Numerical predictions of wind turbine noise in urban environments

Akshay Anand[1]

[1] Research Engineer at Aerospace Department

Georgia Tech Lorraine & CNRS, France

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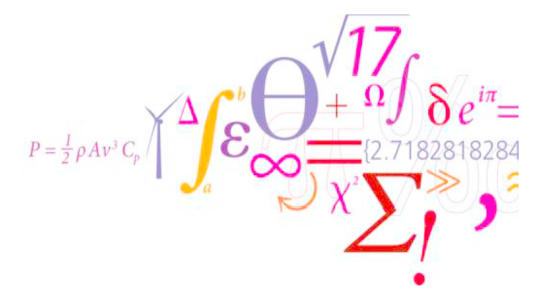
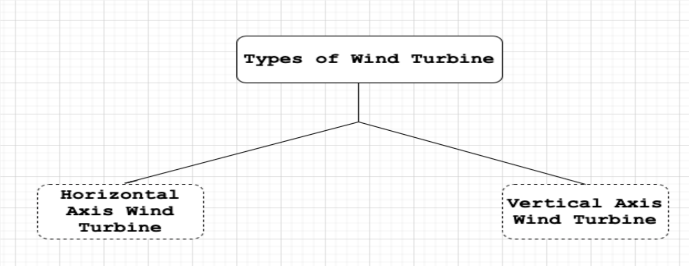


What is a Wind Turbine?

A wind turbine is a device that converts kinetic energy from the wind into electricity.



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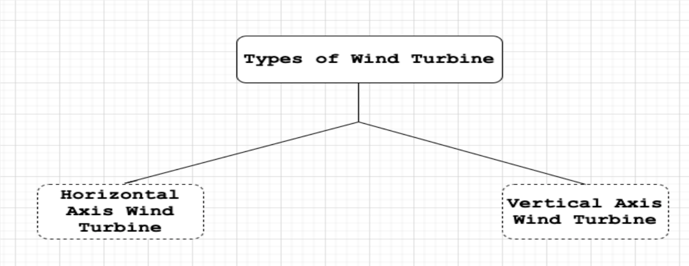
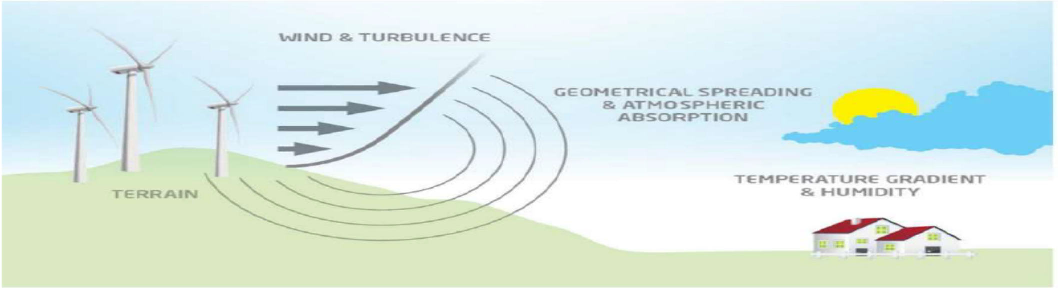


Introduction



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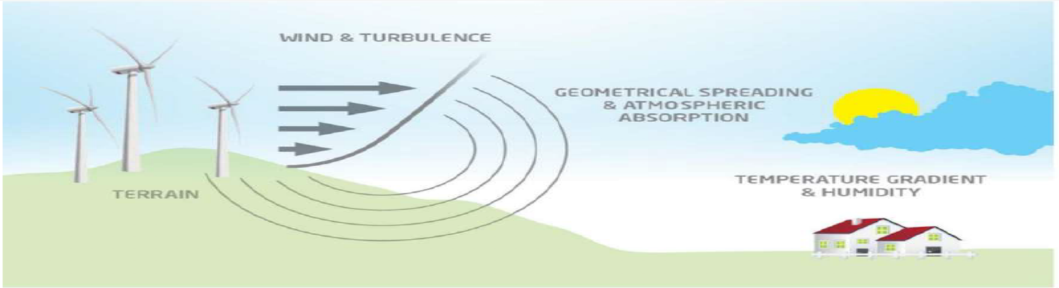
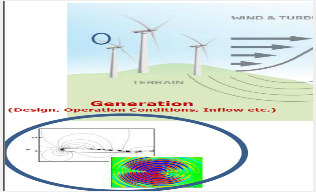
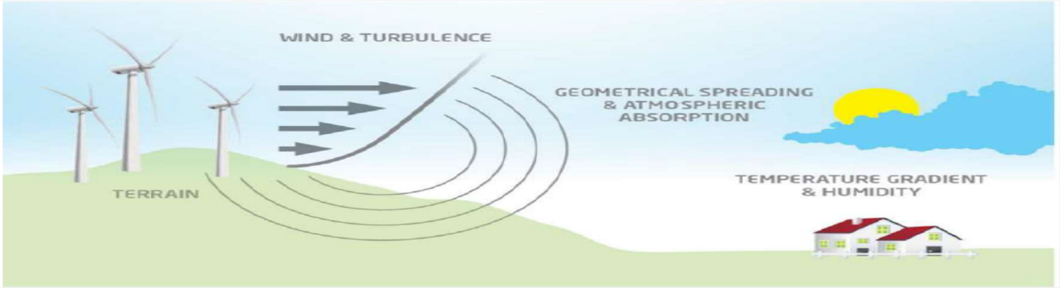
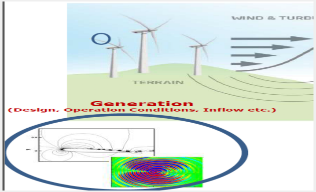
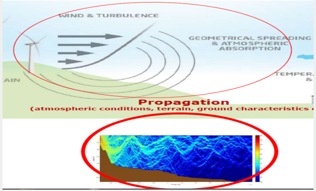


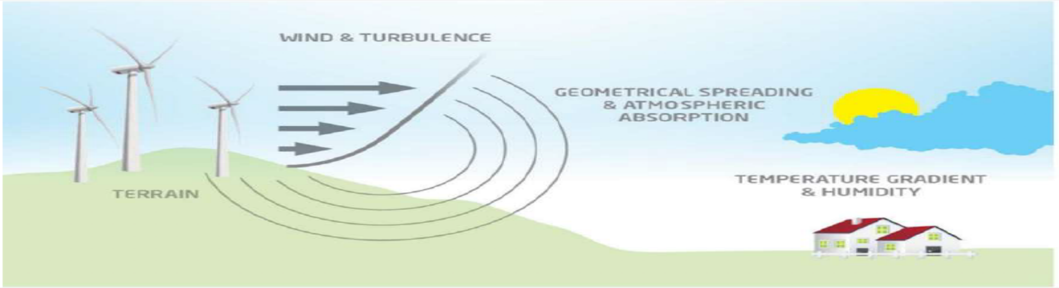


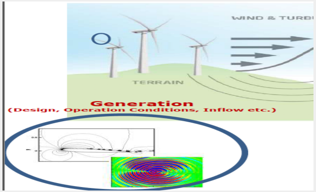

WIND & TURBULENCE
GEOMETRICAL SPREADING & ATMOSPHERIC ABSORPTION
TERRAIN
TEMPERATURE GRADIENT & HUMIDITY


TERRAIN
Generation
(Design, Operation Conditions, Inflow etc.)


WIND & TURBULENCE
GEOMETRICAL SPREADING & ATMOSPHERIC ABSORPTION
Propagation
(atmospheric conditions, terrain, ground characteristics

Introduction





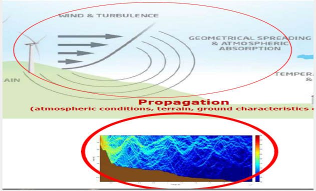


Figure Source: Emre Barlas, PhD Dissertation

Objectives of zEPHYR Project

- The idea is to develop innovative numerical methods in order to predict the noise radiated by wind turbine located in complex urban environment
- Project aims to design a complete workflow, starting from the wind turbine and meteorological inputs, to the far field audio rendering in a complex urban environment

Near field prediction of WT noise can be done by

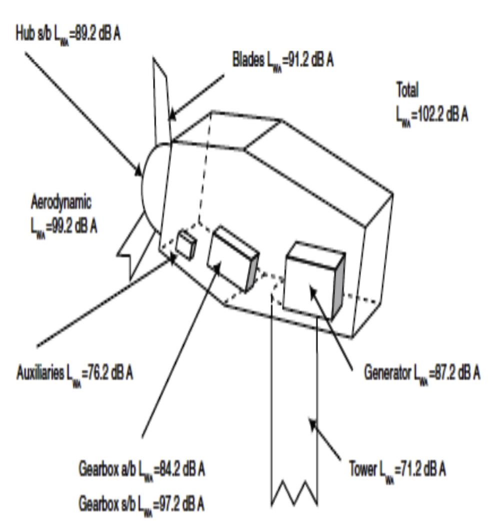
1. Low Order Semi Analytical Model
2. Finite Element Solver
    - Developed by Siemens Digital Industries Software

Expertise of Centre Scientifique et Technique du Bâtiment will help us to understand

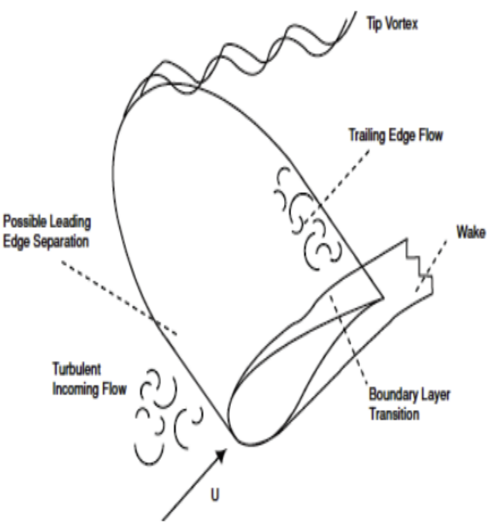
1. The propagation of sound waves in urban environments, over large distances, including meteorological, turbulence and topography effects
2. CSTB outdoor propagation models and auralization techniques will be used

Sources of Wind Turbine Noise

Mechanical Noise



Aerodynamic Noise



Mechanical Noise

Mechanical noise usually originates within the components within WT

- Generator, hydraulic system and the gearbox
- Fans, inlets/outlets / ducts

  This noise tend be more tonal and narrow band in nature which is more irritating than broadband sound[1]

Mechanical noise is propagated by two major ways

1. Airborne Noise

[1] Klug H et al. Standards and Noise Reduction Procedures Forum Acusticum, 2002, Sevilla, Spain

[2] Romero Sanz et al. Noise management on modern wind turbines, 2008, Madrid, Spain

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Mechanical noise is propagated by two major ways

1. Airborne Noise

   ▶This is straightforward as sound is directly emitted to surroundings
2. Structural Noise

   ▶It is a bit complex as it can be transmitted along the structure of turbine and then into the surroundings through different surfaces such as casing, nacelle cover, rotor blades[2]

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Aerodynamic Noise

- ✓ Aerodynamic Noise is more complex and dominant source of noise from WT, with SPL of 99.2 dB [3]
- ✓ Six major regions along the blade create independently their specific noise as noise produced are fundamentally different and as they occur in different region along the blade, they do not interfere with each other

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1. Turbulent boundary layer trailing edge noise
2. Laminar-Boundary-Layer Vortex- Shedding (LBL VS) Noise
3. Separation-Stall Noise
4. Trailing-Edge-Bluntness Vortex-Shedding Noise
5. Tip Vortex Formation Noise
6. Turbulent Inflow Noise

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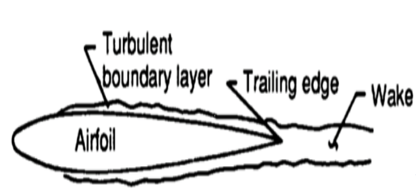
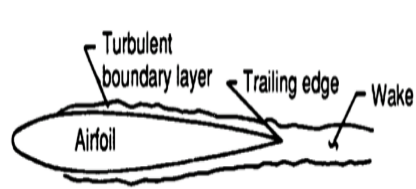


[4]

Turbulent Boundary Layer Trailing Edge Noise

- TBL - TE is a predominant source of noise in WT and it originates as a result of interaction of boundary layer and trailing edge of airfoil
- When Reynolds Number is too high (> 1 million) typically a turbulent boundary layer develops along the blade surface, which remains attached to the trailing edge
- As the turbulent eddies are convected past the trailing edge, their sound is scattered at the trailing edge causing Broadband Noise

[4] Ofelia Jianu et al. Noise Pollution Prevention in Wind Turbines: Status and Recent Advances



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- TBL - TE noise determines the lower bound of WT noise and considered to be an important noise source in WT

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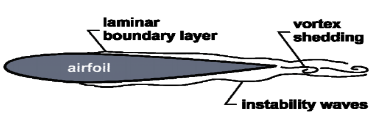
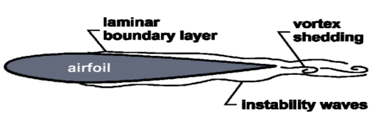


[5]

Laminar - Boundary Layer Vortex Shedding Noise

- When Re < 1 Million, the BL on either side of airfoil may remain laminar until trailing edge
- Upstream radiating noise from trailing edge may then trigger Laminar- Turbulent Transition or Boundary Layer Instabilities (Tollmien-Schlichting Waves) which in-turns trailing edge noise
- If such a feedback occurs, high level of Tonel noise maybe generated
- A whistling noise can be encountered which is called Laminar BL- Vortex Shedding Noise

[5] S. Oerlemans et al. Wind turbine noise: primary noise sources, 2011, The Netherlands



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- A whistling noise can be encountered which is called Laminar BL- Vortex Shedding Noise
- However, this noise source is considered only relevant for small wind turbines, which have relatively small blades
- Laminar BL- Vortex Shedding Noise can be prevented by tripping the boundary layer, which induces transition from laminar to turbulent flow

[5] S. Oerlemans et al. Wind turbine noise: primary noise sources, 2011, The Netherlands

Separation - Stall Noise

- As the AoA increases, at some point the flow will separate from the suction side of the airfoil & it corresponds to the so-called stall
- Stall causes a substantial level of unsteady flow around the airfoil, which may lead to a significant increase in noise

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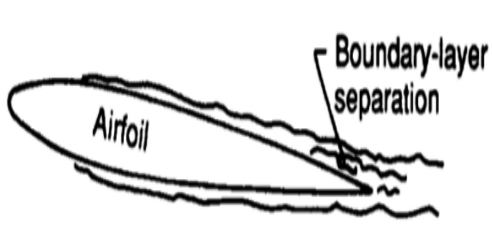

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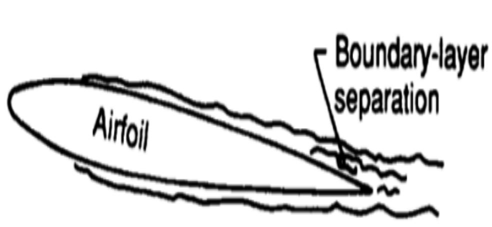
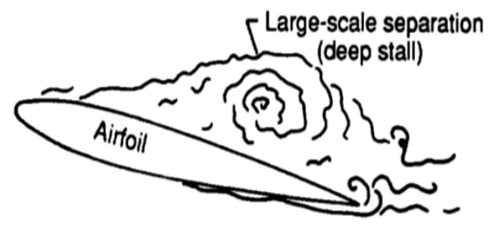
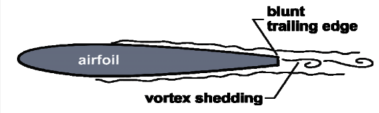




Trailing-Edge-Bluntness Vortex-Shedding Noise



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- It occurs when trailing edge noise is increased above a critical value
- Periodic Von Karman type vortex shedding from the trailing edge may then result in tonal noise
- Blunt edge noise can be prevented by proper design of blades, i.e sufficiently small thickness of trailing edge

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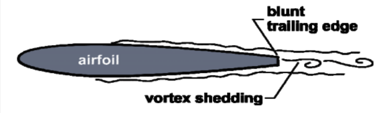

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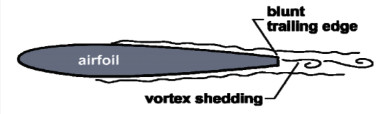

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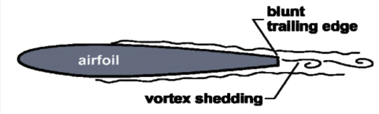

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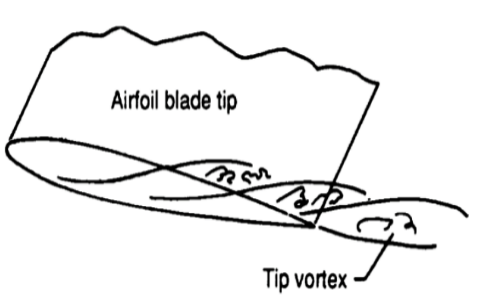

Turbulence Inflow Noise

- At low frequencies, the interaction of the turbulent inflow with the leading edge of the turbine blades proves to be a significant source of noise
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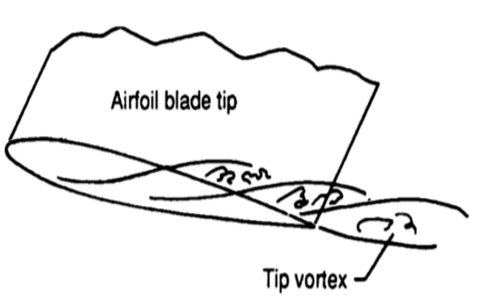

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- Dipole noise source is dependent on the Mach number to the sixth power
- Scattered quadrupole noise source is dependent on the Mach number to the fifth power

- Literature demonstrates that broadband trailing edge noise is the dominant noise source for both turbines [7]
- To predict effectively the trailing edge noise, generated by WT a series of process should be followed

[7] S. Oerlemans et al. Prediction of wind turbine noise and validation against experiment, International Journal of Aeroacoustics, 2009,UK

Prediction Method of Noise

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✓ Blade Aerodynamics

✓ Trailing edge noise source

✓ Directivity and convective amplification

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★ Noise radiated to the far-field can be predicted by Ffowcs WilliamseHawkings (FWeH) equation

★ FWeH equation was developed in 1969 from Lighthill's acoustic analogy by including the effect of the moving solid body

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★ This equation is a rearrangement of continuity equation and Navier Stokes equations into an inhomogeneous wave equation with sources of sound

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Generalised, continuity equation can be written as

$$\frac{\bar{\partial}\tilde{\rho}}{\partial t} + \frac{\bar{\partial}\tilde{\rho}\tilde{u}_i}{\partial x_i} = \left(\rho' \frac{\partial f}{\partial t} + \rho u_i \frac{\partial f}{\partial x_i}\right) \delta(f) \tag{1}$$

$\delta(f)$is the Dirac's delta function which is derivative of Heaviside function

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$\delta(f)$is the Dirac's delta function which is derivative of Heaviside function

Similarly, the generalised conservation of momentum equation is obtained by substituting the generalised variables into the ordinary equation

$$\frac{\overrightarrow{\bar{\partial}\rho}\tilde{u}_i}{\partial t} + \frac{\bar{\partial}\left(\tilde{\rho}\tilde{u}_i\tilde{u}_j + \tilde{p}_{ij}\right)}{\partial x_j} = \left(\rho u_i \frac{\partial f}{\partial t} + \left(\rho u_i u_j + p'_{ij}\right)\frac{\partial f}{\partial x_j}\right)\delta(f) \tag{2}$$

These equations are combined and rearranged, by assuming no fluid flow through the control surface, to give differential FWeH equation

$$\frac{1}{c_0^2}\frac{\partial^2 p'}{\partial t^2} - \overline{\nabla^2} p' = \frac{\partial}{\partial t}\left[\left(\rho_0 v_n\right)\delta(f)\right] - \frac{\partial}{\partial x_i}\left[l_i \delta(f)\right] + \frac{\overline{\partial^2}}{\partial x_i \partial x_j}\left[T_{ij} H(f)\right] \tag{3}$$

Solution of Ffowcs Williamse Hawkings (FWeH) equation

Integral form of Eq. (3) is obtained by using Green's function of wave equation in unbounded 3D

$$G(\vec{x}, t; \vec{y}, \tau) = \begin{cases} 0 & \tau > t \\ \frac{\delta(g)}{4\pi r} & \tau \leq t \end{cases} \quad where g = \tau - t + r/c_0, r = |x_i - y_i| \tag{4}$$

Only the surface source terms are considered and the integral form of FWeH equation is obtained as

$$\begin{aligned} p'(\vec{x}, t) =& \frac{\partial}{\partial t} \int_{-\infty}^{t} \int_{-\infty}^{\infty} \frac{\rho_0 v_n \delta(f) \delta(g)}{4\pi r} \mathrm{d}\vec{y} \mathrm{d}\tau \\ & - \frac{\partial}{\partial x_i} \int_{-\infty}^{t} \int_{-\infty}^{\infty} \frac{l_i \delta(f) \delta(g)}{4\pi r} \mathrm{d}\vec{y} \mathrm{d}\tau \end{aligned} \tag{5}$$

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The changes of variables are required for integrating the delta functions. First, integration over τ is performed.

$$\mathbf{d}\tau \equiv \frac{\mathrm{d}g}{|\mathbf{d}g/\mathrm{d}\tau|} = \frac{\mathrm{d}g}{|\mathbf{1} - \mathbf{M}_r|} \tag{6}$$

Secondly, the integrating over one space dimension is performed

$$\mathrm{d}\vec{y} \equiv \frac{\mathrm{d}y_1\mathrm{d}y_2\mathrm{d}f}{|\mathrm{d}f/\mathrm{d}y_3|} = \mathrm{d}S\mathrm{d}f \tag{7}$$

After the integration of the delta functions, the retarded-time formulation of FWeH equation is obtained

$$
\begin{aligned}
4\pi p'_T(x,t) = &\int_{f-0} \left[\frac{\rho_0 \left(\dot{v}_n + v_n \right)}{r \left(1 - M_r\right)^2} \right]_{ret} \mathrm{d}S \\
&+ \int_{f=0} \left[\frac{\rho_0 v_n \left(r M_i r_i + c_0 M_r - c_0 M^2 \right)}{r^2 \left(1 - M_r\right)^3} \right]_{ret} \mathrm{d}S
\end{aligned}
\tag{8}
$$

$$
\begin{aligned}
4\pi p'_L(x,t) = &\frac{1}{c_0} \int_{f=0} \left[\frac{l_i r_i}{r \left(1 - M_r\right)^2} \right]_{ret} \mathrm{d}S \\
&+ \int_{f=0} \left[\frac{l_r - l_i M_i}{r^2 \left(1 - M_r\right)^2} \right]_{ret} \mathrm{d}S \\
&+ \frac{1}{c_0} \int_{f=0} \left[\frac{l_r \left(r M_i r_i + c_0 M_r - c_0 M^2 \right)}{r^2 \left(1 - M_r\right)^3} \right]_{ret} \mathrm{d}S
\end{aligned}
\tag{9}
$$

P_T is thickness noise, P_L is loading noise & $M_r$is the relative mach number in radiation direction (Most common solution to the FWeH equation and called Farassat's formulation 1)

Thank You!