Center for Turbulence Research
Annual Research Briefs 2007

Issues in combustion noise

By R. Mani†

1. Motivation and objectives

The prinicipal concept pursued in Mani *et al.* (2000, 2006) and the present project is that inclusion of the "boundary conditions" imposed by turbomachnery is an essential ingredient of a rational approach to the physics and calculation of combustion noise. The calculation is carried to the noise output that may be expected at the downstream end of the turbine. The proposed analysis is linear and hence the noise output is proportional to the fluctuating heat release. The calculation includes details of all the waves produced fore and aft of the plane of fluctuating heat release prior to the calculation of noise (pressure wave) produced aft of the turbine. The boundary conditions needed to "close" the analytical problem and to solve it are indicated along with assessments of their validity. The fact that interest in combustion noise is in low frequencies *i.e.,* in relatively long wavelength phenomena, is used to simplify the calculation of "turbine transfer functions". If trends indicated by these calculations are actually representative of what might be the outcome of a more comprehensive approach, it could have significant impact on issues concerning combustion noise of aircraft engines, including issues such as experimental evaluation of combustion noise based on combustor component tests as well as the issue of approaches to the reduction of combustion noise.

A useful summary of the state of the art in core noise may be obtained from Krejsa (2003) and Mathews (2003). In Mani *et al.* (2000) it was argued that under conditions of inhomogeneous, steady heat release, the resulting inhomogeneous steady temperature distribution is a significant source of generation of entropy waves (much along the lines of how regions of high velocity gradients produce turbulence) and the so-called "indirect noise" due to passage of such entropy waves through the multi-stage turbine seemed to be the predominant source of combustor noise as opposed to the "direct noise" usually associated with the generation of pressure waves by unsteady combustion. Presumably a significant if not predominant reason for the generation of pressure waves by unsteady combustion would be the unsteady heat release produced by unsteady combustion. There could in turn be many reasons for unsteady combustion, both kinetic and fluid mechanical. A source of unsteady combustion followed by unsteady heat release which is fluctuations of mixture fraction can be estimated by 3D combustor codes even in the limit of equilibrium or fast chemistry models. It was this level of combustor CFD that was used in Mani *et al.* (2000) to derive estimates of the level of entropy waves, albeit the emphasis in that study was very much on the case of entropy wave generation by steady temperature gradients and not by unsteady heat release.

In Mani *et al.* (2000) indirect experimental data was presented in support of the thesis of entropy wave interaction with the (downstream) turbine as the dominant source of combustor noise, though (in those studies) this conclusion regarding entropy wave interaction with the (downstream) turbine being the dominant source of combustor noise was argued only in the case of spatially inhomogeneous steady heat release. The specific

---

† Current address: Aeroacoustics LLC 34 Ramlewood Court, Niskayuna, NY 12309

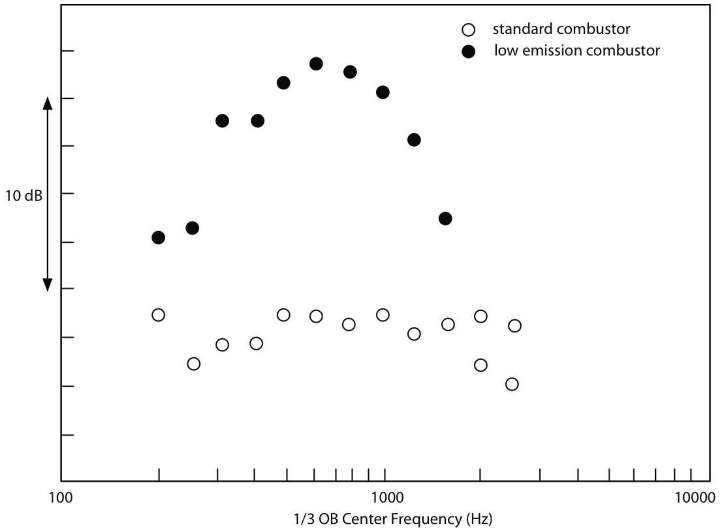

FIGURE 1. Approach power peak angle combustor noise spectra. SPL at 120° to inlet axis.

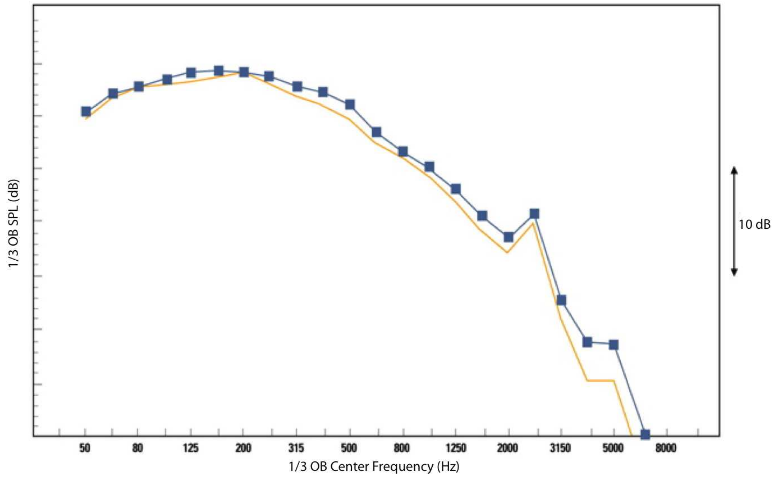

FIGURE 2. Peak angle noise spectra. SPL at 120° to inlet axis. Full power condition.

motivation of that study was the observation that dual annular combustors (DAC) relative to single annular combustors (SAC) seemed to have significantly more combustor noise at part load operation (approach condition). At such part load conditions the DAC produce a much more inhomogeneous steady temperature profile than equivalent SAC due to the difference in mode of burning. Figures 1 and 2 describe these results and figure 3 illustrates the difference between SAC and DAC. In figure 2 (full power condition) there is virtually no difference in the noise of the SAC and the DAC. In terms of figure 3, the DAC operates with only the pilot dome "lit" at approach, whereas both main and pilot domes are lit at the full power condition. Mani *et al.* (2000) provides details of the background to figures 1 and 2.

In a pioneering study, Cumpsty (1979) forcefully advocates the predominance of "indirect" noise for the case of noise produced by fluctuating heat release rather than due to

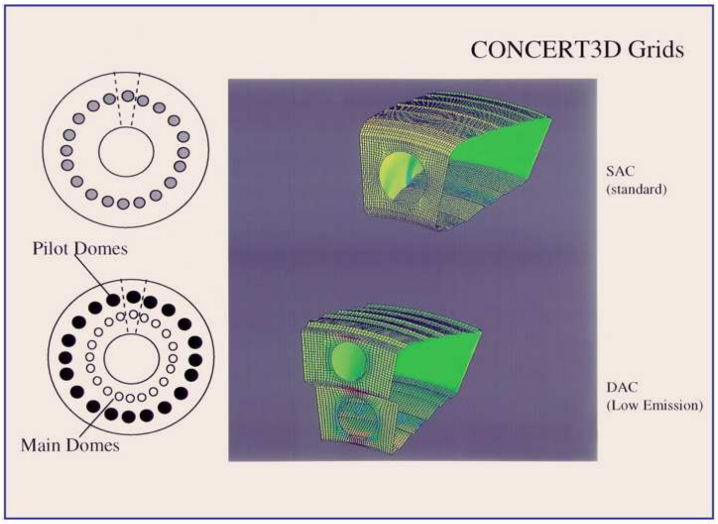

Figure 3. Single annular combustor (SAC) and double annular combustor (DAC).

spatially inhomogeneous steady heat release. He also presents two uncoupled calculations (the first a calculation of sound, shear and entropy waves produced by unsteady hear release from a flame sheet and the second, of "indirect noise" produced by the passage of entropy waves through a multi-stage turbine), and then examines the product of the two solutions for a turbine and combustor typical of the RB211 at take-off conditions. His concluding remarks are quoted below:

"It suffices to say that the method predicts the noise below 1 kHz to be overwhelmingly generated by the interaction of entropy fluctuations with the turbine ("indirect" combustion noise) ...

The fluctuating addition of heat to flow of gas produces pressure and entropy perturbations and in two (or three) dimensions, vorticity perturbations as well. The generation of all three types of disturbances are inextricably connected. In particular, it is inaccurate to associate noise from gas turbines with the pressure disturbance from the combustor in isolation: the interaction of entropy (and vorticity) with downstream components should also be considered. A simplified one-dimensional calculation of the interaction between a combustor and turbine indicates that it is the entropy interacting with the turbine (indirect noise) which predominates."

Figures 1 and 2 illustrate the noise differences found (by test) at approach and full power conditions between a DAC design and a (standard) SAC design for a GE aircraft engine . Figure 3 illustrates the differences between a DAC and a SAC. It should be noted that most combustor codes for aircraft engines used in industry are "incompressible" in that only density and pressure changes due to combustion are allowed for, not those due to compressibility. This is justifiable due to the low Mach numbers involved in aircraft engine combustors but renders these codes of poor utility in directly estimating the level of pressure fluctuations.

A multi-blade row actuator disk method similar to Cumpsty & Marble (1977) was used in the present study to estimate multi-stage "turbine transfer functions". This is justifiable at least as a first step, given the low frequency nature of combustion noise and in view of the great simplicity of multi-blade row actuator disk methods.

Interest in combustion noise focuses on the pressure waves present downstream of the turbine. This has been addressed in Cumpsty (1979) but in an uncoupled fashion, i.e., the mix of aft-generated pressure, vorticity and entropy waves first calculated from a flame sheet model in "isolation" followed by calculations of pressure waves and entropy waves incident on a multi-stage turbine assuming reflection free boundary conditions upstream and downstream of the turbine. The second calculation in Cumpsty (1979) was based on multi-blade row actuator disk (AD) methods. AD theory with its basic assumption that the wavelength of the waves involved substantially exceeds dimensions of the various length scales in the problem considered (*e.g.,* turbine blade chord, spacing between adjacent blades, etc.) is justifiable. However, there is one exception: that at entrance to the inlet nozzle Mach numbers / flow velocities are low and hence the wavelength of entropy waves (which are propagated at flow velocity and not at the speed of sound) could be too short at the higher frequencies to justify applicability of AD methods. Both choked and unchoked blade row situations can be handled by AD methods, though Mani *et al.* (2000) noted some unique aspects of solution procedure needed for the multi-stage case when one or more choked blade rows are involved.

2. Method of analysis

Uncoupled combustor turbine calculations in Cumpsty (1979) indicate that unsteady heat release is more a source of entropy waves aft of it than of downstream traveling pressure waves and that the "transfer function" for the pressure wave downstream of the turbine is similar in level for both incident pressure and entropy waves. Mani (2006) showed that there is no significant change in these conclusions when a fully coupled calculation is carried out. The conclusion is that even in the case of unsteady heat release induced combustion noise, the predominant chain of events is "unsteady heat release → entropy waves aft of flame → sound waves aft of the turbine" upon interaction with the multi-stage turbine. Considerable doubt is cast on the conventionally assumed view of the chain of events of "unsteady heat release → pressure waves aft of the flame → "transmission loss" through the turbine. This result has a significant impact on the technical community concerning many aspects of combustion noise - physics of generation, relation of combustor component tests (typically executed without the turbine at the aft end of the combustor) to the engine case, strategies for combustor noise reduction, etc.

Figure 4 defines the present project in schematic form. A linearizedv, two dimensional analysis (neglecting variations in the spanwise or radial direction) has been carried out with the compressor exit at the left end, the steady combustion process modeled as a discontinuous change of properties created by "constant area" heat addition in a flame sheet and the turbine leading edge defining the right boundary.

The flame related inputs needed are upstream pressure, density, axial velocity (entry into the combustor is assumed to be axial), stagnation temperature ratio across the flame and an estimate of axial location of the "flame sheet" relative to the compressor trailing edge plane and to the turbine leading edge plane. The magnitude or phase of the unsteady heat release is not needed for the analysis reported on, as all predictions of complex amplitudes of the various waves are made as multiples of this unsteady heat release (as mentioned previously, the analysis is linear). At compressor inlet we can assume that P_t and T_t are constant (independent of time). A "quasi steady" relation between the P_t ratio across the compressor due to variations of mass flow rate at the compressor exit is assumed and used to yield a boundary condition at the cold end for the variation of

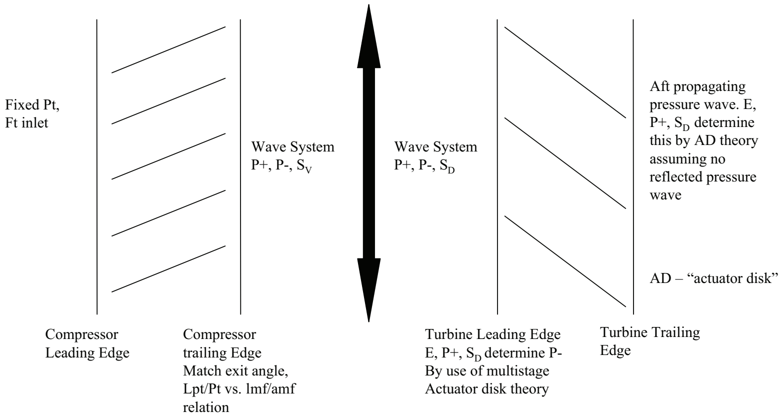

FIGURE 4. Schematic of analysis "model" used in project. Fluctuating heat release plane assumed moving in space such that burning velocity is unchanged. Match ρu, $x-$ & $y-$ momentum, T_t relative to flame across it.

linearized P_t at the cold end in terms of variations of linearized ρu. A similar exercise based on the T_t versus ρu relation could be used to derive a relation for linearized T_t variation at the cold end. However it is simpler to assume that the low frequency unsteady behavior of the compressor is isentropic and hence that the linearized $P_t' - T_t'$ relation at the cold end is also isentropic. The consequence of isentropic low frequency unsteady behavior of the compressor (since there are no entropy waves at compressor inlet) is also that there are no entropy waves between the compressor trailing edge and the flame in figure 4.

Finally the least controversial additional boundary condition to be used at the cold end is that the compressor outlet guide vanes impose a constant leading angle condition there, which we will assume to be the axial direction. Summarizing, the three boundary conditions at the cold end are (a) absence of entropy waves (b) axial flow direction and (c) a relation between the linearized total pressure fluctuation (P_t') and linearized mass flow perturbation (linearized ρu).

At the turbine end, using multi-stage AD methods and the assumption of reflection free termination at the downstream end of the turbine, a relation can be obtained between the incident entropy, pressure and shear waves and the reflected pressure wave.

Across the flame are matching conditions of linearized ρu, linearized axial and tangential momentum and linearized stagnation enthalpy. In the absence of solid object flame holding devices as in augmentors, matching of linearized axial and tangential momentum imply matching of linearized $p + \rho u^2$ and of v across the flame where v is the tangential velocity. In the present project, the flame is assumed to move such that there is no change in "burning velocity" due to the heat release, and hence $u_f = u_1$ (see Appendix A for notation). Matching of ρu and of $p + \rho u^2$ need to reflect the fact that the necessary u here is relative to the flame. The matching of linearized stagnation enthalpy across the flame will serve to bring into focus that all final amplitudes of the various wave systems will be in terms of the unsteady heat release.

Calculations are carried out for prescribed frequency and prescribed tangential wave number k_y. In the results shown in figures 5 and 6, the tangential wave number range considered is limited by 2D cut-off considerations and k/k_y is a convenient way of accounting for this since $k/k_y > 1$ corresponds roughly to cut on waves In figure 4, consider first the region bounded by the compressor trailing edge and the flame. Due to absence of entropy waves, there are three unknown wave amplitudes here - the shear wave SU, upstream and downstream propagating sound waves P^- and P^+. Downstream of the flame and upstream of the turbine leading edge there are similarly four unknown wave amplitudes the extra wave type being an entropy wave E. These seven unknown wave amplitudes can now be determined by seven boundary and matching conditions - two at compressor trailing edge, four across the flame and one at turbine leading edge all of which have been discussed above and the seven wave amplitudes will be known in terms of the unsteady heat release. We will only be interested in the acoustic power radiated aft of the turbine and this is determined by knowledge of E, SD and P^+. While the power in principle is related to the sum of the effects of E, SD and P^+ (added with proper attention to phase relations) , the separate contributions of E, SD and P^+ were calculated and as expected the contribution of E dominates. Of course, the downstream power is known only in terms of the (unknown) amplitude of the unsteady heat release but clearly this does not prevent the ability to allocate the power to contributrions from E, SD and P^+. The results of the study should provide a reasonably “first principles” based understanding of combustion noise generated by unsteady heat release in a combustor bounded by turbomachinery though several simplifying assumptions have been made.

3. Results and conclusion

Many calculations were carried out but in summary, the key relevant results are as shown in figures 5 and 6. Figure 5 contrasts the “moving flame sheet” versus “stationary flame sheet” cases and figure 6 shows the impact (for a “stationary flame sheet” case) for four different compressor exit “quasi steady” P_t versus ρu relations .

The principal conclusion of the present study is as follows:

The conclusion concerning the predominance of indirect noise is not affected by consideration of “moving” flame matching conditions or by use of boundary conditions at the compressor end other than zero mass flux. The ratio of indirect to direct noise is affected by consideration of “moving” flame matching conditions or by use of different boundary conditions at the compressor end other than zero mass flux, while the indirect noise is almost unaffected by choice of flame matching conditions or compressor end boundary conditions, the direct noise is affected. But in view of the predominance of indirect noise, the predicted total noise is not affected much at all by consideration of “moving” flame matching conditions or by use of different boundary conditions at the compressor end. Entropy waves “participate” very little in the mass flux or momentum flux balances when the Mach numbers approaching the turbine are low (as is the case in gas turbine combustors) but the stagnation temperature flux associated with entropy waves is relatively large and hence entropy wave generation is determined mostly by the fluctuating heat release with little effect of flame matching conditions or by different boundary conditions at the compressor end. Not shown in Mani (2006) or in present report is the reflected pressure wave coefficient (with appropriate normalization of entropy and pressure waves) abbreviated as RPWC- from entropy or pressure waves incident on the turbine. For a one dimensional choked nozzle , with “M” denoting mthe Mach number of the approach flow, to $O(M)$, these RPWCs for entropy and pressure waves are $-M/2$ and $(1-(?-1)M)$ respectively indicating that the RPWC for pressure waves is much greater than that for

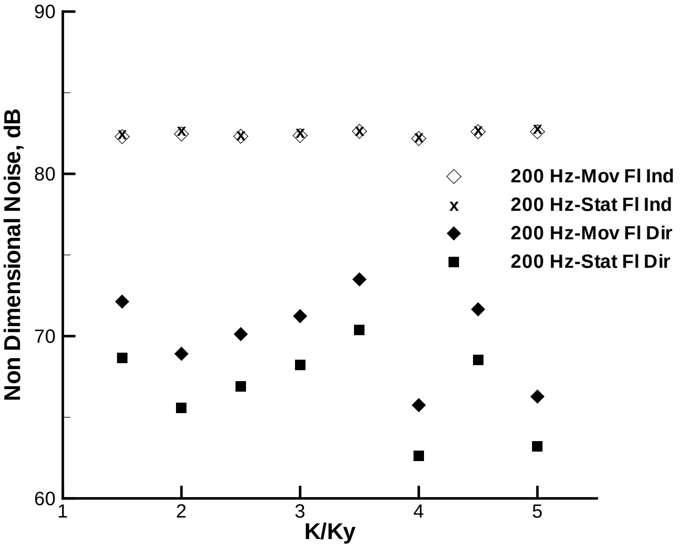

FIGURE 5. Effect of matching conditions: moving vs. stationary flame - sheet : 90" inlet diameter, 3600 rpm, 20:1 press ratio, turbine. Assume no change in burning velocity in moving flame case.

entropy waves. This result is also true for reflected pressure waves (RPW) from turbines. Since the RPW from incident waves are important for providing feedback in combustion instability, in case of combustion instability analysis, it would be erroneous to say that the generation of entropy waves by fluctuating heat release is dominant relative to the generation of pressure waves by fluctuating heat release. In case of combustion noise however it can be said that the generation of entropy waves by fluctuating heat release is dominant relative to the generation of pressure waves by fluctuating heat release. The present study has complemented Mani (2006) in a valuable way by confirming that this conclusion regarding the predominance of the generation of entropy waves by fluctuating heat release relative to the generation of pressure waves by fluctuating heat release as far as noise generated downstream of the turbine is not affected by use of a moving flame sheet model or by the choice of upstream boundary conditions other than zero mass flux.

4. Future work

Areas of further research suggested by the present work are:

- Tractable flame sheet models that include effect of curvature of flame sheet. Obliquity of flow and flame sheet orientation should also be examined.
- Is it the case that the primary unsteady output of combustors are entropy waves rather that pressure or vorticity waves? (determined by high fidelity simulations such as LES calculations)
- Possible attenuation mechanisms for entropy waves before they impinge on the turbine.
- How LES could help answer several questions such as transverse length scales and autocorrelations of the fluctuating heat release.

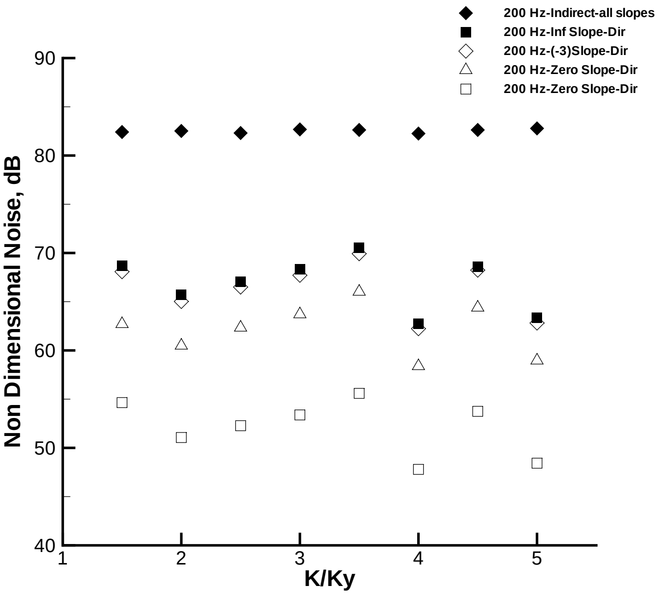

FIGURE 6. Effect of boundary conditions at the compressor trailing edge - stationary flame: 90” inlet diameter, 3600 rpm, 20:1 press ratio, turbine.

Acknowledgments

I would like to thank Dr. Donghyun You for his assistance in preparing this brief.

Appendix A. Notation and definitions

When a letter is followed by 1 or 2, reference is to conditions upstream of the flame or downstream of it. It is assumed thatthere is no mean swirl in the combustor. Fluctuating heat addition is assumed to be specified per unit mass (see Mathews (2003) for a discussion of this issue). Oscillations assumed to be of type $exp(i(y.ky - \omega t))$.

amf	steady axial mass flux, *i.e., RU*
c	speed of sound
C_p	specific heat at constant pressure
k	ω/c
k_t	$\sqrt{(kx^2 + ky^2)}$
ktsh	$sqrt(kxsh2 + ky2)$
kx	axial wave number acoustic waves. Roots of $(k - kx.M)2 = kx^2 + ky^2$: consider only real roots situation : less negative or more positive root downstream root while other root is upstream root.
kxe	axial wave number entropy waves
kxsh	axial wave number shear waves: note that $kxsh = kxe = \omega/U$
ky	tangential wave number
lamf	linearized axial momentum flux, $p + 2Ru + \rho U2$: u relative to flame velocity in axial direction in case of matching conditions across flame
lmf	linearized mass flux, $Ru+\rho U$, u relative to flame velocity in axial direction in case of matching conditions across flame

lpt	linearized total pressure. With isentropic compressor behaviour, $lpt/P_t = (\gamma/(\gamma-1))(ltt/T_t)$
lse	linearized stagnation enthalpy: $C_p.\ T_f + Uu$, u relative to flame velocity in axial direction in case of matching conditions across flame
ltv	linearized tangential velocity tangent to flame sheet: $[v + U.i.ky.\xi]$ and $\xi = i.u_f./\omega$ with $u_f = u_1$ in present case
ltt	linearized total temperature: $T_f + T(\gamma-1)Mu/c$
M	Mach number
P, p	steady and fluctuating pressure
P_t	total pressure
R	mean density
s	fluctuating entropy
t	time
T, T_f	mean and fluctuating temperature
T_t	total temperature
U, u	mean and fluctuating axial velocity
u_f	flame sheet axial velocity $= u_1$ in present case
v	fluctuating tangential velocity
x, y	axial and tangential coordinates
ξ	flame displacement parallel to x-axis
ω	oscillation frequency, radians per second
ρ	fluctuating density
γ	specific heat ratio

Appendix B. Boundary and matching conditions

At the compressor trailing edge (left boundary - figure 4):

- the compressor outlet guide vanes (OGV) are assumed to be able to maintain the flow at the compressor trailing edge as purely axial: hence $v = 0$ here
- a slope (S) relation is assumed between the fractional total pressure increase (lpt/Pt) and the fractional mass flux increase Ilmf/amf) i.e. $(lpt/P_t) = S.\ (\rho/R + u/U)$. If S is ∞, one has a “steep” pressure rise versus weight flow curve and one is typically at the right hand or high flow end of the compressor pressure rise map. If S is 0, one is typically at the left hand or low flow end of the compressor pressure rise map close to stall. Calculations are shown for $S = \infty, -3, -1/3$ and 0.
- Across the flame we match lmf, lamf, lse, ltv all relative to the moving flame sheet. Note that $\partial\xi/\partial y = i.ky.\xi$ and $\partial\xi/\partial t = -i.\omega.t = u_f = u_1$ (no change in burning assumption).
- Finally at the right hand end of figure 4 (turbine end) , we use a boundary condition that the reflected pressure wave (upstream traveling pressure wave) is determined by the incident (downstream traveling entropy , shear and pressure waves) with the (linear) relationship determined by actuator disk methods applied to the multi-stage turbine assuming a reflection free termination at the turbine downstream end.
- These seven matching and boundary conditions determine the seven waves shown to the left and right of the arrow in figure 4 in terms of the fluctuating heat release (which is the driver for creating the system of waves).

Appendix C. elementary properties of two dimensional waves in a flowing medium

- Sound waves: in terms of a non dimensional amplitude A, $(p/(\gamma P)) = A$, $\rho/R = A$, $T_f/T = (\gamma - 1)A$, $s/C_p = 0$, $u/c = (kx/kt)A$, $v/c = (ky/kt)A$.
- Shear or vorticity waves: in terms of a non dimensional amplitude A, $(p/(\gamma P)) = 0$, $\rho/R = 0$, $T_f/T = 0$, $s/C_p = 0$, $u/c = (-ky/ktsh)A$, $v/c = (kxsh/kt)A$
- Entropy waves: in terms of a non dimensional amplitude A , $(p/(\gamma P)) = 0$, $\rho/R = -A$, $T_f/T = A$, $s/C_p = A$, $u/c = 0$, $v/c = 0$

REFERENCES

Chu, B. T. 1955 Pressure waves generated by addition of heat in a gaseous medium. *NACA TN.*

Cumpsty, N. A. 1979 Jet engine combustion noise: pressure, entropy and vorticity perturbations produced by unsteady combustion or heat addition. *J. Sound & Vibration*, **66**, 527-544.

Cumpsty, N. A. and Marble, F. E. 1977 The interaction of entropy fluctuations with turbine blade rows; a mechanism of turbojetengine noise. *Proceedings of the Royal Society London Series* **A357**, 323-344.

Dowling, A. P. 1995 The calculation of thermoacoustic oscillations. *J. Sound & Vibration* **180**, 557-581.

Krejsa, E. J. 2003 Highlights of combustion and turbine noise research from the 1970's and 1980's. *Core Noise Workshop at Honeywell in Phoenix*, Arizona, February 26-27.

Mani, R. 2000 Aeroacoustic prediction codes. *NASA/CR-2000-210244*.

Mani, R. 2006 Combustion noise due to unsteady heat release in the presence of turbomachinery. *AARC Year End Review*, Cleveland, Ohio, December.

Mathews, D. C. 2003 Combustion and turbine noise work at Pratt & Whitney. *Core Noise Workshop at Honeywell in Phoenix*, Arizona, February 26-27.