On the Source Modeling Technique in Tam & Auriault's Fine-Scale Turbulence Jet Noise Theory

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PACS: 43.28.Ra

ABSTRACT

In 1999, Tam and Auriault developed a theory capable of predicting the fine-scale turbulence noise from cold to moderate temperature jets. In this jet noise prediction theory, they proposed a Gauss noise source model function to represent the noise source time-space correlation function mathematically. In 2005, Tam et al. modified the noise model function of Tam and Auriault theory to predict hot jet noise. The calculated results of Tam and Auriault's theory are in good agreement with experimental measurements over a wide range of directions of radiation, jet velocities and temperatures. However, some noticeable deviations still can be observed between the prediction results and experimental data for some cases of single and dual-stream jets. The main objective of this work is to improve the accuracy of the prediction results of Tam and Auriault's theory by modifying the noise source model function. Two alternative noise source model functions are considered here which are proposed by Khavaran et al. and Harper-Bourne. In addition, a frequency dependent length scale proposed by Morris and Boluriaan is applied to the noise source model functions. The effects of above mentioned three noise source model functions are evaluated in Tam and Auriault's theory through comparison with experimental results at several jet Mach numbers for single-stream cold and hot jet. The comparisons indicated that, the usage of frequency dependent length scale can provide better agreement with measurements for some cases. In addition, Khavaran et al's and Harper-Bourne's source model which give good noise prediction for cold jet, are not applicable to the prediction of hot jet noise.

1 INTRODUCTION

The methods predicting noise generated and radiated by a turbulent flow can be divided into two categories: the direct prediction method and the hybrid prediction method. The direct prediction methods such as Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) are computationally expensive, and therefore the hybrid methods based on a steady RANS-based CFD calculation and an acoustic model are still the main methods for noise prediction.

Jet noise is dominant in the low frequency range during takeoff, and therefore it is very imperative and necessary to predict and reduce it. For subsonic jet, large turbulent structures and fine-scale turbulence are thought to be the main noise sources. Since Lighthill proposed the Lighthill's equation by rearranging the N-S equation, the development of jet noise prediction methods are based on the acoustic analogy. The hybrid jet noise prediction methods based on mean flow and turbulence information and an acoustic model have been studied extensively, most of them are on the basis of acoustic analogy, such as MGBK method [1],[2] and JeNo method [3]. However, they cannot provide accurate predicted spectrum in a wide frequency range. In 1999, Tam and Auriault [4] developed a theory capable of predicting fine-scale turbulence jet noise from cold to moderate temperature jet. In 2005, Tam et al. [5] modified the noise source model function of Tam and Auriault's theory to predict fine-scale turbulence noise of hot jet.

Though the prediction results of Tam and Auriault's prediction theory are in good agreement with experimental measurements over a wide range of directions of radiation, jet velocities and temperatures, yet some noticeable derivations can still be observed between the prediction results and experimental data for some cases of single and dual-stream jets. For instance, for single-stream jet of low jet Mach numbers (0.3, 0.5) and 1.0 jet temperature ratio, the prediction results deviate from experimental measurements in the high frequency range.

In this paper, in order to improve the accuracy of prediction results of Tam and Auriault's theory, the noise source model function is modified. Two alternative noise source model functions are considered here, which were proposed by Khavaran et al [3]. and Harper-Bourne [6] respectively. In addition, a frequency dependent length scale proposed by Morris and Boluriaan [7] is applied to the noise source model functions considered here.

2 NOISE SOURCE MODEL FUNCTIONS

Assume that two point noise source time-space correlation function is $R\left(\vec{y},\vec{\xi},\tau\right)$, and its Fourier transform is written as $Q\left(\vec{y},\vec{\xi},\omega\right)=\int_{-\infty}^{\infty} R\left(\vec{y},\vec{\xi},\tau\right)e^{i\omega\tau}d\tau$. According to Harper-Bourne's expression[6],

$$Q\left(\vec{y},\vec{\xi},\omega\right)=Q\left(\vec{y},0,\omega\right)G\left(\vec{y},\vec{\xi},\omega\right)\exp\left(i\omega\tau_p\right) \quad (1)$$

$G\left(\vec{y},\vec{\xi},\omega\right)$ is irrelevant to frequency, and therefore it can be expressed as $G\left(\vec{y},\vec{\xi}\right)$. Phase is expressed as the product $\omega\tau_p$, and τ_p is a corresponding time delay.

$$R\left(\vec{y},0,\tau\right) = R\left(\vec{y},0,0\right)T\left(\tau\right) \tag{2}$$

In Tam and Auriault's prediction theory, they proposed a Gauss noise source model function to represent the noise source time-space correlation function mathematically.

$$\left\langle \frac{Dq_s\left(\vec{x}_1,t_1\right)}{Dt_1}\frac{Dq_s\left(\vec{x}_2,t_2\right)}{Dt_2}\right\rangle = \frac{\hat{q}_s^2}{c^2\tau_s^2}\exp\left\{-\frac{\xi}{\bar{u}\tau_s}-\frac{\ln 2}{l_s^2}\left[\left(\xi-\bar{u}\tau\right)^2+\eta^2+\zeta^2\right]\right\} \tag{3}$$

In acoustic analogy prediction methods, the noise source model function is obtained based on turbulence theory, and usually has the following form [3],

$$\begin{aligned}&\left\langle u_1u_1u_1u_1\right\rangle = 2\left\langle u_1u_1\right\rangle = R_{11}h\left(\tau\right) = 2\overline{u_1^2}\\&\left[1-\frac{\pi}{2\vec{\xi}l_s}\left(\eta^2+\zeta^2\right)\right]\exp\left(-\pi\vec{\xi}/l_s\right)\exp\left(-\left|\tau/\tau_s\right|\right)\end{aligned} \tag{4}$$

where $\vec{\xi} = \left[\left(\xi - U_C\tau\right)^2+\eta^2+\zeta^2\right]^{1/2}$.

According to the experimental measurements, Harper-Bourne [6] proposed another noise source model function.

The exact expression of these three noise source model functions are indicated as follows.

For the noise source model function proposed by Tam and Auriault,

$$T\left(\tau\right) = \exp\left(\frac{-\ln 2}{l_s^2}\bar{u}^2\tau^2\right) \tag{5}$$

$$T\left(\omega\right) = \frac{\sqrt{\pi}}{\sqrt{\ln 2}}\frac{l_s}{\bar{u}}\exp\left(-\frac{l_s^2\omega^2}{4\ln 2\bar{u}^2}\right) \tag{6}$$

$$G\left(\vec{y},\vec{\xi}\right) = \exp\left(-\frac{\left|\xi\right|}{\tau_s\bar{u}}-\frac{\ln 2}{l_s^2}\left(\eta^2+\zeta^2\right)\right) \tag{7}$$

$$G\left(\vec{y},\omega\right) = \frac{\pi l_s^2}{\ln 2}\frac{2\tau_s\bar{u}}{\tau_s^2\omega^2\left(\frac{\bar{u}\cos\theta}{a_\infty}-1\right)^2+1} \tag{8}$$

For the noise source model function proposed by Khavaran et al.,

$$T\left(\tau\right) = e^{-\lambda\left|\tau\right|}\quad\left(\lambda = 2\pi\left(\frac{\bar{u}}{l_s}+\frac{1}{\tau_s}\right)\right) \tag{9}$$

$$T\left(\omega\right) = \frac{\lambda}{\pi\left(\lambda^2+\omega^2\right)} \tag{10}$$

$$\begin{aligned}&G\left(\vec{y},\vec{\xi}\right) = \left[1-\frac{1}{2\left|\vec{\xi}\right|l_s}\left(\eta^2+\zeta^2\right)\right]^2\exp\left(-2\pi\left|\vec{\xi}\right|/l_s\right)\\&\left(\left|\vec{\xi}\right| = \sqrt{\xi^2+\eta^2+\zeta^2}\right)\end{aligned} \tag{11}$$

$$\begin{aligned}&G\left(\vec{y},\omega\right) = \frac{4\pi^2}{l_sA^4}\left[\frac{3}{l_sA}\arctan\left(\frac{Al_s}{2\pi}\right)-\frac{2\pi\left(5l_s^2A^2+12\pi^2\right)}{\left(l_s^2A^2+4\pi^2\right)^2}\right]\\&\left(A = \frac{\omega}{\bar{u}}\left(1-\frac{\bar{u}}{a_\infty}\cos\theta\right)\right)\end{aligned} \tag{12}$$

For the noise source model function proposed by Harper-Bourne,

$$T\left(\tau\right) = \exp\left(-\lambda\left|\tau\right|\right)\quad\left(\lambda = \frac{\bar{u}}{c_\tau l_s}\right) \tag{13}$$

$$T\left(\omega\right) = \frac{\lambda}{\pi\left(\lambda^2+\omega^2\right)} \tag{14}$$

$$G\left(\vec{y},\vec{\xi}\right) = \exp\left[-\sqrt{\frac{\xi^2}{l_x^2}+\left(\frac{\eta^2}{l_y^2}+\frac{\zeta^2}{l_z^2}\right)^2}\right] \tag{15}$$

$$G\left(\vec{y},\omega\right) = \frac{\pi^2l_xl_yl_z}{\left\{\left[\left(-\frac{1}{\bar{u}}+\frac{\cos\theta}{a_\infty}\right)\omega l_x\right]^2+1\right\}^{\frac{3}{2}}} \tag{16}$$

Where

$$T\left(\omega\right) = \int_{-\infty}^{\infty}T\left(\tau\right)e^{i\omega\tau}d\tau$$

$$G\left(\vec{y},\omega\right) = \int_{-\infty}^{\infty}G\left(\vec{y},\vec{\xi}\right)e^{i\frac{\omega}{\bar{u}}\xi\left(1-\frac{\bar{u}}{a_\infty}\cos\theta\right)}d\vec{\xi}.$$

In Tam and Auriault's jet noise prediction theory, the relation between pressure $p\left(\vec{x},t\right)$ and adjoint pressure $p_a\left(\vec{y}_1,\vec{x},\omega\right)$ is given[4],

$$\begin{aligned}&p\left(\vec{x},t\right) = \iint\int_{-\infty}^{\infty}\iint_{-\infty}^{\infty}p_a\left(\vec{y}_1,\vec{x},\omega\right)\\&\times\exp[-i\omega(t-t_1)]d\omega\frac{Dq_s\left(\vec{x}_1,t_1\right)}{Dt_1}dt_1d\vec{x}_1\end{aligned} \tag{17}$$

Where $\dfrac{D}{Dt_1} = \dfrac{\partial}{\partial t_1}+\bar{u}\dfrac{\partial}{\partial x_1}$.

Based on this relation, the far-field spectral density can be derived.

$$\overline{p^2}\left(\vec{x},\omega\right) = 4\pi^2 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left|p_a\right|^2 Q\left(\vec{y},\vec{\xi},\omega\right) \exp\left(-i\frac{\omega}{a_\infty}\cos\theta\xi\right) d\vec{\xi}\,d\vec{y} \tag{18}$$

Assume that $F\left(\omega\right) = \int_{-\infty}^{\infty} Q\left(\vec{y},\xi,\omega\right) e^{-i\frac{\omega}{a_\infty}\cos\theta\xi} d\vec{\xi}$. It also can be written as $F\left(\omega\right) = Q\left(\vec{y},0,0\right) T\left(\omega\right) G\left(\vec{y},\omega\right)$, and therefore the far-field spectral density can be written as $\overline{p^2}\left(\vec{x},\omega\right) = 4\pi^2 \int_{-\infty}^{\infty} \left|p_a\right|^2 F\left(\omega\right) d\vec{y}$.

Based on the Tam and Auriault's fine-scale turbulence jet noise prediction theory, the noise source model function proposed by Tam and Auriault and two alternative noise source model functions proposed by Khavaran et al. and Harper-Bourne respectively are considered here. In order to compare these three noise source model functions, the definition of $Q\left(\vec{y},0,0\right)$ is similar in these three model functions and has the following form.

$$Q\left(\vec{y},0,0\right) = \frac{\hat{q}_s^2}{c^2\tau_s^2} \tag{19}$$

The model parameters of the three noise source model functions are given by the $k-\varepsilon$ turbulence model as follows.

$$\frac{\hat{q}_s^2}{c^2\tau_s^2} = A_m^2 q^2, \quad q = \frac{2}{3}\bar{\rho}k \tag{20}$$

$$l_s = C_l \frac{k^{3/2}}{\varepsilon}, \quad \tau_s = C_\tau \frac{k}{\varepsilon} \tag{21}$$

A_m, C_l, C_τ are empirical constants to be determined.

Morris and Boluriaan[7] proposed a frequency dependent length scale and assumed that all length scales are proportional. That is, let $l_S = C_l D_j s_\omega / St$, $l = C_l\, k^{3/2}/\varepsilon$, $s_\omega = 1 - \exp\left(-C_s St l / D_j\right)$, where the Strouhal number $St = f D_j / U_j$, and D_j and U_j are the jet exit diameter and velocity respectively. The characteristic of this length scale is that it remains constant in the low frequency range, and decreases with increasing frequency in the high frequency range. This frequency dependent length scale is applied to the three noise source model functions considered here.

The empirical constants of the three noise source model functions are determined by the matching of prediction results and experimental measurements. The values of them are shown as follows.

For the noise source model function proposed by Tam and Auriault,

$$c_\tau = 0.256, c_l = 0.233, Am = 0.755 \tag{22}$$

(as given in Ref. 4)

$c_\tau = 0.192, c_l = 0.8899, Am = 0.577, c_s = 0.3148$ (with frequency dependent length scale) (23)

For the noise source model function proposed by Khavaran et al.,

$$c_\tau = 0.369, c_l = 2.003, Am = 29.419 \tag{24}$$

$c_\tau = 0.7895, c_l = 1.2516, Am = 81.2973, c_s = 1.0593$ (with frequency dependent length scale) (25)

For the noise source model function proposed by Harper-Bourne,

$$c_\tau = 1.001, c_l = 0.297, Am = 20.379 \tag{26}$$

$c_\tau = 1.01, c_l = 0.4972, Am = 11.0038, c_s = 1.1537$ (with frequency dependent length scale) (27)

In 2005, Tam et al. [5] extended Tam and Auriault's theory to hot jet noise prediction. They argued that the large density gradient in hot jet flow exerts effect on both the jet mean flow and jet mixing noise. The effects of density gradient on mean flow have been studied by Tam and Ganesan [8]. For noise prediction purposes there is also a change in the noise source model function. Tam et al. modified the two point space-time noise source correlation function of Tam and Auriault's theory to predict correctly the hot jet noise.

Here, the two alternative noise model functions are applied to the prediction of hot jet noise to check whether they are appropriate noise source model function for hot jet noise calculation.

In addition, the frequency dependent length scale proposed by Morris and Boluriaan is applied to the modified noise source model function proposed by Tam et al. The empirical constants of the modified noise source model with frequency dependent length scale are determined by comparison with experimental measurements. The values of them are as follows. The other four empirical constants $(c_\eta, B, c_{l\rho}, c_\tau)$ of the modified source model are assigned the values as given in Ref. 5.

$$c_\tau = 0.233, c_l = 0.22867, Am = 3.96752, c_s = 1.70316 \tag{28}$$

3 RESULTS

The effects of above mentioned three noise source model functions are evaluated in Tam and Auriault's jet noise theory through comparison with experimental results at several jet Mach numbers for cold and hot single stream jet.

In Figures 1a-1c, the jet Mach numbers are 0.3, 0.5, 0.7, 0.9 and the temperature ratio is 1.0. The spectra are scaled to a distance of $100D_j$. In the legend of Figures 1a-1c, TA, K and HB represent the prediction results of noise source model functions proposed by Tam and Auriault, Khavaran et al. and Harper-Bourne respectively. Figure 1a is for noise radiation at $\theta = 60^\circ$, where θ is the polar observer angle with respect to downstream jet axis. As shown in Figure 1a, for all the Mach numbers, the calculated spectra of the three noise source model functions are all in good agreement with experimental measurements in low and mid frequency range. In the case of 0.3 and 0.5 jet Mach number, in high frequency range, the prediction results of Harper-Bourne's noise source model function are in slightly better agreement with experimental measurements. Figure 1b and 1c show comparison at $\theta = 90^{\circ}$ and $\theta = 120^{\circ}$ respectively. Similarly, in these two figures, the calculated spectra of the three noise source model functions agree with the experimental measurements well in low and mid frequency range for all jet Mach numbers. For 0.3 and 0.5 jet Mach number cases, at high frequency, the prediction results of Harper-Bourne's noise source model function agree with the measurements slightly better.

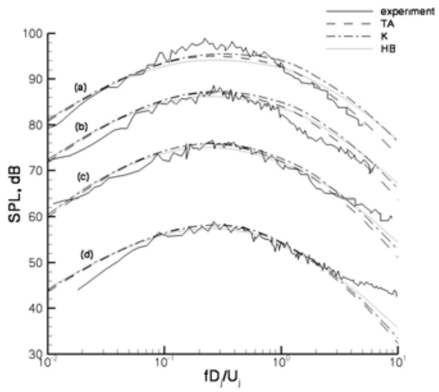

Figure 1a Comparisons between calculated nosie spectra and experiment, where $R = 100D_j$, $\theta = 60\,\text{deg}$, $T_r / T_\infty = 1.0$, and M_j = (a) 0.9, (b) 0.7, (c) 0.5, (d) 0.3 TA: Tam and Auriaultl's source model K: Khavaran et al's source model HB: Harper-Bourne's source model

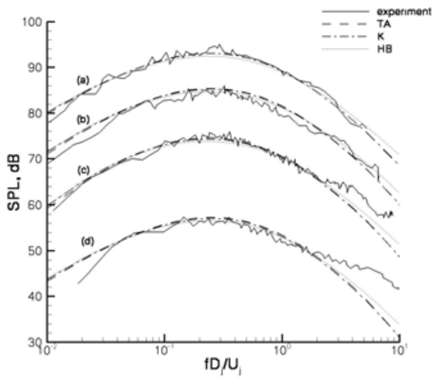

Figure 1b Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $\theta = 90\,\text{deg}$, $T_r / T_\infty = 1.0$, and M_j = (a) 0.9, (b) 0.7, (c) 0.5, (d) 0.3

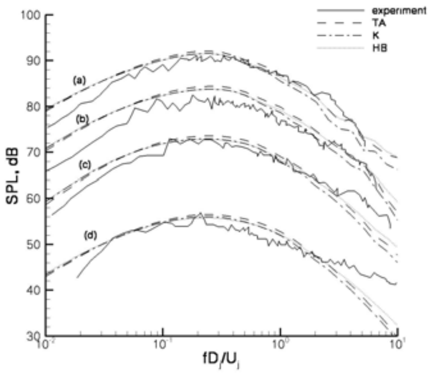

Figure 1c Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $\theta = 120\,\text{deg}$, $T_r / T_\infty = 1.0$, and M_j = (a) 0.9, (b) 0.7, (c) 0.5, (d) 0.3

Figures 2a-2c show comparison of the calculated noise spectra of the three noise source model functions with frequency dependent length scale and experimental measurements. Figure 2a, 2b and 2c are for noise radiation at $\theta = 60^{\circ}$, $\theta = 90^{\circ}$ and $\theta = 120^{\circ}$ respectively. In the legend of Figures 4-6, TA, K and HB represent the prediction results of the three source model functions with frequency dependent length scale, and TA_orig represents the results of Tam and Auriault's source model function with original length scale. As shown in these three figures, in low and mid frequency range, the calculated spectra of the three noise source model functions are in good agreement with experimental measurements for all jet Mach numbers. For cases of 0.3 and 0.5 jet Mach number, in high frequency range, a better agreement is obtained using Harper-Bourne's and Khavaran et al.'s noise source model functions with frequency dependent length scale. The experimental measurements of Figures 1a-1c and 2a-2c are cited from Ref. 3.

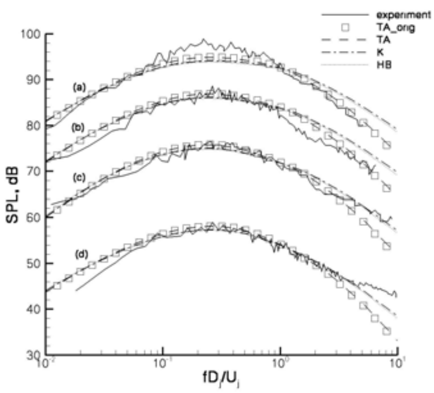

Figure 2a Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $\theta = 60\,\text{deg}$, $T_r / T_\infty = 1.0$, and M_j = (a) 0.9, (b) 0.7, (c) 0.5, (d) 0.3 TA_orig: Tam and Auriault's source model with original length scale TA: Tam and Auriault's source model with frequency dependent length scale K: Khavaran et al's source model with frequency dependent length scale HB: Harper-Bourne's source model with frequency dependent length scale

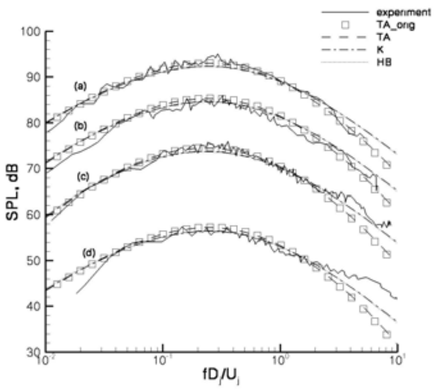

Figure 2b Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $\theta = 90\,\deg$, $T_r/T_\infty = 1.0$, and M_j = (a) 0.9, (b) 0.7, (c) 0.5, (d) 0.3

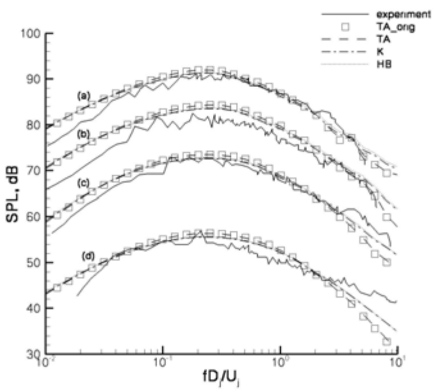

Figure 2c Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $\theta = 90\,\deg$, $T_r/T_\infty = 1.0$, and M_j = (a) 0.9, (b) 0.7, (c) 0.5, (d) 0.3

Figure 3a shows comparisons between calculated noise spectra and experimental measurements. The jet Mach numbers are 0.9, 0.7 and 0.5. The jet temperature ratio is 1.8. The direction of radiation (inlet angle) is 90deg. Figure 3b is similar to Figure 3a except that it is for jet Mach number 1.0, 0.8 and 0.6. In the legend of Figure 3a and 3b, TA, K and HB represent the prediction results of Tam et al's modified source model, Khavaran et al.'s source model and Harper-Bourne's source model respectively. It is shown in Figure 3a and 3b that the prediction results of Khavaran et al. and Harper-Bourne source model are obviously lower than experimental measurements, especially for low jet Mach numbers (0.5 and 0.6). The comparison results of Figure 3a and 3b indicate that Khavaran et al's and Harper-Bourne's source model are not applicable to the prediction of hot jet noise.

Figure 4a and 4b show comparisons between calculated noise spectra and experimental measurements. The jet temperature ratio is 1.8 and direction of radiation (inlet angle) is 90deg. The jet Mach numbers are 0.9, 0.7 and 0.5 for Figure 4a and 1.0, 0.8 and 0.6 for Figure 4b. In the legend of Figure 4a and 4b, TA_orig represents the results of modified source model proposed by Tam et al. with original length scale as given in Ref. 5, and TA represents the results of the same source model with frequency dependent length scale. As Figure 4a and 4b show, for jet Mach numbers of 0.5, 0.6 and 0.7, in the high frequency range, the prediction results of source model with frequency dependent length scale are in better agreement with experimental measurements. For high jet Mach numbers (0.8, 0.9 and 1.0), the agreement of results calculated by modified source model with original length scale with measurements is better. Figure 4c and 4d show similar comparisons at inlet angle of 110deg. Similarly, for jet Mach numbers of 0.5, 0.6 and 0.7, in the high frequency range, the prediction results of modified source model with frequency dependent length scale are in better agreement with experimental measurements. However, for jet Mach numbers of 0.8, 0.9 and 1.0, in the high frequency range, there is derivation between the results of modified source model with frequency dependent length scale and experimental data.

The experimental measurements of Figures 3a, 3b, 4a-4d are extracted from Ref. 5.

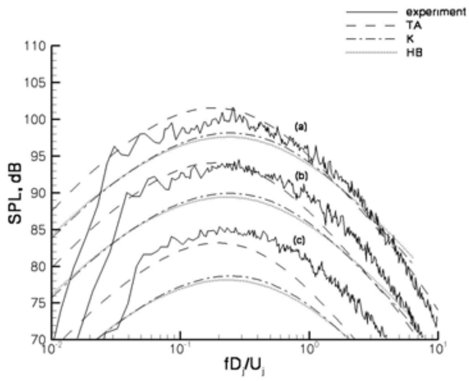

Figure 3a Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $T_r/T_\infty = 1.8$, inlet angle =90deg and M_j = (a) 0.9, (b) 0.7, (c) 0.5 TA: Tam et al.'s modified source model K: Khavaran et al's source model HB: Harper-Bourne's source model

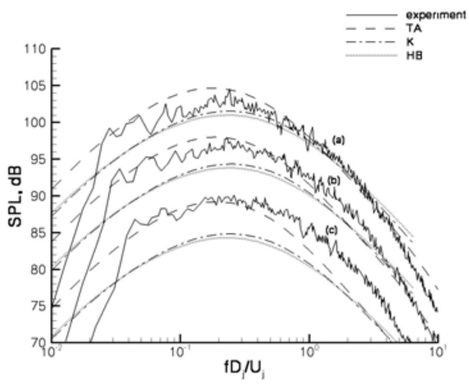

Figure 3b Comparisons between calculated nosie spectra and experiment, where $R = 100D_j$, $T_r/T_\infty = 1.8$, inlet angle =90deg and M_j = (a) 1.0, (b) 0.8, (c) 0.6

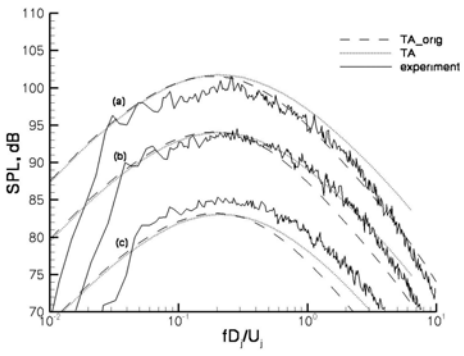

Figure 4a Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $T_r / T_\infty = 1.8$, inlet angle =90deg and M_j = (a) 0.9, (b) 0.7, (c) 0.5 TA_orig: Tam et al's modified source model TA: Tam et al's modified source model with frequency dependent length scale

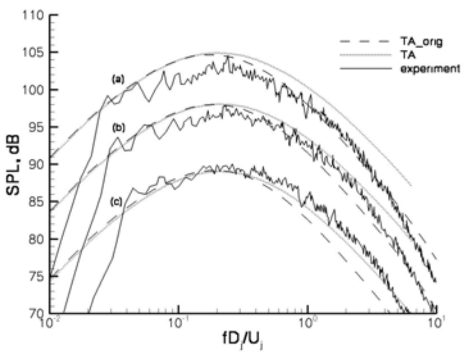

Figure 4b Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $T_r / T_\infty = 1.8$, inlet angle =90deg and M_j = (a) 1.0, (b) 0.8, (c) 0.6

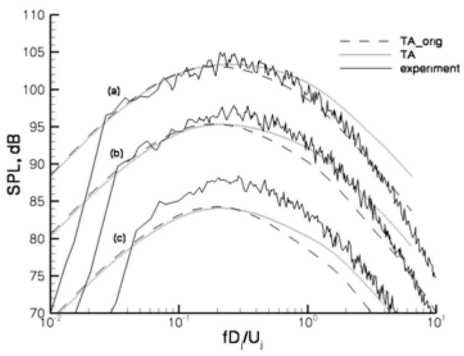

Figure 4c Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $T_r / T_\infty = 1.8$, inlet angle =110deg and M_j = (a) 0.9, (b) 0.7, (c) 0.5

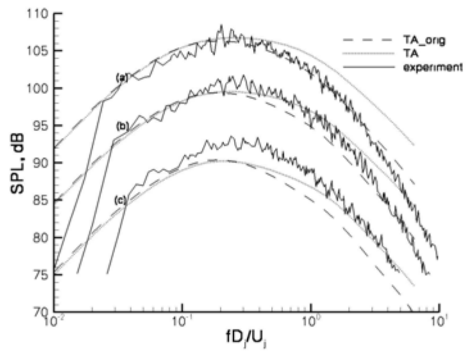

Figure 4d Comparisons between calculated noise spectra and experiment, where $R = 100D_j$, $T_r / T_\infty = 1.8$, inlet angle =110deg and M_j = (a) 1.0, (b) 0.8, (c) 0.6

4 CONCLUSIONS

The noise source model function of Tam and Auriault's theory is modified in order to improve the accuracy of prediction results of this theory. Two alternative source model functions are considered here which are proposed by Khavaran et al. and Harper-Bourne respectively. In addition, a frequency dependent length scale proposed by Morris and Boluriaan is applied to the noise source model functions. The effects of the three noise source model functions are evaluated in Tam and Auriault's theory by the comparison of calculated noise spectra and experimental measurements for several jet Mach numbers of cold and hot single-stream jet. The comparisons indicate that in the high frequency range, the prediction results of Harper-Bourne and Khavaran et al's source model with frequency dependent length scale are in better agreement with measurements for low Mach numbers (0.3 and 0.5) of cold jet. Harper-Bourne's and Khavaran et al's source model are used to calculate hot jet noise and there is obvious derivation between their prediction results and measurements, which indicates that these two noise source model functions are not applicable to the prediction of hot jet noise. A frequency dependent length scale is applied to the modified source model for hot jet noise prediction proposed by Tam et al., and a better agreement with measurements is obtained in the high frequency range for jet Mach numbers of 0.5, 0.6 and 0.7.

ACKNOWLEDGMENT

This work is supported by grants from the NCET-07-0038, the 973 Program-2007CB714604 and the NSFC-50890181. The authors would also like to acknowledge the partial support from the 111 projects B07009 and B08009 of China.

REFERENCES

1Khavaran, A., Krejsa, E. A., and Kim, C. M., "Computation of Supersonic Jet Mixing Noise from an Axisymmetric CD Nozzle Using $k-\varepsilon$ Turbulence Model," AIAA Paper 92-0500, Jan. 1992.

2Khavaran, A., and Krejsa, E. A., "On the Role of Anisotropy in Turbulent Mixing Noise," AIAA 98-2289

3Khavaran, A., "Prediction of Turbulence-Generated Noise in Unheated Jets, Part 1," NASA/TM-2005-213827.

4Tam, C. K. W., and Auriault, L., "Jet Mixing Noise from Fine-Scale Turbulence," AIAA Journal, Vol. 37, No. 2, 1999, pp. 145-153

5Tam, C. K. W., Pastouchenko, N. N., and Viswanathan, K., "Fine-Scale Turbulence Noise from Hot Jets," AIAA Journal, Vol. 43, No. 8, 2005, pp. 1675-1683.

6Harper-Bourne, M., "Jet Noise Turbulence Measurements," AIAA paper 2003-3214.

7Morris, P.J., and Boluriaan, S., "The Prediction of Jet Noise from CFD Data," AIAA paper 2004-2977.

8Tam, C. K. W., and Ganesan, A., "A Modified $k-\varepsilon$ Turbulence Model for Calculating the Mean Flow and Noise of Hot Jets," AIAA Journal, Vol. 42, No. 1, 2004, pp. 26-34.