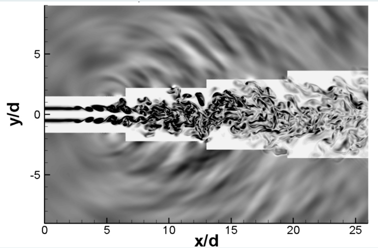

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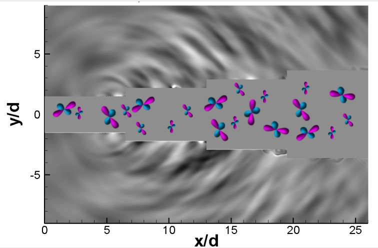

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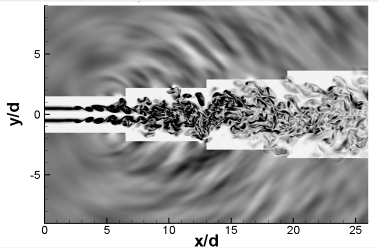

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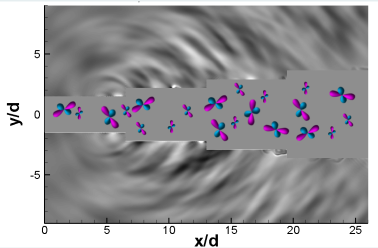
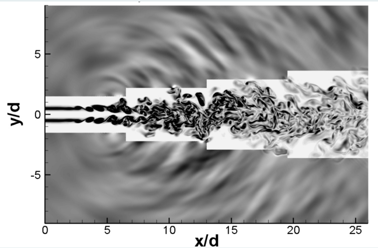


Great but...

These are equivalent sources, not true sources!

Silent base flow analogy

Jet



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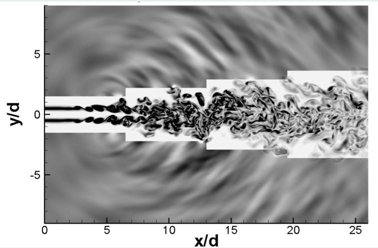
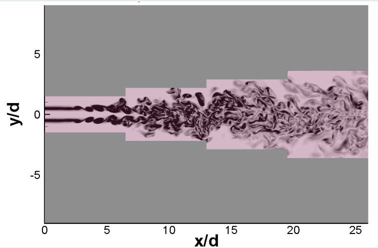


Silent jet

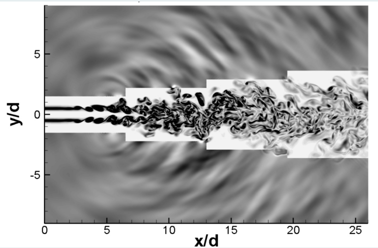


⇒ Filter removing acoustic components

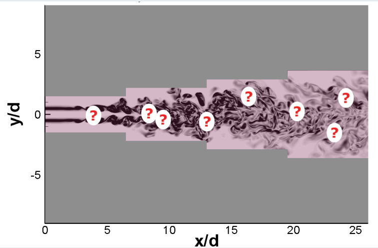
Source definition

Silent base flow analogy

Jet



Filtered jet

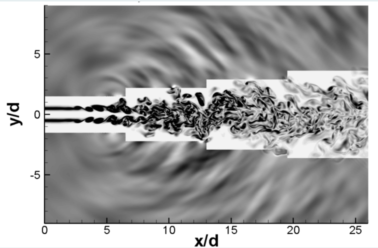


$\Rightarrow$ Source calculation

Source definition

Silent base flow analogy

Jet



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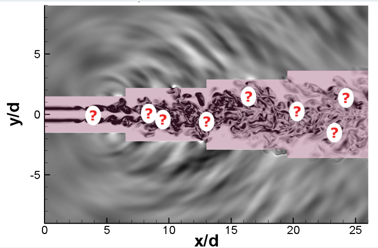
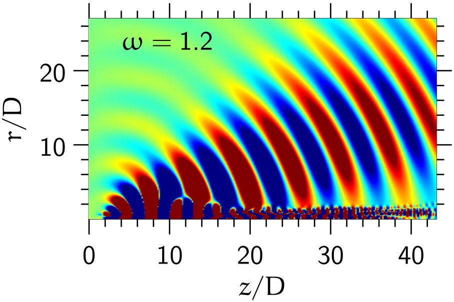


$\Rightarrow$ Sound propagation

Sources are close to the true sources of sound.

Flow filtering



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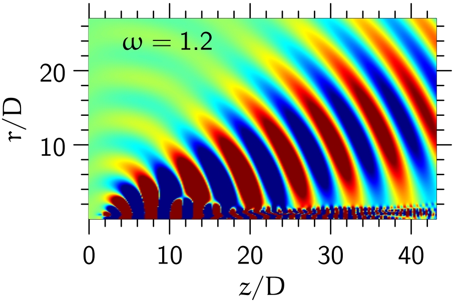

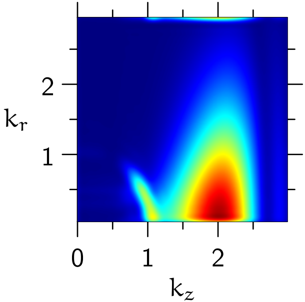

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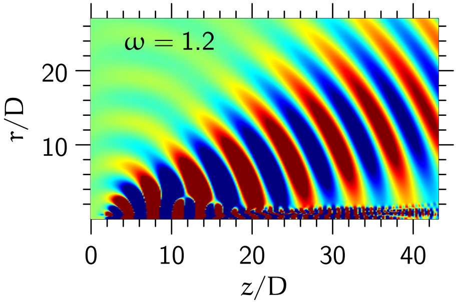

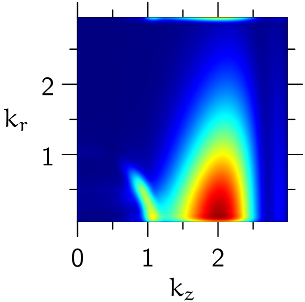

Filtering criterion for "acoustic" waves

Radiating components satisfy $k = \omega/c_\infty$ in the frequency domain

Sound sources in a simplified jet

References

S. Sinayoko, A. Agarwal, and Hu Z.
Flow decomposition and aerodynamic noise generation.
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Achievements

1. Computed silent base flow
2. Computed sound sources

Sound sources in a simplified jet

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Achievements

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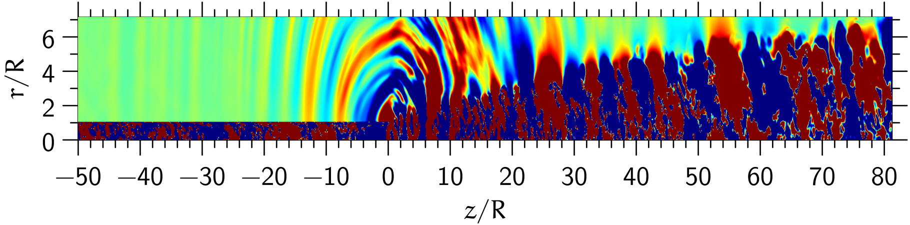
4. Dominant source: $\rho \bar{u}_0 \bar{u}_z'$

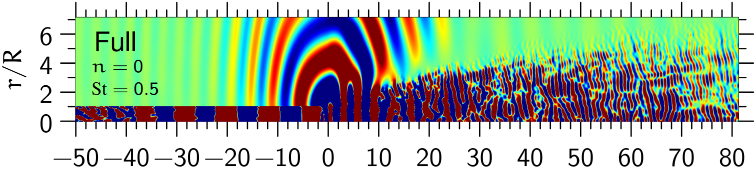
Sound sources in turbulent jet

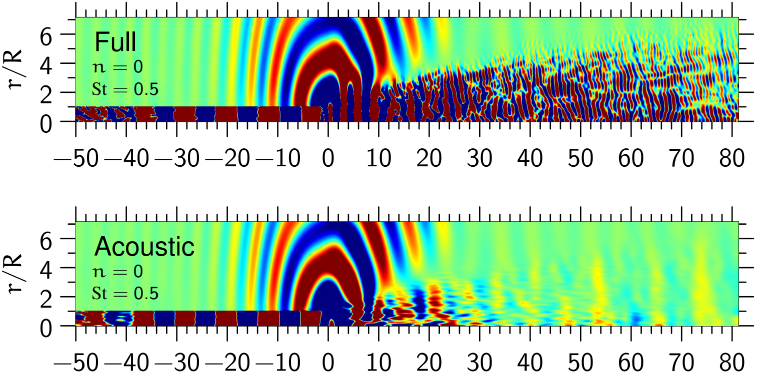
Density fluctuations



Sound sources in turbulent jet

Flow decomposition $n = 0 \quad St_D = 0.5$

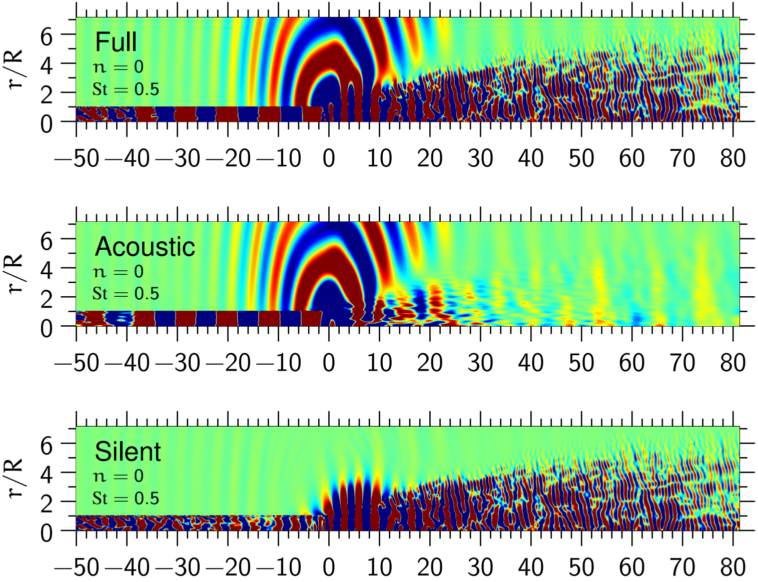




Full
$n = 0$
$St = 0.5$
r/R
0
2
4
6
−50
−40
−30
−20
−10
0
10
20
30
40
50
60
70
80
Acoustic
$n = 0$
$St = 0.5$
r/R
0
2
4
6
−50
−40
−30
−20
−10
0
10
20
30
40
50
60
70
80

Sound sources in turbulent jet

Flow decomposition $n = 0$ $St_D = 0.5$



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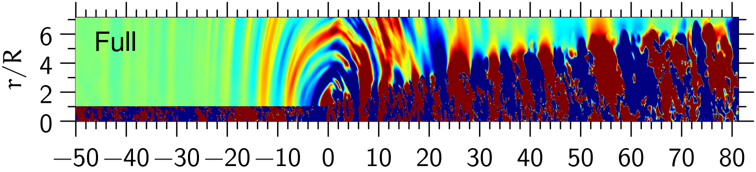

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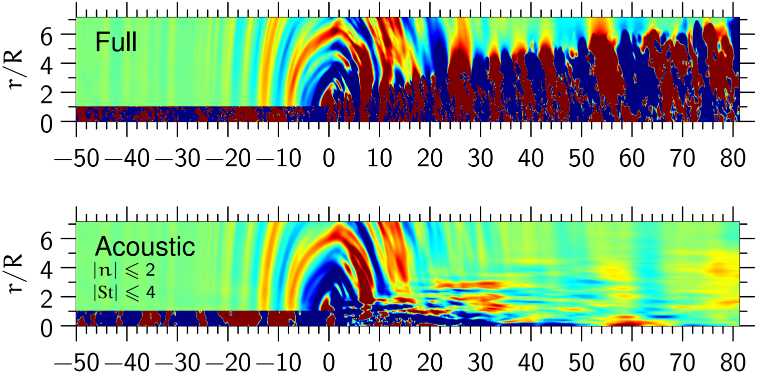

Sound sources in turbulent jet

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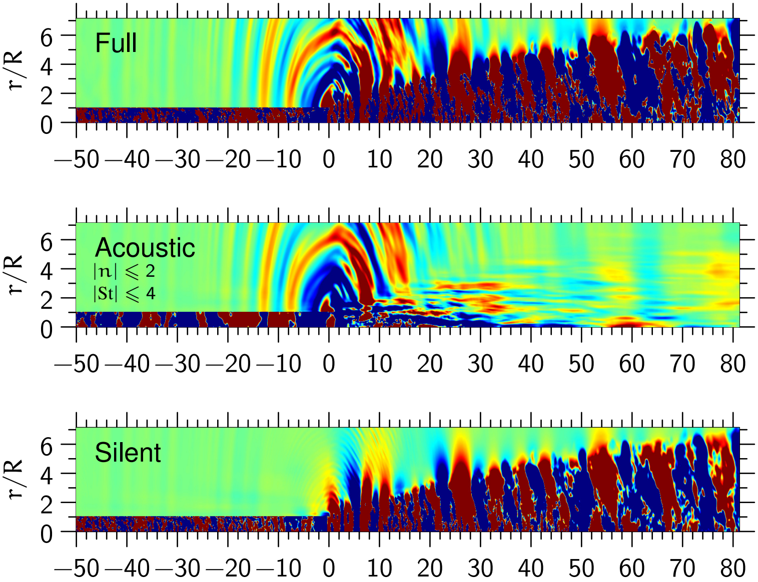
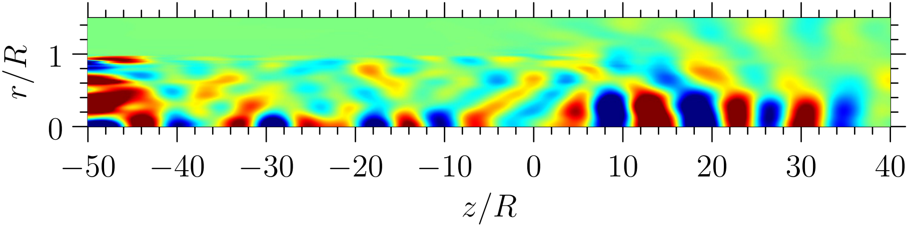


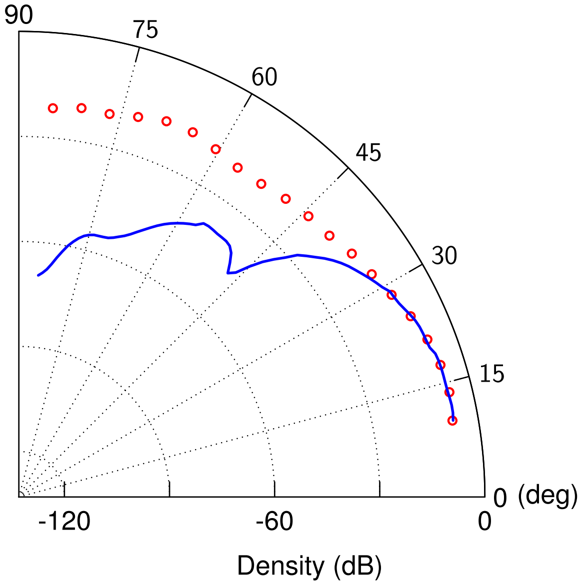
Sound sources in turbulent jet

Axial source $\quad n = 0 \quad St_D = 0.3$



Sound sources in turbulent jet

Validation $n = 0$ $St_D = 0.3$



Sound sources in turbulent jet

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Achievements

- Silent base flow
- Computed sound sources
- Validated $n = 0 \quad \text{St} = 0.3$

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Achievements

- Silent base flow
- Computed sound sources
- Validated $n = 0 \quad \mathrm{St} = 0.3$

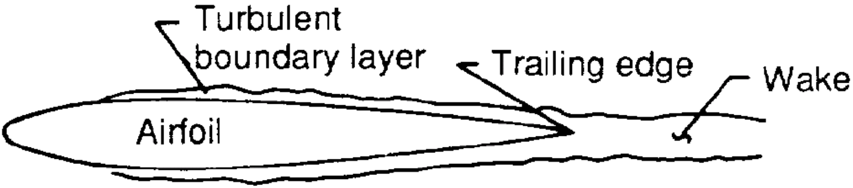
Future

- $n > 0 \quad \mathrm{St} \neq 0.3$
- Apply to LES data
- Improve filtering criterion

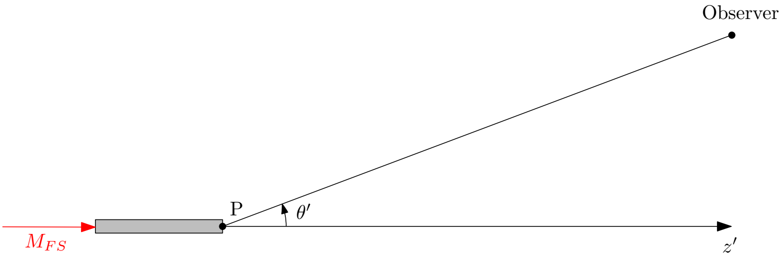
Acknowledgements

- Mike Kingan
- Anurag Agarwal
- Graham Pullan
- Phil Joseph
- Michel Roger
- Ann Dowling

Trailing Edge Noise

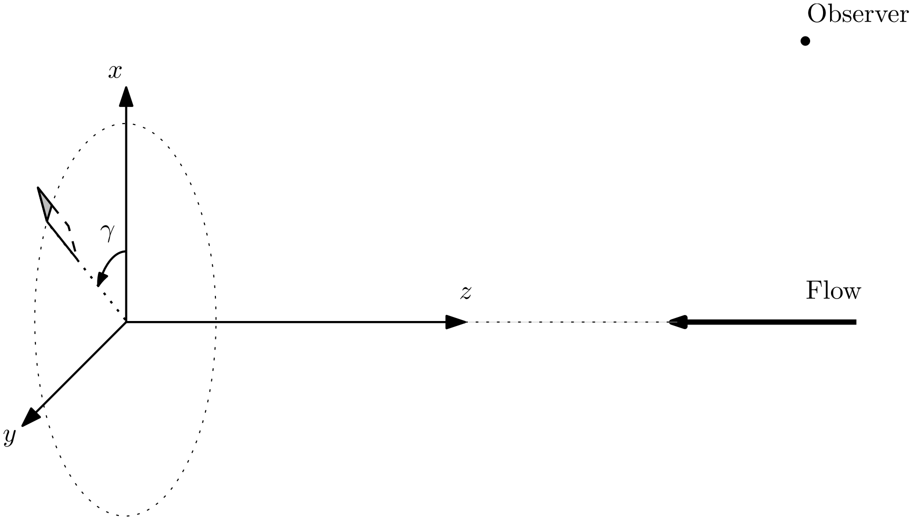


Isolated airfoil



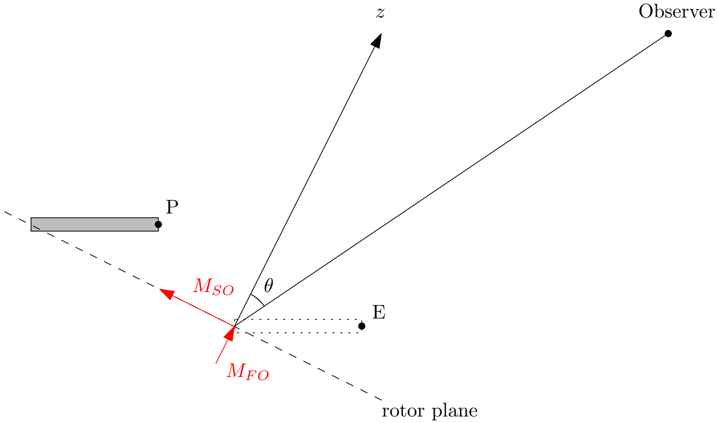
Amiet's (1976) theory predicts noise radiating to observer.

Rotating airfoil



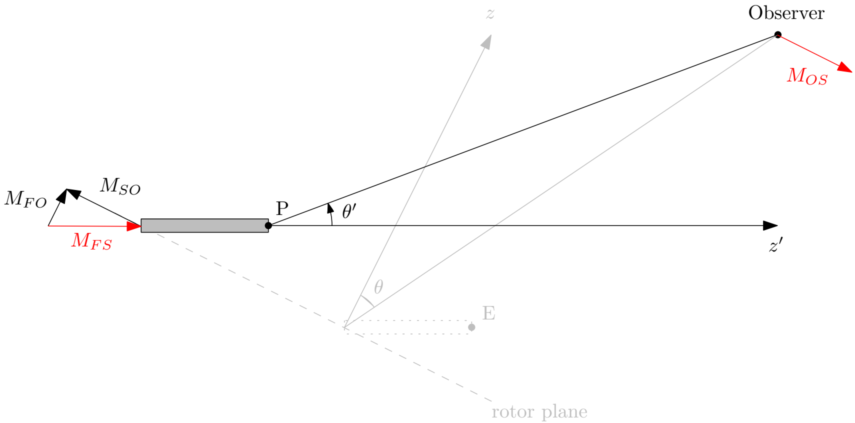
Change of reference frame

Observer frame



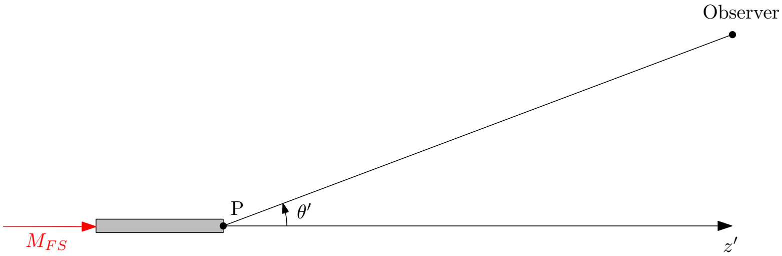
Change of reference frame

Source frame



Change of reference frame

Wind tunnel case



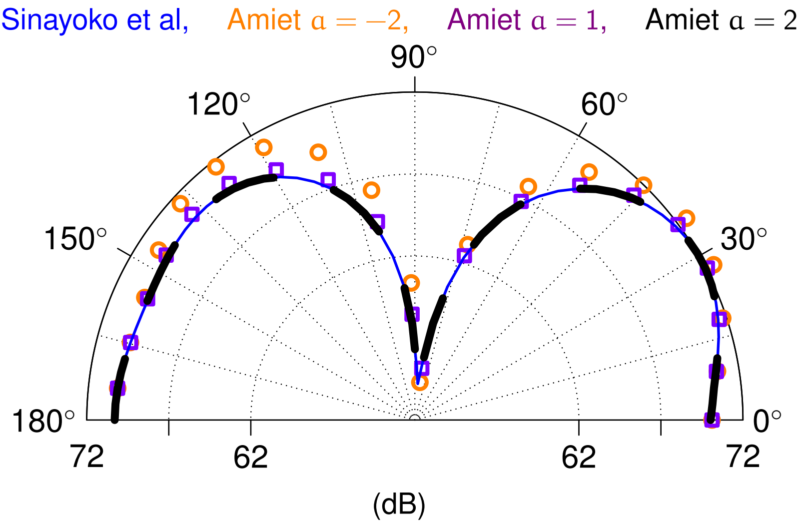
Amiet's formulation(s)

$$S_{\mathrm{pp}}(\omega) = \frac{1}{2\pi}\int_0^{2\pi}\left(\frac{\omega'}{\omega}\right)^{e} S'_{\mathrm{pp}}(\omega',\gamma)\,\mathrm{d}\gamma$$

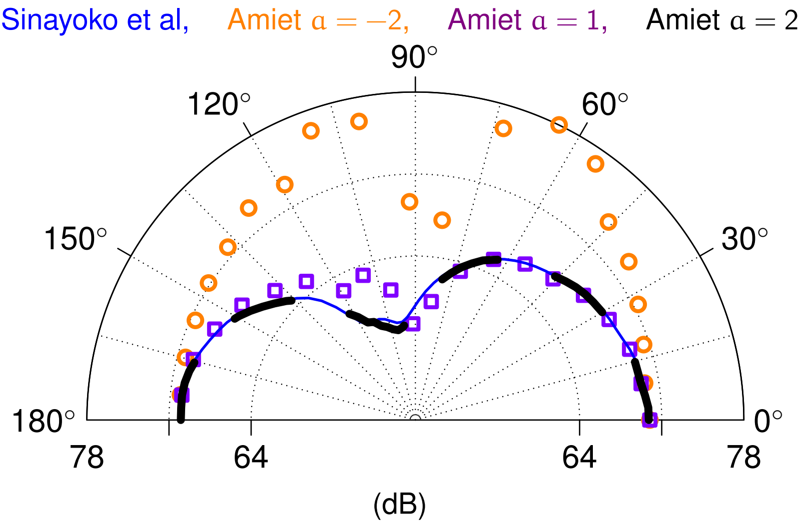
Source	Exponent e
Amiet (1976)	1
Rozenberg et al (2010)	1
Schlinker and Amiet (1981)	2
Blandeau and Joseph (2011)	-2

Which value of the exponent is correct?

Wind turbine $kc = 5$



Open propellor takeoff $kc = 5$



Trailing edge noise

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Proc. R. Soc. A, 2013 469

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Achievements

1. New exact theory

Trailing edge noise

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Achievements

1. New exact theory
2. Correct value: $\alpha = 2$

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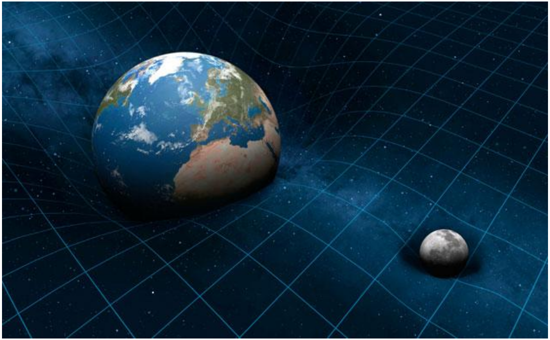
Future

- Acceleration effects high Mach
- Wake-vortex interaction



Acknowledgements

- Alastair Gregory
- Anurag Agarwal
- Joan Lasenby

Motivation

Unanswered questions

- Lorentz transformation comes from relativity (Einsten et al)
- "Lorentz transformation" common in aeroacoustics
- They are not the same thing...?
- More questions: Chapman (2001) and the frequency factor...?
- How about the Prandtl-Glauert transformation?

Outline

1. Principle of relativity
2. Lorentz transform in physics
3. Lorentz transform in aeroacoustics
4. Acoustic space-time

Principle of Relativity

Governing equations must independent of the observer frame.

Example

Wave Equation

- Stationary frame (x, t):
  $\left\{\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right\} p = 0$

Principle of Relativity

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Example

Wave Equation

- Stationary frame (x, t):
  $\left\{\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right\} p = 0$
- Moving frame $(x' = x + \mathbf{U}t, t' = t)$ (Galilean Transformation):
  $\left\{\nabla^2 - \frac{1}{c^2}\left(\frac{\partial}{\partial t} + \mathbf{U}\cdot\boldsymbol{\nabla}\right)^2\right\} p = 0$

The convected wave equation violates the principle of relativity!

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The convected wave equation violates the principle of relativity!
$\rightarrow$ The wave operator is not Galilean invariant.

Principle of Relativity

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Principle of Relativity

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Example

Wave Equation (revisited)

- Stationary frame (x, t):
  $\left\{\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right\} p = 0$
- Moving frame (x'', t'') (Lorentz Transformation):
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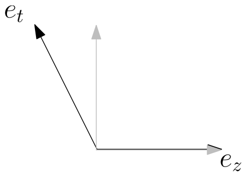
$\rightarrow$ The wave equation is Lorentz-invariant.

Acoustic space-time

Observer frame

$\nabla^2 - \frac{1}{c^2}\left(\frac{\partial}{\partial t} + \mathbf{U}\cdot\nabla\right)^2$



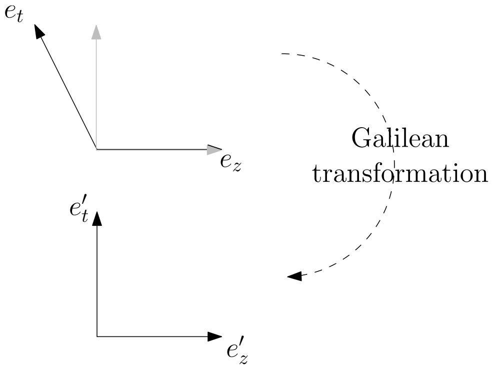
Acoustic space-time

Observer frame

$\nabla^2 - \frac{1}{c^2}\left(\frac{\partial}{\partial t} + \mathbf{U}\cdot\nabla\right)^2$

Fluid frame

$\nabla'^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t'^2}$



Acoustic space-time

Observer frame

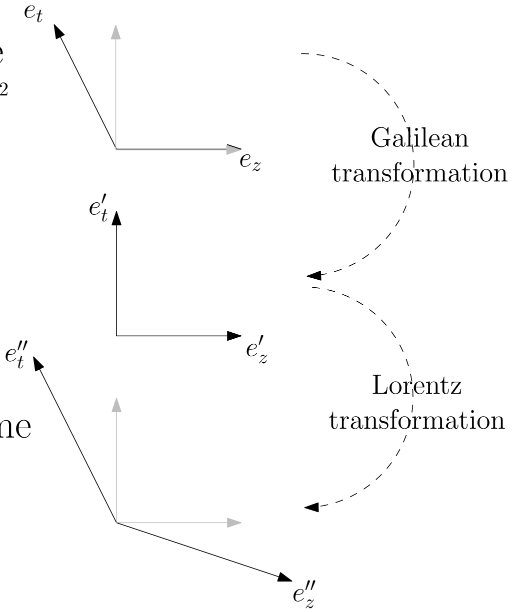
$$\nabla^2 - \frac{1}{c^2}\left(\frac{\partial}{\partial t} + \mathbf{U}\cdot\nabla\right)^2$$

Fluid frame

$$\nabla'^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t'^2}$$

Lorentzian frame

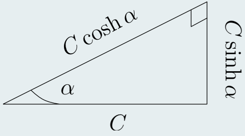
$$\nabla''^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t''^2}$$



Acoustic space-time

Cons

- Unfamiliar world

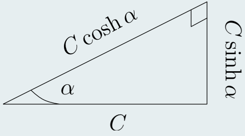


- Need time

Acoustic space-time

Cons

- Unfamiliar world



- Need time

Pros

- Explains the physics (no longer need to be a genius!)
- Geometric interpretation: new intuition and insights ($\mathrm{d}t' = (\omega/\omega')\mathrm{d}t$, Fourier transform)
- Very powerful:
  - Doppler shift
  - Green's function
  - Dispersion relation and null vectors ($\kappa^2 = 0$)
  - Scales to more complex flows (e.g. potential)

$\rightarrow$ Highly recommended!

Aeroacoustics and relativity

Reference

A. Gregory, S. Sinayoko, A. Agarwal, and J. Lasenby.
An acoustic spacetime and the Lorentz transformation in aeroacoustics.
arXiv:1403.7511, submitted to *Journal of Sound and Vibration*

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Future

- Deal with non-uniform flows
- Find better definition for acoustic waves than $k = \omega/c_\infty$

Thank you!

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Web: www.sinayoko.com
Twitter: @sinayoko