

MAE 298 Aeroacoustics – Homework #2

Lilley’s Equation Solution and Application to Jet Noise

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Nomenclature

R_j	Axisymmetric jet radius	E	Exponential term: $kz + n\theta - \omega t$
W_j	Jet exit mean velocity	P	
$\bar{\rho}_j$	Jet exit mean density	k	
W_0	Ambient mean velocity	ω	
$\bar{\rho}_0$	Ambient mean density	n	
$W(r)$	Radial distribution of axial velocity	r	
$\bar{a}^2(r)$	Radial distribution of speed of sound squared	θ	
p'	Perturbation pressure	z	
i	Imaginary number $\sqrt{-1}$		

I. Background

The following analysis will derive solutions to Lilley’s equation for parallel axisymmetric flow (Eqn 1):

$$\left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right)^3 p' - \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) \left(\bar{a}^2 \nabla^2 p'\right) - \frac{d\bar{a}^2}{dr} \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) \frac{dp'}{dr} + 2\bar{a}^2 \frac{dW}{dr} \frac{\partial^2 p'}{\partial z \partial r} = S(\vec{x}, t) \quad (1)$$

$$\text{where } \nabla^2 \equiv \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r}\right) + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}$$

$W(r)$ is the radial distribution of axial velocity and $\bar{a}^2(r)$ is the radial distribution of speed of sound squared.

After a general solution is derived, it will be applied to find homogeneous solutions to the far-field and potential core regions of an axial jet. Finally, the conditions for matching the solutions for this regions will be discussed.

II. Problem 1 – Solution to Lilley’s Equation

Seek solutions of Lilley’s equation in the form:

$$p'(r, \theta, z, t) \sim P(r) \exp[i(kz + n\theta - \omega t)] \quad (2)$$

Assume:

1. $\bar{a}^2 = \frac{\gamma \bar{p}}{\bar{\rho}}$
2. $\bar{p} = \text{const}$

where $\bar{\rho}(r)$ is the radial distribution of the mean density. Show that Lilley's equation reduces to (Eqn 3):

$$\frac{d^2 P}{dr^2} + \left\{ \frac{1}{r} - \frac{1}{\bar{\rho}} \frac{d\bar{\rho}}{dr} + \frac{2k}{(\omega - kW)} \frac{dW}{dr} \right\} \frac{dP}{dr} + \left\{ \frac{(\omega - kW)^2}{a^2} - k^2 - \frac{n^2}{r^2} \right\} P = RHS \quad (3)$$

To aid in this derivaiton, we find the results for the first-order partial derivatives of parameters relevant to the solution. First, we compute the derivative of the perturbation pressure p' with respect to (WRT) time t :

$$\begin{aligned} \frac{\partial p'}{\partial t} &= \frac{\partial}{\partial t} \{P(r) \exp[i(kz + n\theta - \omega t)]\} \\ &= P \frac{\partial}{\partial t} [i(kz + n\theta - \omega t)] \exp[i(kz + n\theta - \omega t)] \\ &= iP \left[\frac{\partial}{\partial t} (kz) + \frac{\partial}{\partial t} (n\theta) - \frac{\partial}{\partial t} (\omega t) \right] \exp[i(kz + n\theta - \omega t)] \end{aligned}$$

$$\boxed{\frac{\partial p'}{\partial t} = -iP\omega \exp[i(kz + n\theta - \omega t)] = -iP\omega e^{iE}} \quad (4)$$

where $E = kz + n\theta - \omega t$, $\frac{\partial E}{\partial t} = -\omega$, and $\frac{\partial E}{\partial z} = k$. Next, we compute the derivative of p' WRT the angular direction θ :

$$\begin{aligned} \frac{\partial p'}{\partial \theta} &= \frac{\partial}{\partial \theta} \{P(r) \exp[i(kz + n\theta - \omega t)]\} \\ &= P \frac{\partial}{\partial \theta} [i(kz + n\theta - \omega t)] \exp[i(kz + n\theta - \omega t)] \\ &= iP \left[\frac{\partial}{\partial \theta} (kz) + \frac{\partial}{\partial \theta} (n\theta) - \frac{\partial}{\partial \theta} (\omega t) \right] \exp[i(kz + n\theta - \omega t)] \end{aligned}$$

$$\boxed{\frac{\partial p'}{\partial \theta} = iPn \exp[i(kz + n\theta - \omega t)] = iPn e^{iE}} \quad (5)$$

Next, we compute the derivative of p' WRT the axial flow direction z :

$$\begin{aligned} \frac{\partial p'}{\partial z} &= \frac{\partial}{\partial z} \{P(r) \exp[i(kz + n\theta - \omega t)]\} \\ &= P \frac{\partial}{\partial z} [i(kz + n\theta - \omega t)] \exp[i(kz + n\theta - \omega t)] \\ &= iP \left[\frac{\partial}{\partial z} (kz) + \frac{\partial}{\partial z} (n\theta) - \frac{\partial}{\partial z} (\omega t) \right] \exp[i(kz + n\theta - \omega t)] \end{aligned}$$

$$\boxed{\frac{\partial p'}{\partial z} = iPk \exp[i(kz + n\theta - \omega t)] = iPk e^{iE}} \quad (6)$$

Next, we compute the derivative of p' WRT the radial direction r :

$$\frac{\partial p'}{\partial r} = \frac{\partial}{\partial r} \{P(r) \exp[i(kz + n\theta - \omega t)]\}$$

$$\boxed{\frac{\partial p'}{\partial r} = \frac{dP}{dr} \exp[i(kz + n\theta - \omega t)] = \frac{dP}{dr} e^{iE}} \quad (7)$$

II.A. Term 1

To simplify the derivation, we will apply the solution form individually to each term in Lilley's equation. For the first term, we must apply the multi-derivative operator a total of three times:

$$\begin{aligned} \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right)^3 p' &= \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right)^2 \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) p' \\ &= \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right)^2 \left(\frac{\partial p'}{\partial t} + W \frac{\partial p'}{\partial z}\right) \\ &= \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right)^2 (-P\omega i e^{iE} + PkWi e^{iE}) \\ &= \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) (-\omega + kW)Pi(e^{iE}) \\ &= \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) (-\omega + kW)Pi(-i\omega e^{iE} + ikWe^{iE}) \\ &= \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) (-\omega + kW)^2 Pi^2(e^{iE}) \\ &= (-\omega + kW)^3 Pi^3(e^{iE}) = (-\omega + kW)^3 P(-i)(e^{iE}) \\ &= (\omega - kW)^3 iP(e^{iE}) \end{aligned}$$

The cubed imaginary number i^3 simplifies to $-i$ and the -1 is distributed into the cubed factor. This results in the final expression for Term 1:

$$\boxed{\left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right)^3 p' = i \exp[i(kz + n\theta - \omega t)](\omega - kW)^3 P} \quad (8)$$

II.B. Term 2

Application of the solution form to second term (Eqn 9) of Lilley's equation is slightly more involved.

$$\left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) (\bar{a}^2 \nabla^2 p') \quad (9)$$

Term 2 requires computing the double divergence of perturbation pressure $\nabla^2 p'$:

$$\begin{aligned} \nabla^2 p' &= \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial p'}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 p'}{\partial \theta^2} + \frac{\partial^2 p'}{\partial z^2} \\ &= \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{dP}{dr} e^{iE} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} (P n i e^{iE}) + \frac{\partial}{\partial z} (P k i e^{iE}) \\ &= \frac{1}{r} e^{iE} \left(\frac{dP}{dr} + r \frac{d^2 P}{dr^2} \right) + \frac{1}{r^2} P n^2 i^2 e^{iE} + P k^2 i^2 e^{iE} \\ &= e^{iE} \frac{d^2 P}{dr^2} + e^{iE} \frac{1}{r} \frac{dP}{dr} + i^2 e^{iE} \left(\frac{n^2}{r^2} + k^2 \right) P \end{aligned}$$

Thus, the double divergence of p' can be expressed in the following expression, which is separated into like differential terms of P :

$$\boxed{\nabla^2 p' = \exp[i(kz + n\theta - \omega t)] \left[\frac{d^2 P}{dr^2} + \frac{1}{r} \frac{dP}{dr} - \left(\frac{n^2}{r^2} + k^2 \right) P \right]} \quad (10)$$

Substituting Eqn 10 into Term 2 (Eqn 9), we can perform the multi-derivative expression to derive the final term. All terms grouped with P as well as a are constant WRT t and z and can be carried outside of the derivative expression.

$$\begin{aligned} \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) (\bar{a}^2 \nabla^2 p') &= \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) \bar{a}^2 e^{iE} \left[\frac{d^2 P}{dr^2} + \frac{1}{r} \frac{dP}{dr} - \left(\frac{n^2}{r^2} + k^2 \right) P \right] \\ &= \bar{a}^2 \left[\frac{d^2 P}{dr^2} + \frac{1}{r} \frac{dP}{dr} - \left(\frac{n^2}{r^2} + k^2 \right) P \right] \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) e^{iE} \\ &= \bar{a}^2 \left[\frac{d^2 P}{dr^2} + \frac{1}{r} \frac{dP}{dr} - \left(\frac{n^2}{r^2} + k^2 \right) P \right] (-\omega i e^{iE} + k W i e^{iE}) \\ &= -\bar{a}^2 i e^{iE} (\omega - kW) \left[\frac{d^2 P}{dr^2} + \frac{1}{r} \frac{dP}{dr} - \left(\frac{n^2}{r^2} + k^2 \right) P \right] \end{aligned}$$

This results in the final expression for Term 2:

$$\boxed{\left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z}\right) (\bar{a}^2 \nabla^2 p') = -\bar{a}^2 i \exp[i(kz + n\theta - \omega t)] (\omega - kW) \left[\frac{d^2 P}{dr^2} + \frac{1}{r} \frac{dP}{dr} - \left(\frac{n^2}{r^2} + k^2 \right) P \right]} \quad (11)$$

II.C. Term 3

Applying the solution form to third term of Lilley's equation:

$$\begin{aligned}\frac{\overline{da^2}}{dr} \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z} \right) \frac{dp'}{dr} &= \frac{\overline{da^2}}{dr} \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z} \right) \frac{dP}{dr} e^{iE} \\ &= \frac{\overline{da^2}}{dr} \frac{dP}{dr} \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z} \right) e^{iE} \\ &= \frac{\overline{da^2}}{dr} \frac{dP}{dr} i(-\omega + kW) e^{iE}\end{aligned}$$

Applying the isentropic relationship assumption for speed of sound and taking the derivative WRT r :

$$\begin{aligned}\frac{\overline{da^2}}{dr} \frac{dP}{dr} i(-\omega + kW) e^{iE} &= \frac{d}{dr} \left(\frac{\gamma \overline{p}}{\overline{\rho}} \right) \frac{dP}{dr} i(-\omega + kW) e^{iE} \\ &= - \left(\frac{\gamma \overline{p}}{\overline{\rho}^2} \right) \frac{d\overline{p}}{dr} \frac{dP}{dr} i(-\omega + kW) e^{iE} \\ &= \left(\frac{\overline{a^2}}{\overline{\rho}} \right) \frac{d\overline{p}}{dr} \frac{dP}{dr} i(\omega - kW) e^{iE}\end{aligned}$$

This results in the final expression for Term 3:

$$\boxed{\frac{\overline{da^2}}{dr} \left(\frac{\partial}{\partial t} + W \frac{\partial}{\partial z} \right) \frac{dp'}{dr} = \overline{a^2} i \exp[i(kz + n\theta - \omega t)] (\omega - kW) \frac{1}{\overline{\rho}} \frac{d\overline{p}}{dr} \frac{dP}{dr}} \quad (12)$$

II.D. Term 4

Apply solution form to fourth term of Lilley's equation:

$$\begin{aligned}2\overline{a^2} \frac{dW}{dr} \frac{\partial^2 p'}{\partial z \partial r} &= 2\overline{a^2} \frac{dW}{dr} \frac{\partial}{\partial z} \frac{\partial p'}{\partial r} = 2\overline{a^2} \frac{dW}{dr} \frac{\partial}{\partial z} \left(\frac{dP}{dr} e^{iE} \right) \\ &= 2\overline{a^2} \frac{dW}{dr} \frac{dP}{dr} \frac{\partial}{\partial z} (e^{iE}) = 2\overline{a^2} \frac{dW}{dr} \frac{dP}{dr} i k e^{iE}\end{aligned}$$

This results in the final expression for Term 4:

$$\boxed{2\overline{a^2} \frac{dW}{dr} \frac{\partial^2 p'}{\partial z \partial r} = \overline{a^2} i \exp[i(kz + n\theta - \omega t)] 2k \frac{dW}{dr} \frac{dP}{dr}} \quad (13)$$

II.E. Lilley's Equation Solution

To derive the final form of Lilley's equation, we combine Terms 1 through 4:

$$Eqn\ 8 - Eqn\ 11 - Eqn\ 12 + Eqn\ 13 = S(\vec{x}, t)$$

Which becomes the following in expanded form:

$$\left\{ie^{iE}(\omega - kW)^3P\right\} - \left\{-\overline{a^2}ie^{iE}(\omega - kW)\left[\frac{d^2P}{dr^2} + \frac{1}{r}\frac{dP}{dr} - \left(\frac{n^2}{r^2} + k^2\right)P\right]\right\} \\ - \left\{\overline{a^2}ie^{iE}(\omega - kW)\frac{1}{\bar{\rho}}\frac{d\bar{\rho}}{dr}\frac{dP}{dr}\right\} + \left\{\overline{a^2}ie^{iE}2k\frac{dW}{dr}\frac{dP}{dr}\right\} = S(\vec{x}, t)$$

Dividing both sides of the equation by the term $\overline{a^2}ie^{iE}(\omega - kW)$:

$$\frac{(\omega - kW)^2}{\overline{a^2}}P + \frac{d^2P}{dr^2} + \frac{1}{r}\frac{dP}{dr} - \left(\frac{n^2}{r^2} + k^2\right)P - \frac{1}{\bar{\rho}}\frac{d\bar{\rho}}{dr}\frac{dP}{dr} + \frac{1}{\omega - kW}2k\frac{dW}{dr}\frac{dP}{dr} = \frac{S(\vec{x}, t)}{\overline{a^2}ie^{iE}(\omega - kW)} \\ \frac{d^2P}{dr^2} + \frac{1}{r}\frac{dP}{dr} - \frac{1}{\bar{\rho}}\frac{d\bar{\rho}}{dr}\frac{dP}{dr} + \frac{1}{\omega - kW}2k\frac{dW}{dr}\frac{dP}{dr} + \frac{(\omega - kW)^2}{\overline{a^2}}P - \left(\frac{n^2}{r^2} + k^2\right)P = \frac{S(\vec{x}, t)}{\overline{a^2}ie^{iE}(\omega - kW)}$$

Grouping like terms of P , we obtain the final form of the general solution of Lilley's Equation:

$$\boxed{\frac{d^2P}{dr^2} + \left\{\frac{1}{r} - \frac{1}{\bar{\rho}}\frac{d\bar{\rho}}{dr} + \frac{1}{\omega - kW}2k\frac{dW}{dr}\right\}\frac{dP}{dr} + \left\{\frac{(\omega - kW)^2}{\overline{a^2}} - \left(\frac{n^2}{r^2} + k^2\right)\right\}P = \frac{S(\vec{x}, t)}{\overline{a^2}ie^{iE}(\omega - kW)}} \quad (14)$$

where $E = kz + n\theta - \omega t$.

III. Problem 2 – General Solution for Jet Flow Far-Field

Next, we will solve the homogeneous form of Lilley's equation (Eqn 14) to determine the general solution for the pressure fluctuation outside of the jet in the ambient medium where the sources vanish. This region can be considered to be the far-field of the jet, so the solution must be chosen to ensure decaying solutions (outgoing waves).

Since this is far-field, ambient flow, we will assume that the mean velocity and density in this region are equal to the ambient mean values:

$$W(r) = W_\infty = \text{const} \\ \bar{\rho} = \bar{\rho}_0 = \text{const} \quad (15)$$

which allows us to simplify the homogeneous equation:

$$\frac{d^2P}{dr^2} + \left\{\frac{1}{r} - \frac{1}{\bar{\rho}}\frac{d\bar{\rho}}{dr} + \frac{1}{\omega - kW}2k\frac{dW}{dr}\right\}\frac{dP}{dr} + \left\{\frac{(\omega - kW)^2}{\overline{a^2}} - \left(\frac{n^2}{r^2} + k^2\right)\right\}P = 0 \\ \frac{d^2P}{dr^2} + \left\{\frac{1}{r} - \frac{1}{\bar{\rho}_0}\frac{d\bar{\rho}_0}{dr} + \frac{1}{\omega - kW_\infty}2k\frac{dW_\infty}{dr}\right\}\frac{dP}{dr} + \left\{\underbrace{\frac{(\omega - kW_\infty)^2}{\overline{a^2}}}_{\lambda^2} - k^2 - \frac{n^2}{r^2}\right\}P = 0$$

Resulting in the homogeneous Bessel equation:

$$\boxed{\frac{d^2P}{dr^2} + \left\{\frac{1}{r}\right\}\frac{dP}{dr} + \left\{\lambda_\infty^2 - \frac{n^2}{r^2}\right\}P = 0} \quad (16)$$

where the constant term is collected in λ_∞ :

$$\lambda_\infty = \sqrt{\frac{(\omega - kW_\infty)^2}{a^2} - k^2}$$

Substituting the definition of wavenumber $k = \frac{\omega}{a}$, the expression can be reduced:

$$\begin{aligned}\lambda_\infty &= \sqrt{\frac{\left(\omega - \frac{\omega}{a}W_\infty\right)^2}{a^2} - \frac{\omega^2}{a^2}} \\ &= \sqrt{\frac{\omega^2 \left(1 - \frac{W_\infty}{a}\right)^2}{a^2} - \frac{\omega^2}{a^2}} \\ &= \sqrt{\frac{\omega^2}{a^2} \left[\left(1 - \frac{W_\infty}{a}\right)^2 - 1\right]} \\ &= \sqrt{\frac{\omega^2}{a^2} \left(1 - 2\frac{W_\infty}{a} + \frac{W_\infty^2}{a^2} - 1\right)} \\ &= \sqrt{\frac{\omega^2}{a^2} \left(\frac{W_\infty^2}{a^2} - 2\frac{W_\infty}{a}\right)} \\ &= \sqrt{\frac{\omega^2}{a^2} \frac{W_\infty}{a} \left(\frac{W_\infty}{a} - 2\right)}\end{aligned}$$

Substituting the definition of Mach number $M_\infty = \frac{W_\infty}{a}$, we obtain:

$$\lambda_\infty = \sqrt{\frac{\omega^2}{a^2} M_\infty (M_\infty - 2)} \quad (17)$$

where M_∞ is the freestream Mach number and λ_∞ is an imaginary quantity for $M_\infty < 2$.

Eqn 16 is of the same form as Bessel's ordinary differential equation and can be solved using the first $H_n^{(1)}(\lambda_\infty r)$ and second $H_n^{(2)}(\lambda_\infty r)$ order Hankel functions:

$$P = CH_n^{(1)}(\lambda_\infty r) + DH_n^{(2)}(\lambda_\infty r) \quad (18)$$

where C and D are arbitrary constants and the first and second order Hankel functions are equal to the outgoing $H_n^+(x)$ and incoming $H_n^-(x)$ wave solutions, respectively, and $x = \lambda_\infty r$:

$$H_n^{(1)}(\lambda_\infty r) = H_n^+(x) = J_n(x) + iY_n(x) \quad (19)$$

$$H_n^{(2)}(\lambda_\infty r) = H_n^-(x) = J_n(x) - iY_n(x) \quad (20)$$

where the Hankel functions are composed of the first and second order Bessel functions J_n and Y_n , respectively.

Taking the limit of $H_n^+(x)$ and $H_n^-(x)$ as x and r approach infinity (far-field condition):

$$\begin{aligned}\lim_{x \rightarrow \infty} H_n^+(x) &= (-i)^{n+1} \frac{e^{ix}}{x} \\ \lim_{x \rightarrow \infty} H_n^-(x) &= i^{n+1} \frac{e^{-ix}}{x}\end{aligned}$$

In the far-field, flow velocity is subsonic ($M_\infty < 1$), making λ_∞ imaginary according to Eqn 17. This, in turn, makes the limit of $H_n^+(x)$ a diminishing exponential and the limit of $H_n^-(x)$ an increasing exponential, which is impossible. Thus, Eqn 16 reduces to Eqn 21 for the far-field:

$$P = CH_n^{(1)}(\lambda_\infty r) \quad (21)$$

IV. Problem 3 – General Solution for Jet Potential Core

Determine the general form of solution (solution of the homogeneous equation) in the potential core region where the mean velocity and density are constant and equal to the jet exit values.

In this section, we will solve the homogeneous form of Lilley's equation (Eqn 14) to determine the general solution for the potential core region of the jet. We will assume that the mean velocity and density in this region are constant and equal to the jet exit values:

$$W(r) = W_j = \text{const} \quad (22)$$

$$\bar{\rho} = \bar{\rho}_j = \text{const} \quad (23)$$

V. Problem 4 – Matching of Far-Field and Potential Core Solutions

Consider a case in which the real jet is replaced by a vortex sheet at $r = R_j$. If the solutions are to be matched at the vortex sheet, describe what matching conditions should be applied. Give both the physical description and the mathematical expressions.