**On a new jet noise component from high-performance aircraft at afterburner**

by

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**1.** **Introduction**

In Ref.[1], the present authors analyzed the noise of a high performance aircraft . This paper is a continuation of the work. The objective is to report the discovery of a new component of the noise of F-18-E aircraft at afterburner condition. The discovery is facilitated by the experiments of Oertel, Ref. [2] and theoretical analysis by Tam and Hu, Ref. [3]. The existence of this noise component is verified by a careful examination of the far field noise data of F-18E aircraft. This new noise component is found only at afterburner operating condition. The source of this new noise component is identified as a flow instability referred to as supersonic instability in Ref. [4]. Other outstanding characteristics of this new noise component are reported. This new noise component is the dominant component in the downstream direction beginning at 140 degrees.

Laboratory studies over the years have contributed most of our present day knowledge of the noise of supersonic jets. However, the operating parameters are limited in scope. The following are the estimated upper limits of most laboratory facilities.

Jet diameter 6 inches or smaller

Jet velocity ft per sec.

Jet temperature ratio 4

Military jets operate at conditions outside and above these limits. The velocity of the jet could exceed 4500 ft/sec and temperature ratio of 7. The nozzle is full size. These performance parameters will definitely increase for the next generation of aircraft.

Based on laboratory studies, supersonic jet noise is known to consist of many components. There are two turbulent mixing noise components, the large turbulence structures noise and the fine scale turbulence noise. In addition, there are a number of shock related noise components. They are the screech tones and broadband shock cell noise.

Oertel, Ref. [1], was the first to study the noise of very high-speed, high-temperature jets. To achieve these demanding conditions, he used jets produced by a shock tube. The operating

time for shock tubes is very short. Oertel measured the jet flow and noise radiation in the form of

Mach waves by optical means. Fig. 1 summaries the principal results of his work. This figure clearly shows that the jet supports three sets of waves. The first wave has the fastest speed, followed by the second wave. Both waves are supersonic relative to the ambient gas. This is evidenced by the Mach waves emitted by each wave. Because the first wave is faster, the Mach wave angle (exhaust angle) is larger . For this reason, it is expected that its noise is radiated to a higher angle in the far field. The speed of the third wave is subsonic relative to the ambient sound speed. Hence, it radiates no Mach wave and is unimportant as far as jet noise is concerned.

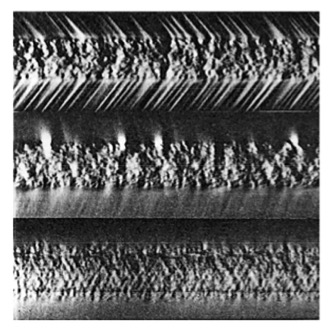


Figure 1. The three sets of waves supported by high-speed, high-temperature jets issued from a shock tube observed by Oertel, Ref. [1].

Tam and Hu, Ref. [3] investigated these waves theoretically by solving the Euler equation. They found such jets support five types of waves including the three waves observed by Oertel, Ref. [2]. The other two sets of waves propagate upstream. This is why they were not observed in the shock tube experiment. The fourth wave propagate upstream inside a subsonic jet. They are responsible for completing the feedback loop of subsonic impinging jets (see Ref.[4, 5, 6, 7] and others). The feedback loop is what generates the impinging tones for jets impinging on a solid surface. The fifth wave propagates upstream following a supersonic jet. They are often referred to as guided waves. They have been studied and verified extensively during the last ten years, e. g. Ref. [8, 9, 10, 11, 12, 13, 14]. They form the feedback wave of screech tones. In Ref. [3], Tam and Hu identified the first wave as the well-known Kelvin-Helmholtz instability wave. The Kelvin-Helmholtz instability has since been recognized as the source of turbulent mixing noise of laboratory jets. Tam and Hu called the second wave “supersonic instability wave”. This is because its wave speed is supersonic relative to ambient gas as well as the gas inside the jet.

**2. The role of Kelvin-Helmholtz instability wave in jet noise generation**

In this section, we will examine the processes of turbulent mixing noise generation initiated by the Kelvin-Helmholtz instability of jet flows. In other words, Kelvin-Helmholtz instability is the progenitor of some components of high-speed jet noise. Figure 2 is a historic picture for turbulent shear flow. This picture was taken by Brown and Roshko, Ref. [15]. It shows unambiguously the existence of large turbulence structures in turbulent shear flow. The shear layer starts with the Kelvin-Helmholtz instability wave (see the left side of the picture). The instability wave grows into a nonlinear wave and then evolve into large turbulence structures accompanied by fine scale turbulence. Both components of turbulence generate noise. They are referred to as large turbulence structures noise and fine scale turbulence noise. For supersonic jets, the large turbulence structures are less orderly and less coherent as in Fig. 2. But they still form the dominant part of the turbulence in jet flows. In the literature, here are many papers on large turbulence structures in high speed shear flows. A short list of them including compressibility effect are Ref.[16 – 22].

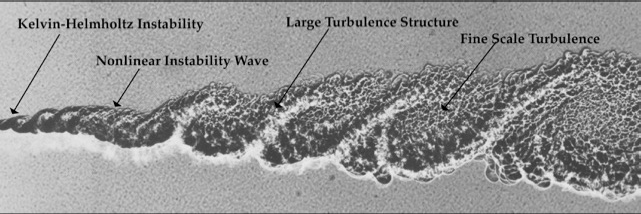


Figure 3. Shadowgraph picture of a shear layer showing the evolution of a Kelvin-Helmholtz instability wave into a non-linear wave then to large turbulence structures accompanied by fine scale turbulence.

Fig. 4 from Ref. [23] shows the noise radiation pattern and characteristics of the two turbulent mixing noise components. The fine scale turbulence is small. The turbulence fluctuations emit short sound pulses in all directions. The large turbulence structures behave like a wavy wall. They emit strong Mach wave radiation within a Mach cone as shown in Fig. 4. Within the Mach cone the Mach waves dominate. Thus, in the sideline and in the upstream direction, the noise is primarily from the fine scale turbulence and has high frequency. Within the Mach cone in the downstream direction, the dominant noise is the large turbulence structures noise. The frequency is low.



Figure 4. The radiation pattern of the large turbulence structures noise and fine scale turbulence

noise.

It has been found experimentally, Ref. [24-26] that a jet has two self-similar regions in which the mean flow velocity profile as well as the root mean square turbulence fluctuations exhibit self-similarity. That is, the mean velocity profiles as well as distribution of turbulence fluctuations can be collapsed into a single profile. The two self-similar regions are shown in Fig. 6. The existence of these self-similar regions has also a theoretical basis. In region1 of Fig. 6, it is easy to see that there is no intrinsic length and time scale. This forces the flow to become self-similar. In region 2, way downstream, the distance from this region to the nozzle exit is much longer than the diameter of the jet. Effectively the jet may be considered as issued from a point or a very localized source with no distinct length scale. For this reason, the flow effectively has, again, no length and time scales. So, it exhibits self-similarity characteristics. Now if one goes upstream from this point all the way up to near the end of the jet core, one expects the similarity of the flow to persist to a large extent. This is the basis why there is a second self-similar region in Fig. 6.



Figure 6. Two self-similar regions in a high-speed jet.

The existence of two self-similar regions in a jet flow, strongly suggests the possibility

that the noise radiated by the jet could have two similarity spectra. This was one of the factors

that motivated Tam et al. [27] to examine a large set of jet noise spectra in the data bank at

NASA Langley Research Center. They were able to identify two such spectra. They are shown

in Fig. 7. The broad spectrum is the spectrum that fits all the measured noise spectra in the

upstream and sideline directions. Based on the discussion above, it is identified as the fine scale

turbulence similarity spectrum. The peaky spectrum fits all measured data inside the conical

region in the downstream direction. It is, therefore, identified as the similarity spectrum of the

large turbulence structures. Figure 7 is a SPL (in dB) versus log(*f*/) plot. Here is the frequency at the peak of the noise spectrum. The choice of using a log-log plot is that the spectral shape would be the same independent of . To compare a similarity spectrum with an experimental spectrum, it is only necessary to align the peaks of the two spectra. Once this is done, the two spectra will fall on top of each other.

A diagram of a function

Description automatically generated

Figure 7. The spectral shapes of the similarity spectra of the large turbulence structures noise and the fine scale turbulence noise. The peaky spectrum is that of the large turbulence structures noise.

Fig. 8 is a demonstration of how well the fits could be. The data to be fitted have a temperature ratio of 3.2 at subsonic (Mach 0.5), transonic (Mach 1.0) and supersonic (Mach 2.0) Mach numbers. In the transition angular directions (100 to 120 deg.) there is a change in the dominance of the noise sources. In this angular sector both similarity spectra are needed to provide a good fit to the data. The data in figure 8 are from NASA Langley Research Center and the Boeing Company.



Figure 8. Comparisons between the two similarity spectra and measured data at

(a) 90°, (b) 100°, (c) 110°, (d) 120°, (e) 130o, (f) 140o inlet angle. Data from Ref.[28, 29]

The validity and quality of the two similarity spectra have been tested by comparing them with noise from different types of jets. The data of Fig. 8 are from laboratory jets. Several investigators have compared the similarity spectra with the noise of full size jets of high performance aircraft and rockets, Ref. [30-33]. The largest size jets on earth are the volcanoes. Because the size of the crater is large, the sound emitted is in the infrasound range. Matoza and coworkers, Ref. [34, 35] have found that the measured spectra are in good agreement with the similarity spectra of the large turbulence structures noise. It is worth to mention that the temperature of all the jets discussed varies widely from cold jet to volcanic temperature jet. Regardless, the measured spectra compared well with the similarity spectra. There have also been efforts to compare the similarity spectra with the noise spectra of non-axisymmetric jets. Ref. [36, 37, 38] all provide favorable reports.

**3. The role of supersonic instability wave in noise generation from high-speed high temperature jets.**

The work of Oertel, Ref.[2] and Tam & Hu, Ref. [3], has shown that a jet at high speed and high temperature supports two independent instabilities. It is known that Kelvin-Helmholtz instability is the result of the shearing motion of the jet flow. On the other hand, supersonic instability is supported by compressibility effects of the gas of the jet. This type of instability does not occur unless the jet speed is exceedingly high (as discussed below) and compressibility becomes an important factor. In the previous section, we have shown that Kelvin-Helmholtz instability is the progenitor of two components of jet noise, namely, the large turbulence structures noise and fine scale turbulence noise. We believe supersonic instability could be the progenitor of a new family of jet noise components. In this and the next section, data will be presented showing the existence of a new jet noise component from high performance aircraft at afterburner. It will be shown that the noise characteristics of this new noise component are consistent with the Mach wave radiation characteristics of supersonic instability waves.

Tam & Hu, Ref. [3], in their analysis found that the second wave is also unstable. Since it propagates at supersonic speed relative to both the ambient gas and the jet fluid, they called the wave supersonic instability wave. Because of these constraints, this wave does not generally exist in jet flows. The requirement for existence may be derived as follows. Let denote the wave speed.

Wave is supersonic with respect to ambient gas (ambient sound speed)

Wave is supersonic with respect to jet flow (speed of sound in jet)

By adding the two inequalities, one obtains the necessary condition for existence of supersonic instability wave

(1)

Eq. (1) can be recast into a relation between jet Mach number, , and jet temperature ratio

(2)

Fig. 7. Shows the curve at which in the vs. plane. Above this curve is the region of existence of supersonic instability wave. It is estimated that F-18E at afterburner condition has and This is indicated by the black dot in Fig. 7. This assures us that at afterburner condition, the noise of F-18E aircraft could have a previously unknown noise component generated by supersonic instability.

Figure 8 shows the velocity triangle of Mach wave radiation. It shows the dependence of Mach wave radiation angle on wave speed. It is clear that the large turbulence structures noise generated by the Kelvin-Helmholtz instability wave (the first wave), having a higher wave speed, would radiate to higher exhaust angle as shown in the left figure. The noise associated with the supersonic instability, having a lower wave speed, would radiate to smaller exhaust angles closer to the jet flow direction. This is observed in the F-18E noise data. It is to be noted that the Mach wave radiation angle is also the Mach cone angle of the noise component. Thus, It is expected that as the inlet angle increases, the large turbulent structures noise will be observed first. Only when the inlet angle increases further will we be able to see the noise from the supersonic instability wave.



Figure 7. This figure shows the region of existence for the supersonic instability wave in a

vs. plot.

One of the main difference between Kelvin-Helmholtz instability and supersonic instability is that the former has a faster propagation speed. The acoustic waves generated by both instabilities are in the form of Mach waves. But Mach wave radiation angle or the direction of radiation is dependent on the wave speed. Fig. 8 shows the velocity triangle and the radiation direction of two waves. One has a high wave speed. As a result, the Mach wave radiation direction is at a higher exhaust angle, left figure of Fig. 8. In other words, in a set of noise data measured by a circular array of microphones, one will observe the Mach waves associated with the Kelvin-Helmholtz instability first as the inlet angle increases. The Mach waves associated with the supersonic instability will be observed only at higher inlet angles.



Figure 8. The velocity triangle of Mach wave radiation. is larger when is larger.

All the F-18E noise data used in this paper were obtained at the same time as those in Ref. [1]. Details of the instrumentations used, the test procedure and the conditions in the field, e.g. cross wind etc. were documented in Ref.[1]. Below are noise spectra of F-18E a afterburner conditions over a wide range of angles.



Figure 9. (a) = 1200, (b) = 1250, (c) = 1300 and (d) = 1410. Dashed red curves are the similarity spectrum for the large turbulence structures noise.



Figure 10. (a) = 1450, (b) = 1500, (c) = 1550 and (d) = 1600. Dashed red curves are the similarity spectrum for the large turbulence structures noise.

**4. Noise at the sound pulse level**

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