Accepted for presentation at the 29th International Symposium on Shock Waves. Madison, WI. July 14-19, 2013. Paper #0301

Spectral characteristics of pitot noise

H. G. Hornung and N. J. Parziale

1 Introduction

For experimental studies of transition from laminar to turbulent boundary layer flow it is important to know the ambient noise spectrum in the facility. In supersonic wind tunnels this is often assessed by measuring pitot pressure noise. A discussion of such measurements is given, *e. g.*, by Salyer *et al.* [1], see also Parziale *et al.* [2]. The question arises as to whether the noise measured by a pitot tube is a good measure of the free–stream noise. In order to examine this question, we performed a parameter study of the problem by making Euler computations of supersonic flow over a pitot tube when white acoustic noise is introduced at the inflow boundary.

2 Computational setup

The computations were made with the Euler code formulation within the computational system Amrita written by Quirk [3]. A kappa–MUSCL scheme was used with HLLE reconstruction and a Cartesian coarse 300×200 grid with adaptive mesh refinement of one level by a factor of 3, so that the effective grid resolution is as for a 900×600 grid. The pitot tube radius was set to 100 coarse grid sizes.

3 Results

Computations were made for three Mach numbers, $M = 2$, 4, and 6, and for two values of the specific heat ratio $\gamma = 1.2$, and 1.4. In each case the noise was introduced

Graduate Aerospace Laboratories, California Institute of Technology
1200 E. California Blvd, Pasadena, CA91125 (USA)

by specifying the density at the inflow boundary to be given by

$$\rho = 1 + A(\mathrm{rand}(0) - 0.5),$$

at each time step, where A is an amplitude parameter (uniformly set to 0.2 in all computations) and rand is a random number generator that returns a random number between 0 and 1. The inflow pressure is set to $p = \rho^{\gamma}$. Figure 1 (left) shows a time trace of the free–stream pressure at a small distance downstream of the inflow boundary against dimensionless time, where U_{∞} is the free–stream velocity and h is the coarse grid size. On the right it shows a spectrum of this in the form of dimensionless magnitude of free–stream pressure against dimensionless frequency. As may be seen, the random number generator does not produce perfectly white noise. The computation is run for 16000 time steps with a cfl number of 0.8.

The second half of each time trace is used in the spectral analysis of the pitot noise so that startup transients are not included. In Fig. 1 this is $4500 < tU_{\infty}/h$, or the last 8000 points. The sampling rate is $> 1.5fh/U_{\infty}$, and the spectral content is estimated using the discrete Fourier transform with 50% overlapping 1000–point Hann windows.

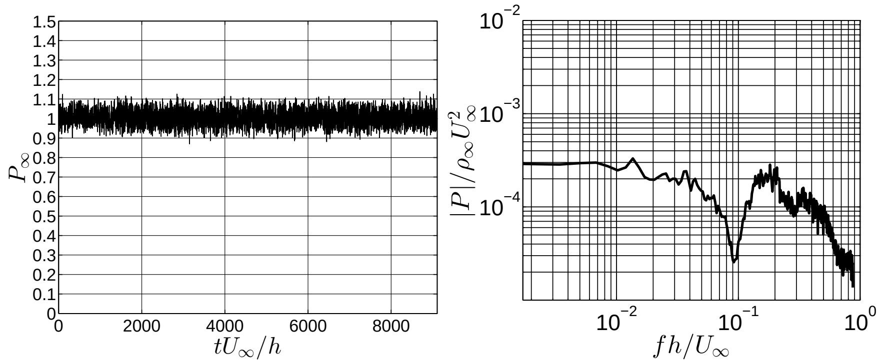

Fig. 1 Left: Time trace of free–stream pressure. Right: Spectrum of free–stream pressure. Both at $M = 4, \quad \gamma = 1.4$

Because it is often the case that pitot tubes are not constructed with a pressure sensor that is part of the front face of the tube, we also performed computations of flow over a pitot tube with a cavity, at the base of which resides the pressure sensor. Pseudo–schlieren images of the computed flow over a flat–faced and cavity pitot tube are shown in Figure 2. These clearly show the noise, because the greyshading is proportional to the density gradient normalized by the local density, thus amplifying it in regions of low density.

By taking the time traces of the pitot pressure as computed at the stagnation points of both the flat–faced and cavity pitot tubes and evaluating the corresponding spectra, we obtain the results presented in Figures 3, 4, and 5. The flat–faced pitot

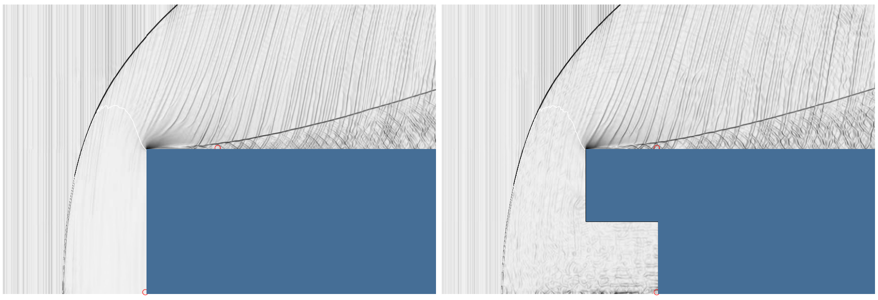

Fig. 2 Pseudo–schlieren images of flow over pitot tube. The greyshading is a monotonic function of the fractional density gradient. The white line is the sonic line. $M = 4$, $\gamma = 1.4$. Left: Without cavity, Right: With cavity

tube shows a fairly constant spectrum for all six cases, up to a frequency f_r above which the amplitude rolls off steeply. In contrast, the cavity pitot tube shows a much higher noise level and exhibits a broad peak at a frequency f_c a little higher than f_r. It is interesting to note that, for all six cases, these frequencies lie within

$$f_r r/a_0 = 12 \pm 1.3 \qquad \text{and} \qquad f_c c/a_0 = 8.6 \pm 1,$$

where a_0 is the speed of sound at the stagnation point, r is the tube radius and c is the cavity depth.

Because it is often the case that pressure noise focuses onto the axis of axisymmetric flows we also took the spectra of the trace of the pressure averaged over half the face radius of the pitot tube. These spectra turned out to be insignificantly different from their stagnation–point equivalents.

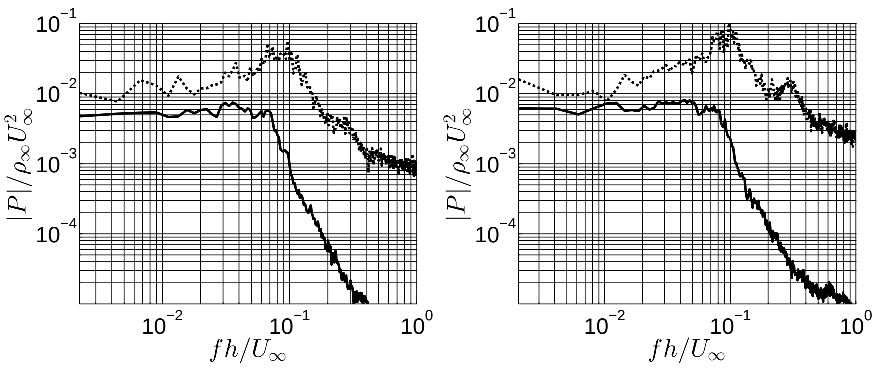

Fig. 3 Spectra of the magnitude of pitot pressure fluctuations in dimensionless coordinates without cavity (full line) and with (broken line) $M = 2$. Left: $\gamma = 1.2$. Right: $\gamma = 1.4$.

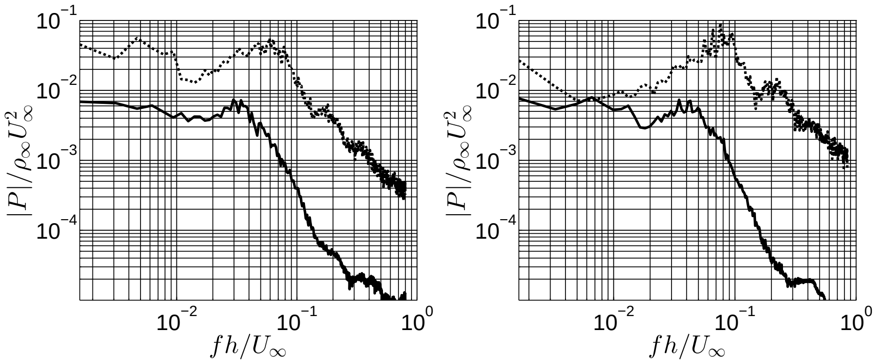

Fig. 4 Spectra of the magnitude of pitot pressure fluctuations in dimensionless coordinates without cavity (full line) and with (broken line) $M = 4$. Left: $\gamma = 1.2$. Right: $\gamma = 1.4$.

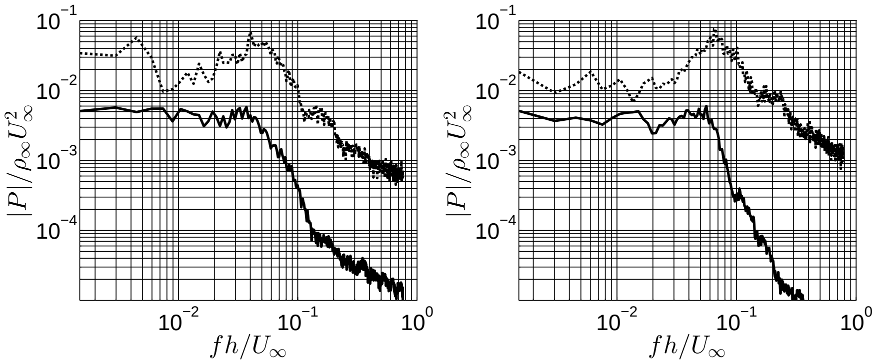

Fig. 5 Spectra of the magnitude of pitot pressure fluctuations in dimensionless coordinates without cavity (full line) and with (broken line) $M = 6$. Left: $\gamma = 1.2$. Right: $\gamma = 1.4$.

In order to examine the roll–off phenomenon in the spectra, we performed two tests. One was to double h while holding the cfl number constant, and the other was to halve the cfl number while holding h constant. The former changes the resolution at virtually constant numerical dissipation, while the latter increases the dissipation at constant resolution. The results are shown in Figure 6. As may be seen, doubling h causes $f_r h/U_\infty$ to double, without significant change of shape of the spectral curve, and halving the cfl number causes $f_r h/U_\infty$ to be halved. We conclude that the roll off is caused by numerical dissipation.

In the range of frequencies where the pitot spectrum is roughly constant, it is possible to obtain a crude amplification factor by dividing the percentage pitot noise by the percentage free–stream noise. To be more precise, the amplification factor is the ratio of pitot noise divided by free–stream noise divided by the theoretical ratio of pitot pressure to free–stream pressure. This amplification factor is shown in

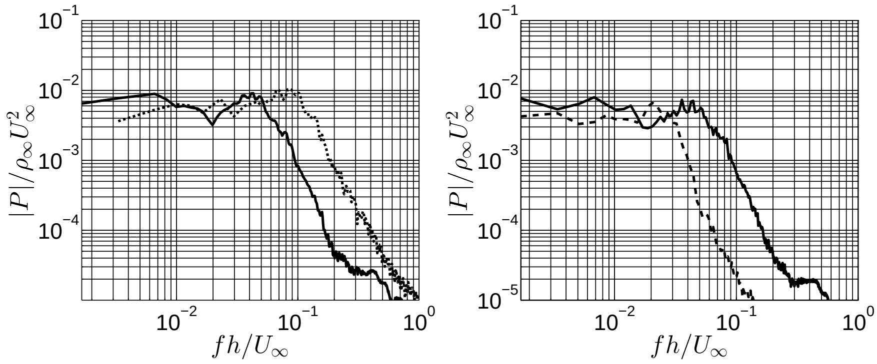

Fig. 6 Left: Test of effect of increasing h by a factor of 2. cfl=0.8 Full line: $h = 0.01r$, dashed line: $h = 0.02r$. Right: Test of halving cfl-number, $h = 0.01r$. Full line: cfl=0.8, dashed line: cfl=0.4. Both at $M = 4$, $\gamma = 1.4$

Figure 7. As may be seen, the distortion of the noise is quite large at lower Mach number and is insensitive to γ.

4 Relation to physical flows

In order to relate these results to physical flows, we take the case of the Caltech Ludwieg Tube at $M = 4$ with a pitot–tube with $r = 6.35$ mm and $U_\infty = 670$ m/s. The grid resolution thus represents $h = 63.5$ μm and the computational time scale at cfl=0.8 represents $\Delta t = 76$ ns. The roll–off frequency $f_r = 12a_0/r$ then has the value 633 kHz. This is well above frequencies relevant to any boundary-layer instabilities in this flow regime, so that the region of the spectra below f_r are likely to be well represented by the computations.

At these experimental conditions, measurements of pitot noise have been made. Figure 7 shows spectra of the measured pitot noise from five consecutive runs, showing very good repeatability. These spectra exhibit a roll–off at around 20 kHz. However, since we do not have any measurements of the free-stream noise, no conclusions can be drawn about distortion of the spectrum. It is reassuring that the frequency range of the computations up to $f = f_r$ well exceed the roll–off frequency of the experiment. The small peak showing at about 6 kHz is quite repeatable, but we do not have an explanation for it.

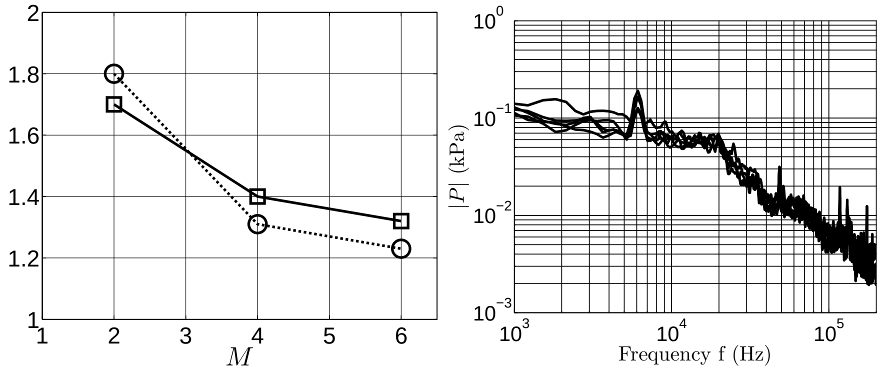

Fig. 7 Left: Amplification factor for the six computed cases circle, $\gamma = 1.4$ square symbol, $\gamma = 1.2$. Right: Spectra from measured pitot noise in the Caltech Ludwieg Tube at $M = 4$.

5 Conclusion

A parameter study of acoustic noise in supersonic flow over a pitot tube was made using Euler computations in which white noise is introduced at the inflow boundary. The spectral distribution of the noise is fairly flat up to a distinct roll–off frequency that scales with pitot tube radius and stagnation point sound speed. However, tests in which grid resolution and cfl number were separately varied, showed that the roll–off is caused by numerical dissipation. In the region where the spectral distribution is flat, the percentage pitot noise is amplified compared to the percentage free–stream noise. The amplification factor decreases with increasing Mach number and is insensitive to γ. Computations of flow over a pitot tube with a cavity in the front face show that the cavity causes the noise to be amplified by at least a factor of 2 relative to the flat–faced tube. Experimental results at M=4 show that a roll–off occurs at a much lower frequency than that of the computations, indicating that the numerical dissipation is sufficiently small. The results emphasize the superiority of optical methods over pitot pressure for measuring noise.

References

1. Salyer TR, Collicott SH, Schneider SP (2000) Feedback stabilized laser differential interferometer for supersonic blunt body receptivity experiments. AIAA-2000-0416
2. Parziale NJ, Shepherd JE, Hornung HG (2012) Reflected shock tunnel noise measurement by focused differential interferometry. AIAA-2012-3261
3. Quirk JJ (1998) Amrita–A computational facility (for CFD modelling) VKI 29th CFD Lecture Series, ISSN 0377-8312. See also: http://www.amrita-ebook.org.