MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Normalization of noise spectra of a single-stream jet from two model-scale tests

Lin, Dakai[1], Zhang, Yingzhe[2], Yang, Zhigang[3], and Lee, Incheol[4],
Beijing Aeronautical Science and Technology Research Institute of COMAC,
Beijing Key Laboratory of Simulation Technology for Civil Aircraft Design
China North of Future Science Park, Changping District Beijing, 102211 P. R. China

ABSTRACT

For the identification of the noise characteristics of a single-stream jet, two model-scale experiments were conducted. The first experiment was carried out at the anechoic chamber of Beijing University of Aeronautics and Astronautics in China and the second one at the anechoic wind tunnel of ONERA in France. In each experiment, spectra were obtained for various nozzle temperature ratios and nozzle pressure ratios. At forward-to-mid angles, the shape of the normalized spectra is consistent, and the level of the normalized spectra moderately changes. At very aft angles, a large scatter at the higher Strouhal numbers less than 0.5 was observed. This means that one velocity exponent could be used for the normalization of spectra at each of forward-to-mid angles and two velocity exponents may need to be introduced for the normalization of spectra at each of aft angles at a given NTR. The velocity exponent which is a critical factor for the normalization of spectra is calculated and compared to other results as well. For unheated jets, the absolute value of the present velocity exponent is off from other results with a similar overall trend whereas, for heated jets, the present velocity exponent is close to other results.

Keywords: Jet noise, Normalization, Scaling law, Empirical analysis, Single jet
I-INCE Classification of Subject Number: 74

1. INTRODUCTION

The noise of a modern commercial airplane powered by high bypass ratio turbofan engines mainly consists of engine noise and airframe noise. The engine noise can be categorized into various components such as jet noise, fan noise, and turbomachinery noise. Among these, jet noise is one of the primary noise sources for take-off conditions. The prediction of jet noise from modern high bypass ratio turbofan engines, which adopts dual stream nozzle exhaust geometries, has been highlighted. It has been widely accepted that dual-stream jet noise consists of four sub-components[1,2] and each component acts as an independent noise source of a single-stream jet. Thus, it is critical to understand the prediction of the generation of noise from a pure round jet.

[1] lindakai@comac.cc
[2] zhangyingzhe@comac.cc
[3] yangzhigang1@comac.cc
[4] incheol.lee2@gmail.com

Prediction of the generation of noise using the equations of motion even from a simple round jet has been challenging due to the complex mechanisms of noise generation[3]. The acoustic analogy of Lighthill[4,5] has been used widely in the analysis and prediction of jet noise. However, the prediction methods based on the acoustic theory have not met the expectation for practical applications that require the spectral predictions at various frequencies and angles with reasonable accuracy. For the prediction of jet noise from dual-stream nozzle exhaust geometries with high accuracy, there has been an extensive reliance on empirical methods. In the early 1970s, experimental approaches[6,7] were conducted to measure jet noise from a single round jet and compare it to Lighthill's acoustic analogy. The correlation between jet noise and flow parameters, such as density, temperature, and velocity, has been investigated[8-13]. Based on the analysis of experimental data, several attempts were made to predict jet noise using acoustic theories and scaling laws[14-18]. However, no practical prediction method was accurate enough to be applied to practical work in the aviation industry since the predictions need to be robust over a wide range of frequencies, and a high level of accuracy is required at all angles.

In 2009, Viswanathan[19] proposed a new scaling law for the spectra of the single-stream jet at any angle, as shown in Equation (1):

$$SPL(\theta, St) = F\left(\theta, St, \frac{T}{T_a}\right)\left[\frac{V}{a}\right]^n \tag{1}$$

$$St = f\frac{D}{V} \tag{2}$$

where *SPL* (sound pressure level with a reference of 20 μPa) denotes the amplitude of jet noise in a logarithmic scale, θ is the emission angle, *St* is the Strouhal number defined in Equation (2), T/T_a is the nozzle total temperature ratio relative to an ambient temperature, and V is the jet velocity. The term n denotes the velocity exponent, which is a function of θ and T/T_a and determined by the measured overall sound pressure levels at each emission angle.

The SPL per unit area was given by the product of a spectrum function, F, and the velocity ratio raised to n. The spectrum function, F, and the exponent, n, were obtained from experimental measurements. The non-dimensional *SPL*, SPL^*, was expressed as shown in Equation (3):

$$SPL^* = SPL - 10log_{10}\left(\frac{A}{A_{ref}}\right) - 10 \times n \times log_{10}\left(\frac{V_j}{a}\right) \tag{3}$$

where A_{ref} denotes the reference area at the nozzle exit.

For the identification of the noise characteristics of a single-stream jet, a series of noise experiments, which consists of two phases was conducted. The first phase of the test, defined as BHU1, was carried out in the anechoic chamber of Beihang University (BUAA) in Beijing, China. The second phase of the test, defined as CEP1, was carried out in the anechoic wind tunnel of ONERA (CEPRA 19) in Saclay, France. In this paper, the data obtained from the two experiments are presented after being scaled. The calculated velocity exponents are compared to other results as well.

2. EXPERIMENTAL SETUP

2.1 Test facility and models

The first phase of the test, BHU1, was conducted in the anechoic chamber of Beihang University where many acoustic experiments have been performed in the past[20]. The jet propulsion system has been used for a variety of subsonic and supersonic jet noise test as well. Figure *1* shows an overview of the interior of the chamber. The detailed information of the chamber, propulsion system and measurement system can be found in Lee et al.[18].

The second phase of the test, CEP1, was conducted in the anechoic wind tunnel of ONERA, CEPRA 19, where various types of aeroacoustic measurement including jet noise have been successfully carried out. Figure *2* shows an overview of the interior of the tunnel with an installed dual nozzle configuration. The chamber is roughly a quarter of a sphere with an internal radius of 9.6 m. The tunnel can provide a free stream of up to 130 m/s through a 2 m diameter nozzle. Two arc-shaped arrays of which radius is 6 m were installed in the tunnel. The two arrays can cover two azimuthal angles, flyover, and sideline angles. In this paper, the spectra obtained with the flyover array of which plane is parallel to the floor of the tunnel are presented.

Figure 1 Anechoic chamber in Beihang University

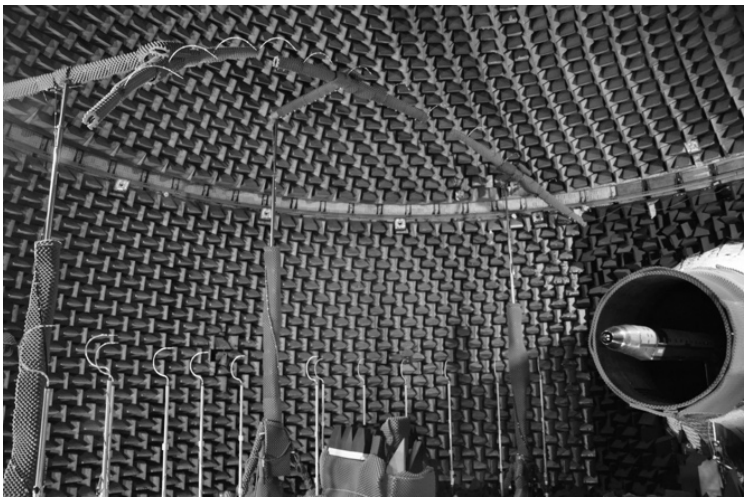

Figure 2 Anechoic wind tunnel in ONERA (CEPRA 19)

In both tests, single round nozzles without a plug part were designed and manufactured to investigate the characteristics of noise generated by a simple jet stream. They were attached to the jet rig which can provide two jet streams at requested nozzle-operating conditions. The nozzles were attached to the core part of the rig to simulate both unheated and heated flow conditions as shown in Figure *3* and Figure *4*. The diameter of the nozzle is 30.5 mm for BHU1, and 82 mm for CEP1. It is expected that the nozzles of two different scales would provide an opportunity to investigate the impact of scale on jet noise.

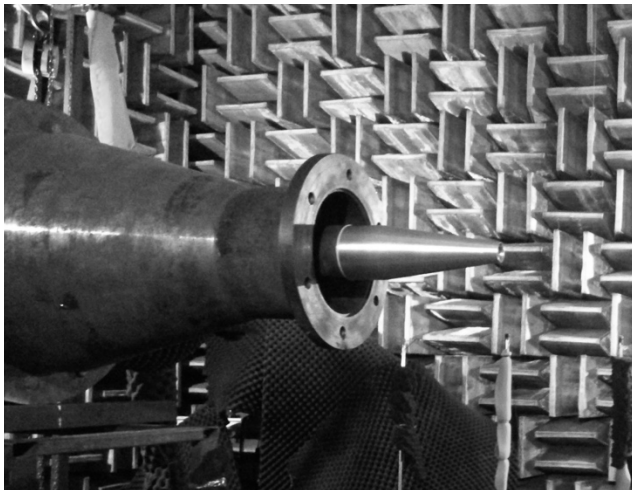

Figure 3 A simple round nozzle installed to the core part of the jet rig (BHU1)

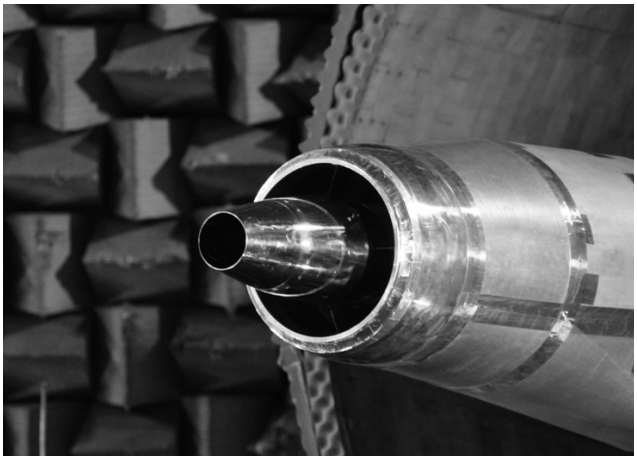

Figure 4 A simple round nozzle installed to the core part of the jet rig (CEP1)

2.2 Nozzle-operating conditions

The jet flow from a single nozzle can be characterized by a couple of flow parameters: *NPR* (nozzle pressure ratio), *NTR* (nozzle temperature ratio), and *D* (diameter of a nozzle at the exit plane. All the aerodynamic values used for the definition of the parameters are total pressure and total temperature values. The noise from a single-stream nozzle is a function of the above thermodynamic and geometric parameters since these parameters can change the velocity of a jet stream, *V*, a key factor of jet noise.

Various nozzle-operating conditions were set up to cover a wide range of unheated ($NTR = 1$) and heated ($NTR > 1$) jet conditions. Attention was paid on systematically changing nozzle-operating conditions during the tests. Four *NTR* values, 1.0, 2.1, 2.4, and 2.7, were considered for BHU1 and five *NTR* values, 1.0, 2.0, 2.4, 2.8, and 3.2 were considered for CEP1. At each *NTR*, noise spectra of various *NPR* values up to 1.85 were measured to obtain a comprehensive database of single-stream jet noise.

Though wind-on conditions could be considered during CEP1, the measurement only in static conditions was made. Since the outer tip of the jet rig which is supposed to be connected to a bypass nozzle would generate unwanted vortices, and they would contaminate the jet noise when the tunnel is on. Thus, all the data presented in this paper were obtained in static conditions.

3. RESULTS AND DISCUSSION

Figure 5 shows the measured spectra from unheated jets (*NTR* = 1) of CEP1. *NPR* values of spectra vary from 1.15 to 1.85, which can simulate the jet flow of a secondary stream of a modern turbofan engine. It is found that the increase of spectra is shown as a shape of a shift for all frequencies as a function of *NPR* at all angles. However, the rate of the spectral increase is not precisely proportional to *NPR*. Spectra shown in Figure 6 were normalized by using Equation (3). Note that the velocity exponent, n, was determined at each angle and the term related to the area, A_{ref}, in Equation (3) was not considered, since there was no change in the nozzle area. Figure 7 shows the normalized spectra from unheated jets obtained during BHU1. In all the following figures of normalized spectra, the x-axis represents the Strouhal number, the y-axis represents the normalized SPL calculated by using Equation (3), and the major grid of the y-axis denotes 10 dB.

For unheated jets, all normalized spectra are on top of each angle at each angle except at very aft angles such as 150 degrees. At forward-to-mid angles, the shape of the normalized spectra is almost identical, and the level of the normalized spectra gradually increases as the angle increases. At 150 degrees, the normalized spectra are collapsed perfectly if the Strouhal number is greater than 0.5, but a noticeable scatter of spectra is observed if the Strouhal number is less than 0.5: the level of the spectra is a function of *NPR,* and the peak of the normalized spectra is not aligned. The spectral trend at aft angles is consistent across the two tests, and it is observed in the analysis performed by Viswanathan[3]. He showed that the Strouhal number of 0.5 is a point of inflection as well, and the normalized spectra are perfectly collapsed if the Strouhal number is higher than the point of inflection. He also showed that the peak of the normalized spectra could be aligned when the velocity exponent increases from 8 to 9.8 but a larger scatter at the higher Strouhal numbers to the right of the spectral peak. When the frequency was normalized as a Helmholtz number, not a Strouhal number, the normalized spectra at 150 degrees were on top of each other. This means that the mechanism of noise generation at aft angles is different from that at forward-to-mid angles, and it is not a function of jet velocity when a jet stream is unheated.

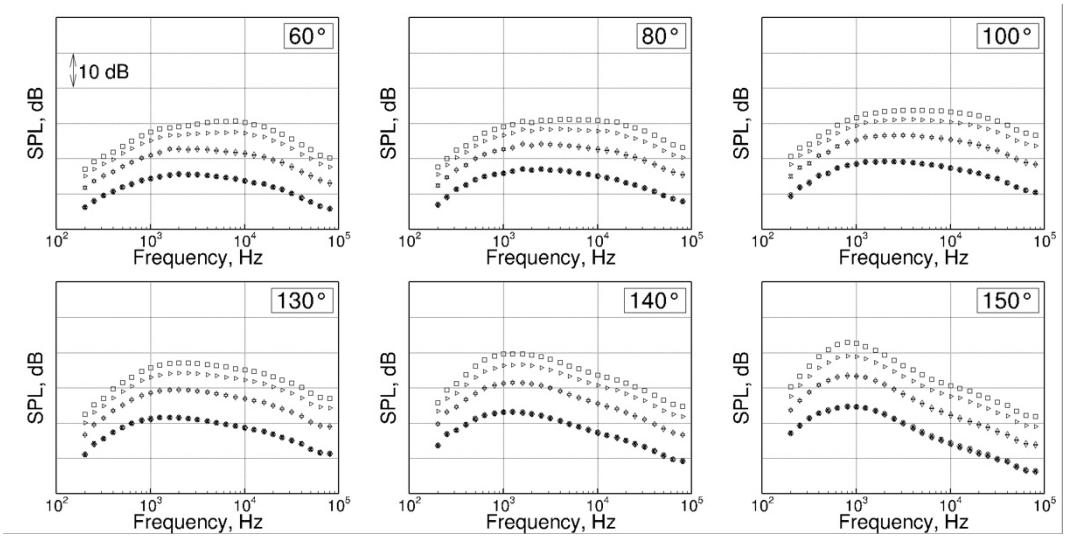

Figure 5 Measured spectra from unheated jets at various angles (CEP1)

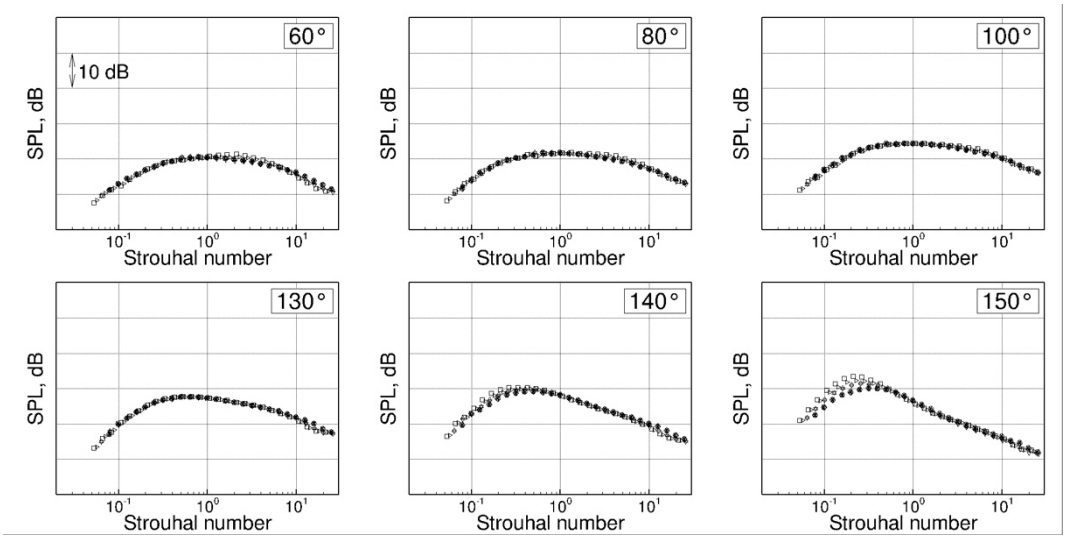

Figure 6 Normalized spectra from unheated jets (CEP1)

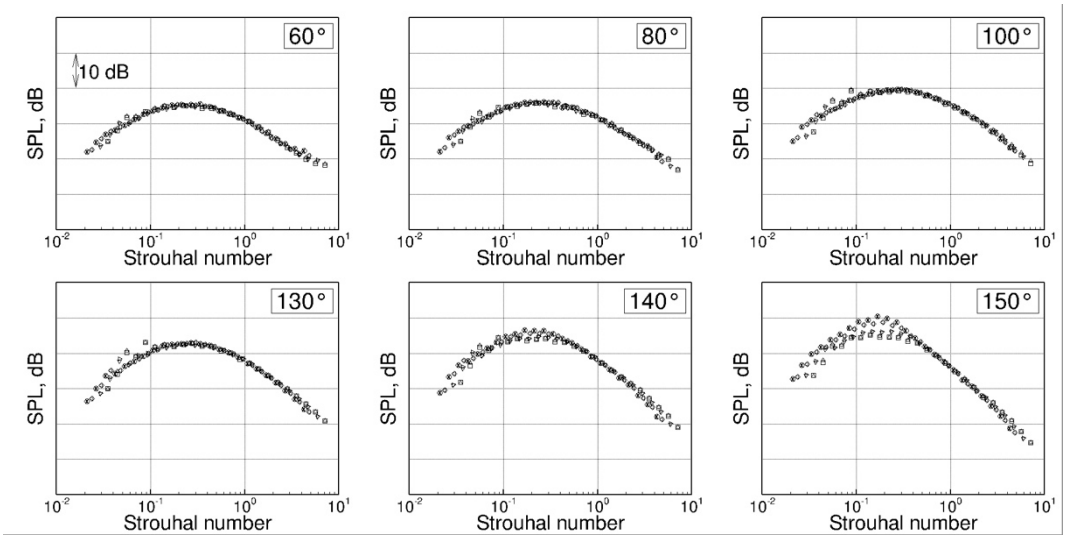

Figure 7 Normalized spectra from unheated jets (BHU1)

Figure 8 to Figure 11 shows normalized spectra from heated jets obtained during the two tests for various *NTR* values from 2.4 to 2.8. The same rule of normalization was applied, and the velocity exponent was calculated for each angle at each *NTR*. The overall trend of the normalized spectra from heated jets is similar to that from unheated jets. At forward-to-mid angles, the shape of the spectra is consistent, and the level of the spectra moderately changes. At very aft angles, a large scatter at the higher Strouhal numbers less than 0.5 was observed. And more scatter at the low Strouhal numbers was observed when *NTR* increases. When *NTR* is 2.8, a scatter of the normalized spectra was observed even at the right of the point of inflection, 0.5. It seems that the directivity of the spectra varies at 150 degrees even the spectra are normalized.

Based on the above observation, it can be concluded that one velocity exponent could be used for the normalization of spectra at each of forward-to-mid angles at a given NTR and two velocity exponents need to be introduced for the normalization of spectra at each of aft angles.

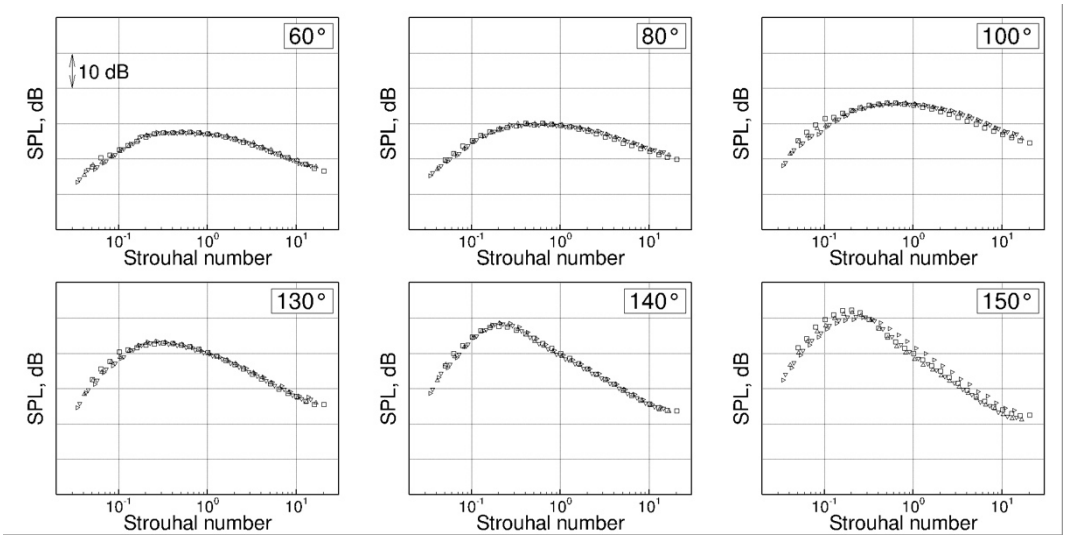

Figure 8 Normalized spectra from heated jets (CEP1, *NTR* = 2.4)

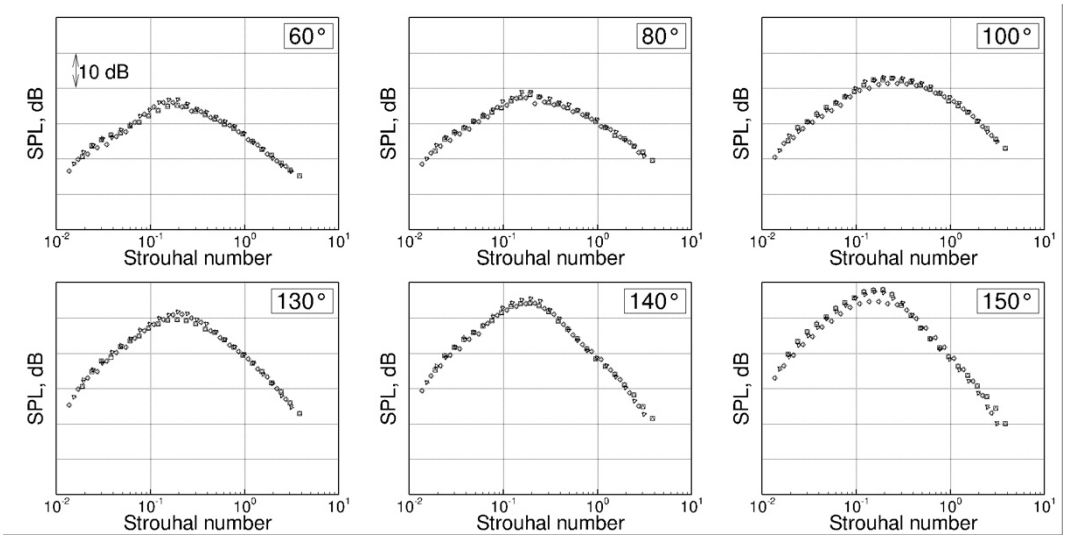

Figure 9 Normalized spectra from heated jets (BHU1, *NTR* = 2.4)

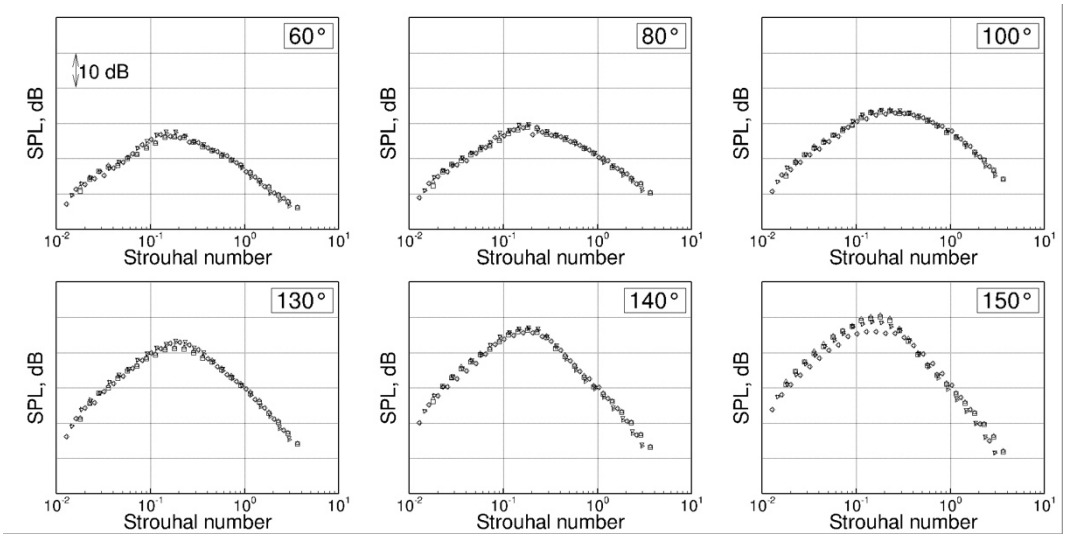

Figure 10 Normalized spectra from heated jets (BHU1, *NTR* = 2.7)

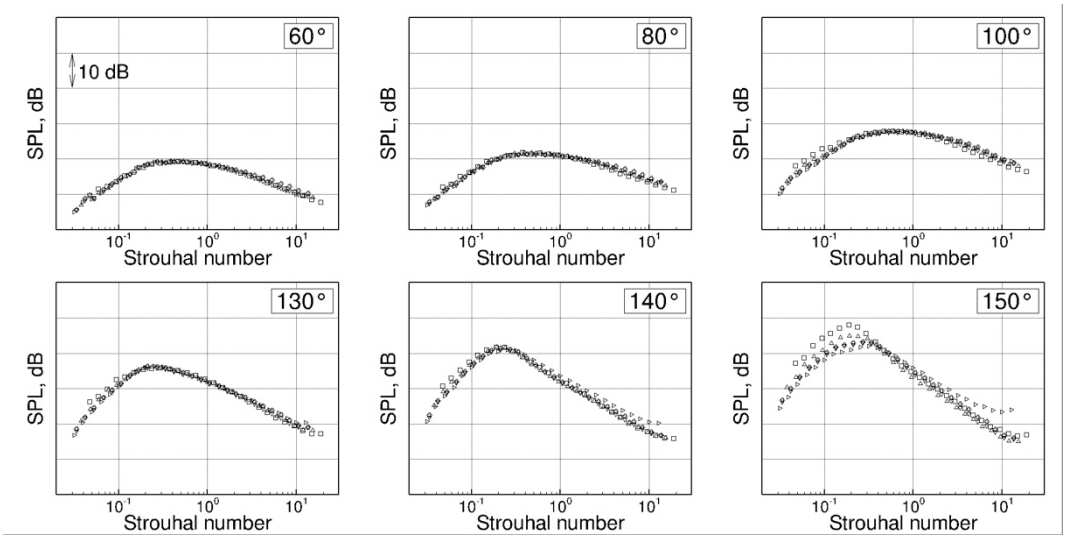

Figure 11 Normalized spectra from unheated jets (CEP1, *NTR* = 2.8)

As described earlier, the velocity exponent (n) was calculated at each angle for a given *NTR*. Figure 12 shows the velocity exponent for three *NTR* values, 1.0, 2.4, and 2.7. The calculated n based on the data of the two tests, BHU1 and CEP1, was compared to other results[21,22] if available. When *NTR* is 1.0, the absolute value of the present result is off from the other results, but the overall trend seems to be similar. A significant discrepancy between the present results and other results at very aft angles might be because the peak of the normalized spectra is not in alignment. If additional treatment is applied to consider the peak component, the discrepancy would be reduced. When *NTR* is 2.4, the velocity exponent of the two tests is similar, and the normalized spectra of each test are on top of each other except at 150 degrees as observed in Figure 8 and Figure 9. When *NTR* is 2.7, all the results are close to each other with a maximum deviation of 1 at all angles. It means that different data sets would yield different velocity components even at the same nozzle-operating condition.

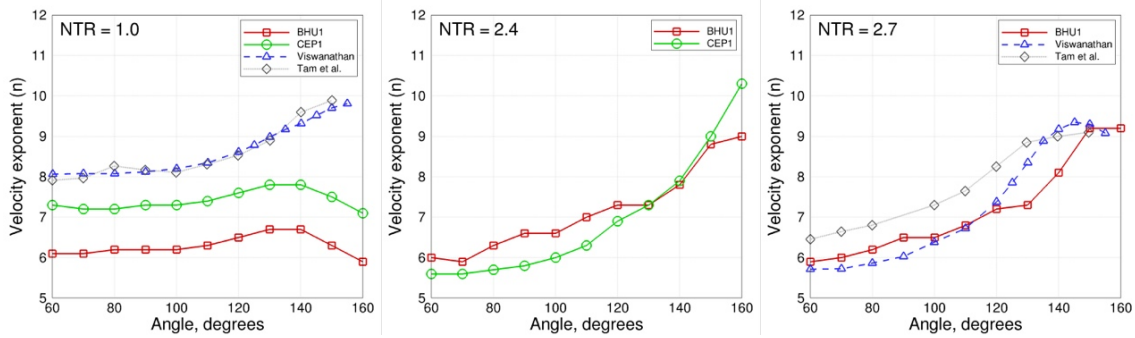

Figure 12 Velocity exponent for three *NTR* values (□: BHU1; ○: CEP1; △: Viswanathan[21]; and ◇: Tam et al.[22])

4. CONCLUSIONS

Prediction of the generation and radiation of noise using the equations of motion even from a simple round jet has been challenging. Therefore, there has been a heavy reliance on empirical methods. There have been recent experimental investigations and computational simulations of the flow fields. To identify the noise characteristics of single-stream jets and to obtain a comprehensive database for the development of reliable

and robust prediction of noise from single-stream jets, the authors carried out two model-scale experiments. The first experiment was carried out at the anechoic chamber of Beijing University of Aeronautics and Astronautics in China in 2016 and the second one at the anechoic wind tunnel of ONERA in France in 2017. In each experiment, spectra were obtained for various nozzle pressure ratios and nozzle temperature ratios. After being processed and normalized, the spectra are compared to other experimental data. The directivity trend with respect to nozzle temperature ratio is investigated. At forward-to-mid angles, the shape of the normalized spectra is almost identical, and the level of the normalized spectra gradually increases as the angle increases. At 150 degrees, the normalized spectra are collapsed perfectly if the Strouhal number is greater than 0.5, but a noticeable scatter of spectra is observed if the Strouhal number is less than 0.5. It can be concluded that one velocity exponent could be used for the normalization of spectra at each of forward-to-mid angles at a given NTR and two velocity exponents may need to be introduced for the normalization of spectra at each of aft angles. The velocity exponent which is a critical factor for the normalization of spectra is calculated and compared to other results as well. For unheated jets, the overall trend of the present velocity exponent with respect to an angle seems to be similar though the absolute value of the present result is off from other results. For heated jets, the present velocity exponent is close to other results. It can be concluded that the velocity exponent doesn't need to be unique and it may vary for different data sets even at the same nozzle-operating condition.

5. ACKNOWLEDGEMENTS

The authors thank Mr. Zhi Deng of BASTRI for their support for the successful execution of the experiments. The support of Prof. Xiaodong Li of Beihang University is appreciated. The support of staff at CEPRA 19 of ONERA for scheduling and conducting the test, maintaining the facility, and measurement system is also appreciated.

6. REFERENCES

1. Fisher, M. J., Preston, G. A., and Mead, C. J., "A modelling of the noise from simple coaxial jets, Part I: With unheated primary flow," Journal of Sound and Vibration, Vol. 209, No. 3, pp. 385-403, 1998.
2. Fisher, M. J., Preston, G. A., and Mead, C. J., "A modelling of the noise from simple coaxial jets, Part II: With heated primary flow," Journal of Sound and Vibration, Vol. 209, No. 3, pp. 405-417, 1998.
3. Viswanathan, K., "Improved Method for Prediction of Noise from Single Jets," AIAA Journal, Vol. 45, No. 1, pp. 151-161, 2007.
4. Lighthill, M. J and Newman, M. H. A., "On sound generated aerodynamically. I. General theory," Proceedings of the Royal Society A 211, pp. 564-578, 1952.
5. Lighthill, M. J., "On sound generated aerodynamically. II. Turbulence as a source of sound," Proceedings of the Royal Society A 222, pp. 1-21, 1954.
6. Lush, P. A., "Measurements of subsonic jet noise and comparison with theory," Journal of Fluid Mechanics, Vol. 46, No. 3, pp. 477-500, 1971.
7. Ahuja, K. K. and Bushell, K. W., "An experimental study of subsonic jet noise and comparison with theory," Journal of Sound and Vibration, Vol. 30, pp. 317-341, 1973.
8. Hoch, R. G., Duponchel, J. P., Cocking, B. J., and Bryce, W. D., "Studies of the influence of density on jet noise," Journal of Sound and Vibration, Vol. 28, pp. 649-668, 1973.

9. Tanna, H. K., Dean, P. D., and Fisher, M. J., "THE INFLUENCE OF TEMPERATURE ON SHOCH-FREE SUPERSONIC JET NOISE," Journal of Sound and Vibration, Vol. 39, No. 4, pp. 429-460, 1975.
10. Tanna, H. K., "AN EXPERIMENTAL STUDY OF JET NOISE PART I: TURBULENT MIXING NOISE," Journal of Sound and Vibration, Vol. 50, No. 3, pp. 405-428, 1977.
11. Tanna, H. K., "AN EXPERIMENTAL STUDY OF JET NOISE PART II: SHOCK ASSOCIATED NOISE," Journal of Sound and Vibration, Vol. 50, No. 3, pp. 429-444, 1977.
12. Viswanathan, K., "Aeroacoustics of hot jets," Journal of Fluid Mechanics, Vol. 516, pp. 39-82, 2004.
13. Lee, I., Zhang, Y., and Lin, D., "A model-scale test on noise from single-stream nozzle exhaust geometries in static conditions," *Chinese Journal of Aeronautics*, Vol. 31, No. 12, pp. 2206-2220, 2018.
14. Ahuja, K. K., "Correlation and prediction of jet noise," Journal of Sound and Vibration, Vol. 29, pp. 155-168, 1973.
15. Tester, B. J. and Morfey, C. L., "Developments in jet noise modelling – theoretical predictions and comparisons with measured data," Journal of Sound and Vibration, Vol. 46, pp. 79-103, 1976.
16. Morfey, C. L., Szewczyk, V. M., and Tester, B. J., "New scaling laws for hot and cold jet mixing noise based on a geometric acoustics model," Journal of Sound and Vibration, Vol. 61, pp. 255-292, 1978.
17. Tam, C. K. W., Golebiowski, and Seiner, J. M., "On the two components of turbulent mixing noise from supersonic jets," AIAA Aeroacoustics Conference, AIAA-96-1716, 1996.
18. Anon, "Gas Turbine Jet Exhaust Noise Prediction," SAE ARP876, Revision E, 2013.
19. Viswanathan K., "Mechanisms of jet noise generation: classical theories and recent developments," International Journal of Aeroacoustics, Vol. 8, No. 4, pp. 355-408, 2009.
20. He, J. and Li, X., "Investigation into Hot Jet Noise Reduction Mechanisms of Chevron Nozzles," Journal of propulsion technology, Vol. 36, No. 2, 2015, pp. 167-174.
21. Viswanathan, K., "Scaling Laws and a Method for Identifying Components of Jet Noise," AIAA Journal, Vol. 44, No. 10, pp. 2274-2285, 2006.
22. Tam, C. K. W., Viswanathan, K., Ahuja, K. K., and Panda, J., "The sources of jet noise: experimental evidence," Journal of Fluid Mechanics, Vol. 615, pp. 253-292, 2008.