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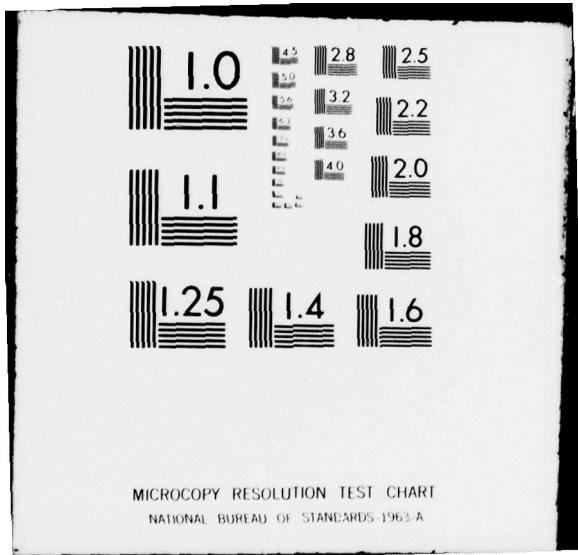
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I. INTRODUCTION

Recently, the author [1] analyzed the noise radiated by boundary-layer transition. An expression for the power spectrum and directivity of the radiated pressure was developed in this analysis. In his examples, it was shown that the predicted spectra agree quite well with available experimental spectral data. It was further discussed that the radiated energy due to fully-developed turbulent motion over the test bodies also contribute significantly to the observed spectra, particularly at higher frequencies. Because of this observation we are motivated to compare the relative efficiencies of the two types of hydrodynamic sources. This comparison is developed in this note.

II. ANALYSIS

In general, the acoustic efficiency is defined by:

$$\eta = N_a / N_h \quad , \quad (1)$$

where N_a is the acoustic power radiated to the farfield by the source under consideration, and N_h is the work expended per unit time by the hydrodynamic motions within the acoustic source region. We will first examine the acoustic efficiency for the transition zone.

A. Transition Zone Acoustic Efficiency

We begin with the power spectrum of the acoustic pressure radiated per unit spanwise width of boundary-layer transition [1]:

$$\frac{\partial G}{\partial x_3} = \frac{\cos^2 \theta \sigma^2(x_0) u_c (\Delta x)^2}{2\pi^2 r^2 c^2} (\kappa \Delta x)^2 F(\kappa \Delta x, u_0/u_c) [1 + (\omega t_i)^2]^{-1} \quad , \quad (2)$$

where θ is the angle between the flow direction and observation point, which is a distance r away from the initial line of laminar flow breakdown, x_0 . The small distance, Δx , is the streamwise extent of intermittent transitional flow, u_c is the velocity of burst convection, c is the velocity of sound, ω is the radian frequency, with

$$\kappa = \omega / u_0 \quad , \quad (3)$$

where u_0 is the free-stream velocity. The stress

$$\sigma(x_1) = \tau_T(x_1) - \tau_L(x_1) \quad (4)$$

represents the difference between the turbulent mean value of wall shear stress at position x_1 and a corresponding laminar value at the same point. The time, t_i , is representative of the time required for the wall shear stress to change from a locally laminar (or turbulent) to a locally turbulent (or laminar) value as turbulent bursts are created or convected by a given location on our rigid planar surface. The frequency function, $(\kappa \Delta x)^2 F(\kappa \Delta x, u_0/u_c)$ is presented graphically in Figure 7 of Reference [1]. Typically, it is only weakly dependent on

u_o/u_c , rises at 12dB/octave for $(\kappa\Delta x) < 1.0$ and approaches a constant (≈ 28 for $u_c/u_o = 0.7$) for $(\kappa\Delta x) > 1.0$.

If we express equation (2) as:

$$\frac{\partial G}{\partial x_3} = \cos^2\theta \langle p_o^2(\omega, u_o/u_c) \rangle,$$

the total acoustic power generated per unit spanwise width of transition is obtained by integrating the intensity over all frequencies and over the surface of a large sphere of radius r , i.e.,

$$N_a = \int_0^\infty \frac{\langle p_o^2 \rangle}{\rho c} d\omega \int_0^{2\pi} \int_0^\pi r^2 \cos^2\theta \sin\theta d\theta d\phi = \frac{4\pi r^2}{3\rho c} \int_0^\infty \langle p_o^2 \rangle d\omega \quad (5)$$

$$N_a = \frac{2\sigma^2(x_o) u_c (\Delta x)^2}{3\pi\rho c^3} \int_0^\infty (\kappa\Delta x)^2 F(\kappa\Delta x, u_o/u_c) [1+(\omega t_i)^2]^{-1} d\omega. \quad (6)$$

For $u_c/u_o = 0.7$, we can approximate the integrand by a constant (28 for this case) and integrate between the half-power points. In particular,

$$\begin{aligned} N_a &\approx \frac{2\sigma^2(x_o) u_c (\Delta x)^2}{3\pi\rho c^3} \left(28 \frac{u_c}{\Delta x}\right) \int_{0.5}^{\Delta x/u_o t_i} d(\kappa\Delta x) \\ &\approx 19.6 \left[\frac{2\sigma^2(x_o) u_o^2 \Delta x}{3\pi\rho c^3} \right] \left[\frac{\Delta x}{u_o t_i} - 0.5 \right]. \end{aligned}$$

Because t_i is very much smaller than $\Delta x/u_o$, we obtain:

$$N_a \approx \frac{4\sigma^2(x_o) u_o (\Delta x)^2}{\rho c^3 t_i} \quad (7)$$

for the total acoustic power generated by boundary-layer transition of unit spanwise width.

The hydrodynamic power generated within a unit spanwise width of boundary-layer transition is given by:

$$N_h = u_o \int_{x_o}^{x_o + \Delta x} \tau_o dx_1, \quad (8)$$

where τ_o is the mean value of the wall shear stress. Because bursting flow occurs between the limits of integration, we would expect that

$$\tau_o(x_1) = \tau_T(x_1)\gamma(x_1) + [1-\gamma(x_1)]\tau_L(x_1),$$

where $\gamma(x_1)$ is the intermittency factor. Because

$$\tau_o = (\tau_T - \tau_L)\gamma + \tau_L,$$

where $(\tau_T - \tau_L) = \sigma \approx 0.9\tau_T$ [1], we let

$$\tau_o(x_1) \approx \gamma(x_1) \sigma(x_1) \quad . \quad (10)$$

The intermittency distribution can be calculated using [2]:

$$\gamma(\bar{x}) = 1 - \exp(-4.185 \bar{x}^2) \quad , \quad (11)$$

where

$$\bar{x} = \frac{x_1 - x_o}{\Delta x} \quad . \quad (12)$$

We again assume, as in the original noise analysis [1], that;

$$\sigma(x_o) \approx \sigma(x_o + \Delta x) \quad (13)$$

such that

$$N_h \approx u_o \sigma(x_o) \int_{x_o}^{x_o + \Delta x} \gamma(x_1) dx_1 \quad .$$

Making the appropriate change of integration variable, we find that

$$N_h \approx u_o \Delta x \sigma(x_o) \left[1 - \int_0^1 \exp(-4.185 \bar{x}^2) d\bar{x} \right] \quad . \quad (14)$$

We now let $t^2 = 4.185 \bar{x}^2$, $d\bar{x} = 0.488 dt$, and find:

$$N_h \approx u_o \Delta x \sigma(x_o) \left[1 - 0.488 \frac{\sqrt{\pi}}{2} \operatorname{erf}(2.046) \right]$$

$$N_h \approx 0.572 u_o \Delta x \sigma(x_o) \quad . \quad (15)$$

We can now divide equation (7) by equation (15) to get:

$$\eta_{tr.} \approx \frac{7 \sigma(x_o) \Delta x}{\rho c^3 t_i} \quad . \quad (16)$$

It will prove expedient to re-work equation (16) a little further. We expect that t_i scales with the turbulent velocities very near and normal to the surface; these velocities scale with the friction velocity, u_* . We might further expect that there is a critical height, y_c , which is comparable to the viscous sub-layer thickness such that:

$$t_i \approx y_c / u_* \quad . \quad (17)$$

By definition,

$$y_c^+ = u_* y_c / \nu \quad , \quad (18)$$

where ν is the kinematic viscosity; thus,

$$t_i \approx y_c^+ \frac{\nu}{u_*^2} \quad , \quad (19)$$

and,

$$\eta_{tr.} \approx \frac{7\sigma(x_o) \Delta x u_*^2}{\rho c^3 y_c^+ \nu} \quad . \quad (20)$$

Now σ is very nearly equal to τ_T , so we let [3]

$$\sigma(x_o) \approx 0.0288 \rho u_o^2 Re_{x_o}^{-1/5} \quad , \quad (21)$$

and also let $u_* \approx u_o/30$ to get

$$\eta_{tr.} \approx 2.24 \times 10^{-4} \frac{Re_{\Delta x} M^3}{Re_{x_o}^{1/5} y_c^+} \quad . \quad (22)$$

In equation (22), Re_{x_o} is the transition Reynolds number and $Re_{\Delta x}$ is the transition streamwise extent Reynolds number which is approximately related to Re_{x_o} by [4]:

$$Re_{\Delta x} \approx 60 Re_{x_o}^{2/3} \quad . \quad (23)$$

A specific value cannot be assigned to y_c^+ at this time. A series of controlled experiments appear to be required in order to find the dependence of t_i on u_o^2/ν from which y_c^+ may be deduced. For order of magnitude estimates, however, we know that y_c^+ must be small ($5 < y_c^+ < 30$), viz., Tennekes and Lumley [5]. We see from equation (22) that the radiation efficiency of the laminar-to-turbulent transition zone depends upon the cube of the free-stream Mach number; a result to be expected for dipole sources.

For comparative purposes we would like to compare this efficiency with that of a fully-developed turbulent boundary layer flow. We must first obtain an expression for the efficiency of the latter.

B. Fully-Developed Turbulent Boundary Layer Acoustic Efficiency

Both Tam [6] and Landahl [7] recently developed theoretical models for the sound power generated by fully-developed boundary layer turbulence. Landahl derived the following proportionality for the efficiency:

$$\eta_{TBL} \sim \frac{u_*}{u_o} M_*^3 \quad ,$$

where $M_* = u_*/c$. Because the constant of proportionality is not implied in this relation, we cannot use it in a quantitative comparison with equation (22).

On the other hand, Tam did not derive an explicit expression for the efficiency, but did give an expression for the acoustic power generated per unit surface area of boundary layer turbulence. In particular,

$$N_{TBL} = \frac{4\pi\tau_T^2}{\rho c} \int_0^\infty F(S, M) dS, \quad (24)$$

where the integral is presented graphically in Reference [6] as a function of Mach number, M . Tam concluded that the magnitude of this integral increases rather rapidly with Mach number (slightly faster than M^2). We have thus been able to approximate it by:

$$\int_0^\infty F(S, M) ds \approx 0.015M^2 \quad (M > 0) \quad (25)$$

The hydrodynamic power generated per unit surface area of boundary layer turbulence is given by:

$$N_{h_T} = u_o \tau_T, \quad (26)$$

so we would expect that:

$$\eta_{TBL} \approx \frac{0.188 \tau_T M^2}{\rho c u_o} \quad (27)$$

Using equation (21) for τ_T , equation (27) reduces to:

$$\eta_{TBL} \approx 5.43 \times 10^{-3} Re_{x_1}^{-1/5} M^3 \quad (28)$$

We compare the transition zone acoustic efficiency with that of the fully-developed turbulent boundary layer flow by dividing equation (22) by equation (28), i.e.,

$$\frac{\eta_{tr.}}{\eta_{TBL}} \approx 4.13 \times 10^{-2} \left(\frac{Re_{x_1}}{Re_{x_0}} \right)^{1/5} \frac{Re_{\Delta x}}{y_c^+} \quad (29)$$

Typically, $Re_{\Delta x} \approx 5 \times 10^5$, a conservative estimate for y_c^+ would be about 30, and the ratio of length Reynolds numbers to the 1/5 power is of order one. Therefore, equation (29) suggests that the laminar-to-turbulent transition zone generates noise more efficiently than does a fully-developed turbulent boundary layer, i.e. the transition zone radiation is approximately a thousand times more efficient.

III. CONCLUSIONS

In this note, we have derived an expression for the acoustic efficiency of boundary-layer transition based on an analysis by Lauchle [1], and a corresponding expression for the efficiency of fully-developed turbulent boundary layer flow based on an analysis by Tam [6]. We have compared these two efficiencies and found that the noise generated by boundary-layer transition

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is considerably more efficient than that noise generated by a fully-developed turbulent boundary layer. For typical values of the Reynolds numbers upon which this comparison depends, transition zone radiation is shown to be about three orders of magnitude more efficient.

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