DATABASE EVALUATION FOR SEMI-EMPIRICAL METHODS APPLIED TO COAXIAL JET NOISE PREDICTION

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Abstract. *The main goal of this work is to evaluate ways to optimize databases that are used in the prediction of noise generated by coaxial jets, to improve an existing semi-empirical method, namely Four-Source, currently being used at the EMBRAER/FAPESP project called "Aeronave Silenciosa". The task is to provide an improved method with a general database that could be applied to predict the noise from commercial turbofan engines. The databases used in this work were SAE ARP876D and ESDU 98019. These databases commonly used in industry, are applied to predict jet noise from single stream jets and are used as part of the Four-Source Model. The method is tested in different conditions and the results are compared with experimental data obtained in the literature. In this work, it was also performed an analysis between the different nozzles area ratio (AR) and velocities ratio (VR). The results show that the Four-Source is an effective tool for noise prediction of coaxial jets. When the model is coupled with the database ESDU, it was observed better results than SAE database, however it was also identified the loss of accuracy with higher or lower ranges of the Strouhal number (where it performs extrapolation of the data). A further work is being developed to mix these databases in order to enhance the prediction capability. Additions of more data in the database through a new experiment are ways to also optimize the Four-Source Method.*

Keywords*: Jet Noise, Semi-empirical, Four-Source, Coaxial Jet, Aeroacoustics*

1. INTRODUCTION

The need for reasonably accurate techniques for predicting the noise of aeronautical engines has become a high priority since the introduction of high-bypass turbofan engines. Moreover, with the application of more restrictive limits imposed on aircraft noise as a certification requirement, prediction techniques are welcomed by the aircraft and engine industries in order to reduce the amount of money spent in doing experimental tests.

In order to predict jet noise, there are many techniques available considering different mathematical and numerical approaches. First principles methodologies such as Lighthill equations are well known. Semi-empirical methods and computational fluid dynamics (CFD) coupled with computational aeroacoustics (CAA) comprehend the other possibilities. By considering semi-empirical or empirical methods, it can be said that these methods are fast, reliable and have a long application in industry. However, one of the greatest problems in these methods is the restriction or applied considerations used to derivate them and also the envelope of operating conditions to be applied. As tailored tools for some specific jet noise predictions, many times they are restrictive to certain geometries, velocities, temperature and pressure ranges. Nevertheless, it is also observed that companies and organizations are interested in predicting the noise from jets using methods related to particular cases, and, sometimes, for just only one family of aeronautical engines. The work performed by Almeida (2008), shows the six most common semi-empirical methods for dual-stream (coaxial) jet noise prediction. These methods were described and compared among them. The methods were: SAE ARP 876D, ESDU 01004, SAE AIR 1905 – Method 1 (Rolls-Royce), SAE AIR 1905 – Method 2 (Boeing), SAE AIR 1905 – Method 3 (NASA) and the Four Source Model. In that work, comparing the results obtained for the prediction of noise from each method with experimental data from literature, it was found that the Four-Source Model was more accurate for the vast majority of cases analyzed.

1.1. The Four-Source Method

This method was proposed by Fisher et al. (1998) and developed at Institute of Sound and Vibration Research (ISVR), in Southampton – UK in order to be applied to predict coaxial jet noise of scaled models and real aeronautical engines. The basis of the method consists of coupling a flow model and an acoustic model, firstly considering the isothermal primary jet and after making considerations for the case where the primary jet is heated.

The flow model consider four distinct regions of generating noise, defined as the Primary to Secondary Shear Layer, Secondary to Ambient Shear Layer, the Fully Mixed Jet and the Interaction Zone, as shown in Fig. 1. This division in noise source regions is the basis for the composition of the method, giving the proper name for the method – *Four-Source*.

In sequence, there are described each one of these four noise sources in a coaxial jet flow.

<u>The Primary to Secondary Shear Layer</u>: Separates the initial portions of the primary and secondary flows.

Generated noise varies with the difference between primary and secondary velocities (V_p-V_s) and has a strong convective amplification resulting from the eddy convection velocity being of the order of (V_p + V_s) / 2. For the velocity ratio (VR) applied in aeroengines, the contribution of this region to the total noise is negligible and is disregarded, although its numerical implementation is quite simple for the method.

The Secondary to Ambient Shear Layer: In the work done by Ko and Kwan (1975), results confirm that the noise produced in this region can be approximated to the noise generated by a single jet with velocity, temperature and nozzle diameter of secondary jet (V_s, T_s and D_s). Also according with this reference, this region is responsible for generating high-frequency noise, and the prevalence of small vortices is larger when the velocity ratio approaches of the unity.

The Interaction Zone: The reference Ko and Kwan (1975) offered a set of figures and turbulence data that allowed the use of an effective diameter for single jet, with velocity equal to the velocity of the primary jet. This effective diameter can be approximated by: $D_e = D_p(1 + \lambda^2\beta)^{\frac{1}{2}}$, where λ is the exit mean velocity ratio and β the exit area ratio.

The Fully Mixed Jet: In this region the jet has the same mass flow, momentum and energy available by summing the contributions of primary and secondary jet. The conservation equations of mass and momentum are used, thus obtaining the equations for diameter and velocity of the fully mixed jet. According to Ko and Kwan (1975), in this region is expected a development of low frequency noise.

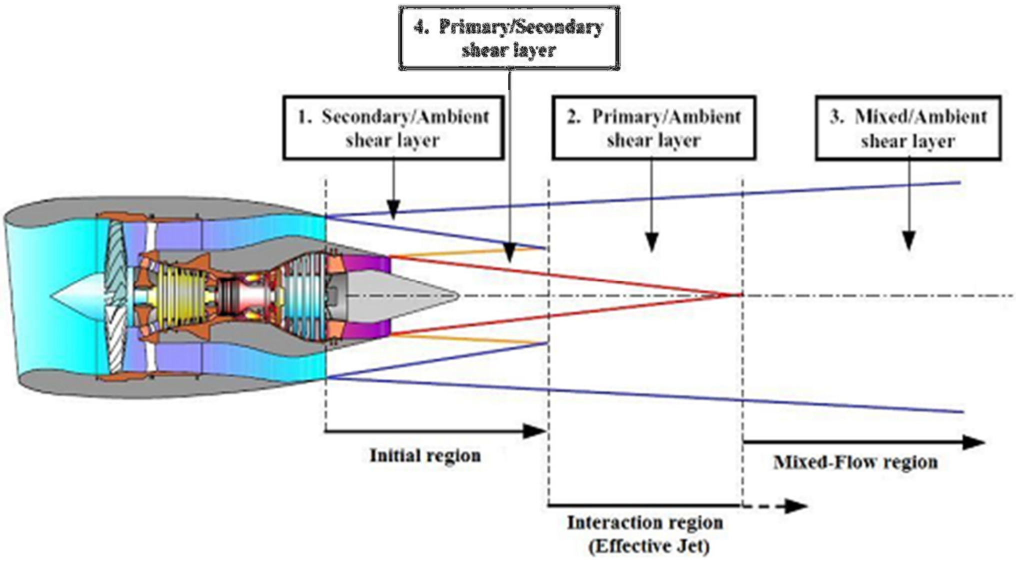

Figure 1. Regions of generating noise for a coaxial jet, after Almeida (2008).

In the acoustic model, techniques are used to predict noise for each region of the coaxial jet separately, comparing them to their respective single jet. It must be observed that each noise source region in the Four-Source model, behaves like a single jet and the final noise computation is composed by the summation of contribution of these noise regions.

This model also takes into account the effect of turbulence level, since there are differences from single jets to coaxial jets. A scaling analysis of the turbulence intensity is performed based on Lighthill's solution to the far field fluctuations at 90° to the jet axis – Fisher et al. (1998).

In the acoustic model is considered the balance of the contribution of each region in total noise generated. At this point, it is necessary to calculate the fraction of the energy radiated for the frequencies, from position upstream and downstream. These parameters (F_U and F_D, respectively), work as spectral filters for those frequencies which do not contribute in some regions.

As the flow model, the acoustic model also has its peculiarities in each region. As previously mentioned, the secondary jet is responsible for the high frequencies and ends with the end of the secondary core. Thus, the calculation of sound pressure level generated by the region takes into account the factor F_U, which represents the cut-off of the spectrum where the primary and secondary layers begin to mix.

The correction for the spectrum of effective jet is related to turbulence intensity, necessary for the correction of 7dB caused by the difference between the jets single and coaxial, where the turbulence levels are 15% and 10%, respectively. And finally for the mixed jet, it has low frequencies and it is only relevant downstream of its potential core where the predicted spectra are cut-off progressively by F_D.

The components are then added for each 1/3 octave frequency for each angle. On other hand, considering the heated primary flow, some changes are made in both models. By summarizing, the equations of sound pressure level (SPL) of each region, in function of each observation angle and frequency, for secondary, effective and mixed jet can be represented respectively by:

$$SPL_s(\theta, f) = SPL(V_s, D_s, \theta, f) + 10log_{10}F_U(f_1, f) \quad (1)$$

$$SPL_e(\theta, f) = SPL\left(V_p, D_e, \theta, f\right) + 40log_{10}(\alpha/\alpha_0) \quad (2)$$

$$\mathrm{SPL_m}(\theta, \mathrm{f}) = \mathrm{SPL}(\mathrm{V_m}, \mathrm{D_m}, \theta, \mathrm{f}) + 10\log_{10}\mathrm{F_D}(\mathrm{f_1}, \mathrm{f}) \quad (3)$$

Where F_U and F_D are the filters above mentioned, α and α_0 are the turbulence level.

A density factor is used for the conservation of momentum, since the temperatures of primary and secondary flow are considerably different. Since the secondary shear layer is totally out of the warm region, one can then consider it identical to the isothermal case, since the heating primary flow does not interfere in the secondary jet. In the fully mixed jet is only necessary to add an energy (enthalpy) equation, obtaining new equations for velocity, temperature and diameter. For the intermediate zone, there are no changes in velocity and temperature (still the same velocity and temperature of the primary flow in a single jet). This region has complex structures and experimental results show that it is reasonable to consider this region identical to that assumed in the isothermal case (flow model).

For the acoustic model, the same cut-off frequency approach as used for the isothermal case is employed. Spectral contributions from the secondary and mixed jets will remain unaltered. However, for the effective jet some modifications are made. For this, all the Lighthill's theory is reviewed and the existence of dipole sources in the heated case makes it a lower attenuation than that emitted by the conventional, single isolated jet, where there are only quadrupole sources. So it is necessary to find the dependence of far field pressure fluctuations upon the turbulence velocity within the dipole source term. The quadrupole sources are proportional to the fourth power of the turbulence level, while dipole sources in a hot turbulent jet is proportional to the square of the rms (root mean square) turbulence velocity. The attenuation of noise depends on the predominance of the dipole or quadrupole source, so each spectrum may be scaled appropriately. The reduced factor varies between -3.5 dB for a completely dipole-dominated jet to 7 dB for an isothermal jet containing only quadrupoles and it is implemented by ΔdB.

Essentially, the equations that describe the sound pressure level of each region now are also function of temperature, so we rewrite:

$$SPL_s(\theta, f) = SPL(V_s, T_s, D_s, \theta, f) + 10log_{10}F_U(f_1, f) \quad (4)$$

$$SPL_e(\theta, f) = SPL\left(V_p, T_p, D_e, \theta, f\right) + \Delta dB \quad (5)$$

$$SPL_m(\theta, f) = SPL(V_m, T_m, D_m, \theta, f) + 10log_{10}F_D(f_1, f) \quad (6)$$

From a physical point of view, a more detailed study of the heated jet and of the thermodynamics involved can be accomplished. However, the model is well established and has been developed by various researchers. A further study of the influence of the nozzle in the generation and propagation of noise would also be a path, for a new model improving the results of the method for short-cowl nozzles, since this change in shape of the nozzle is not considered in the current model. To work in this context, would require a complete review and the results would take significant time to be reached.

Only two methods available bring explicitly corrections for extended primary nozzles (SAE ARP 876D and SAE AIR1905 - Boeing), but have not shown satisfactory results for short-cowl cases. Thus, the database is of great importance in the scope of the method. The experiment performed to obtain the database should contain the lowest possible error and the range of angles, velocity ratio, temperature ratio, Strouhal number and nozzle geometry are decisive for the accuracy of the method. A new experiment is also a viable way to improve the accuracy of the method and especially to reduce the existing limitations to its application. As the Four-Source Model uses a database for single jets, this experiment can also optimize the semi-empirical methods for single jets and could be used as reference for verification and validation of numerical models under development. However, this approach is quite expensive and requires especial facilities to do it.

Another solution is to work with the manipulation of the databases available, which are the SAE ARP 876D and the ESDU 98019 in order to enhance the prediction capability of the method.

1.2. The ESDU and SAE's databases

ESDU 98019 and SAE ARP 876D are databases for single jets obtained in different experiments. Each has specific data for temperature ratio, Strouhal number and ratio between the fully expanded jet velocity and the ambient speed of sound. In this work, the index utilized to represent the parameters of single jet (velocity, diameter, and others) is "j".

For the SAE, the measured values of temperatures ratio (TR) are of 1.0, 2.0, 2.5, 3.0 and 3.5. The logarithm base 10 of the Strouhal number ($\log_{10}(fD_j/V_j)$) ranges from -1.6 to 1.6. The ratio between the fully expanded jet velocity and the ambient speed of sound (V_j/a_0) is integrated into the Strouhal number by the coefficient ξ. These data are measured to angle from 0 to 160º (formed by the line of the observer with the engine exhaust axis).

For the ESDU the temperatures ratio is 1.0, 1.5, 2.0 and 2.5. Strouhal number is bounded between -1.5 and 1.5, but in many cases have their limits reduced because the calculation of sound pressure levels, beyond interpolations and extrapolations too. The ratio V_j/a_0 is also used differently: in this case is an independent variable, fixed at 0.50, 0.75, 1.00, 1.25 and 1.50. The angles used are multiples of 10, ranging from 30 to 120.

Besides the parameters to obtain the data, the calculation procedure is peculiar to each database. So, many factors can be used to manipulate and merge the advantages of these databases and methods. All theoretical justification is taken from SAE (1994) and ESDU (2001). The data were digitized and transformed in graphics for all angles of application. It is noticed that the SAE method data are already normalized, while the ESDU data are not initially treated, as can be seen in figures 2 and 3. The trend shown in the figures follows for the other angles, in both cases.

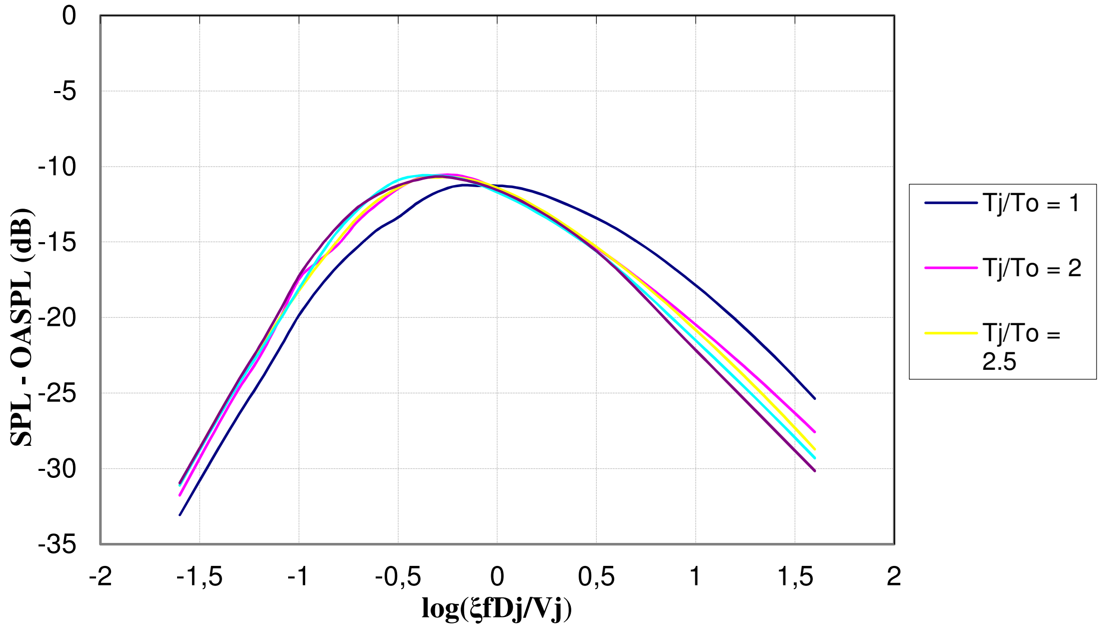

Figure 2. SAE's data for angle of line to observe with engine exhaust axis equals 100º.

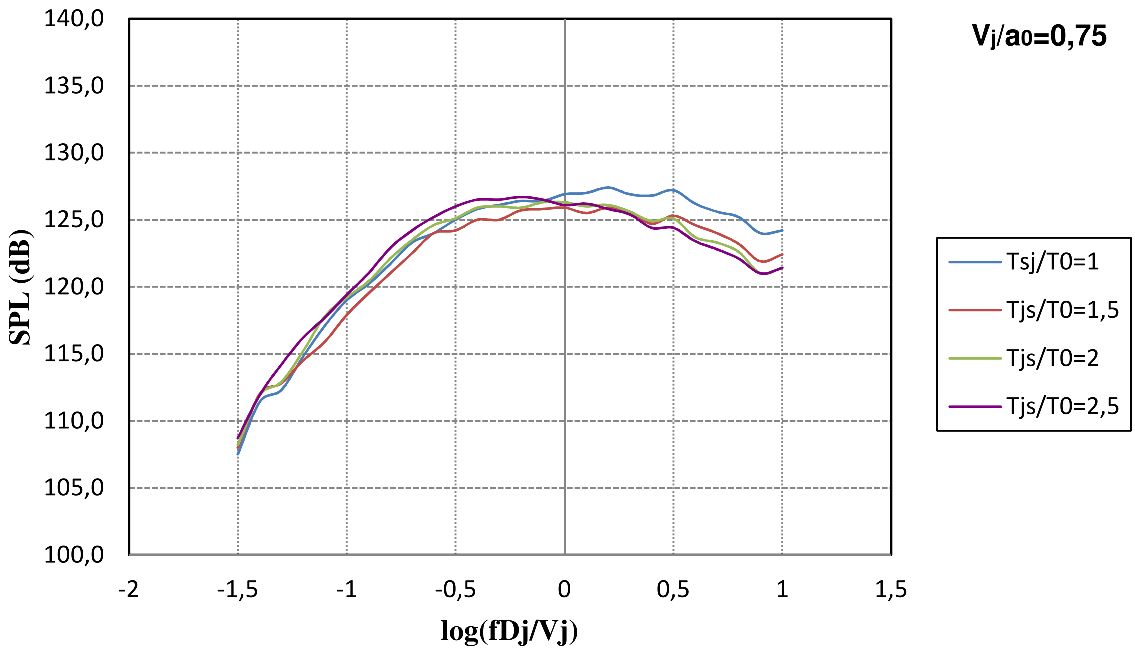

Figure 3. ESDU's data for angle of line to observe with engine exhaust axis equals 100º and velocity ratio of 0.75.

2. METHODOLOGY

The routine of the Four-Source Method is implemented in MATLAB ®. Some adjustments were made in the program since the former routines of the databases were developed in FORTRAN – Almeida (2008). Thus the main program executes a first acquisition and checking of the input data. If everything is consistent, the next step is to match the diameters (and hence area), velocities and temperature for each distinct region (secondary, effective and mixed). Now, an executable file containing the routine database (ESDU or SAE) is incorporated into the program, returning the values of the frequency spectral contributions for each region of the jet. With these contributions, the final prediction is then calculated like the coherent sum of the components for each 1/3 octave frequency and angle. In order to check the applicability of the Four-Source model, a series of experimental noise measurements on coplanar coaxial nozzles were considered. All this data was gathered through an ISVR collaboration project – JEAN (2003). More information about the test facility, test schedule, and data acquisition apparatus can be found at reference cited. The tests were done this work for two area ratios (2.0 and 4.0), one temperature ratio (1.0) and three velocity ratio (0.63, 0.79 and 1.00). Other peculiarity of this experiment is that pressure, temperature and relative humidity were measurements for each test condition performed. The Table 1 shows the conditions chosen for this study.

Table 1. Value of the parameters: primary nozzle area (Ap), secondary nozzle area (As), primary velocity (Vp), secondary velocity (Vs), area ratio (AR), temperature ratio (TR) and velocity ratio (VR) utilized for comparison in this work (in SI units).

AR	Ap [m²]	As [m²]	TR	VR	Vp [m/s]	Vs [m/s]	P_∞ [Pa]	T_∞ [K]
2.0	0.000865	0.001794	1.0	1.00	167.0	165.0	102400.0	275.45
2.0	0.000865	0.001794	1.0	0.79	208.7	167.5	102400.0	275.56
2.0	0.000865	0.001794	1.0	0.63	264.4	167.6	102400.0	275.56
4.0	0.000865	0.003494	1.0	1.00	166.7	167.9	101600.0	279.56
4.0	0.000865	0.003494	1.0	0.79	212.0	168.7	101600.0	279.16
4.0	0.000865	0.003494	1.0	0.63	266.8	168.3	101600.0	279.76

The input data used (area of primary and secondary nozzles, pressure, temperature and relative humidity of the environment, and temperature and velocity of the jets) are found in each file of JEAN (2003) cited in Tab. 1. The angles relative to line to observe with engine exhaust axis used were 60 to 120º.

We can see in Fig.4 more details about the geometry of the nozzle used in JEAN project of noise evaluation.

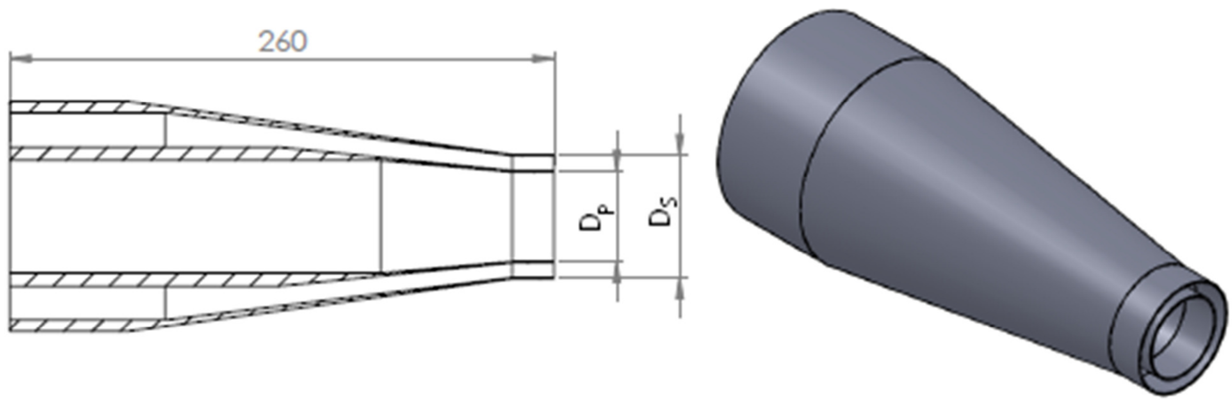

Figure 4. Geometry nozzle utilized on the simulations according to the JEAN project.

The results were obtained using both databases for each specified condition. Comparisons of results obtained with each database related to the experimental results are shown in the next section.

3. RESULTS

The results can be compared through the graphs generated for each angle of analysis. On the vertical axis are the values of sound pressure level (SPL), in decibels. On the horizontal axis is represented the frequency in 1/3 octave bands. Some results have been removed to leave that part not too long and repetitive, moreover, the trend has not changed significantly in these intervals.

The figures containing graphs are presented below and follow the order of Tab. 1.

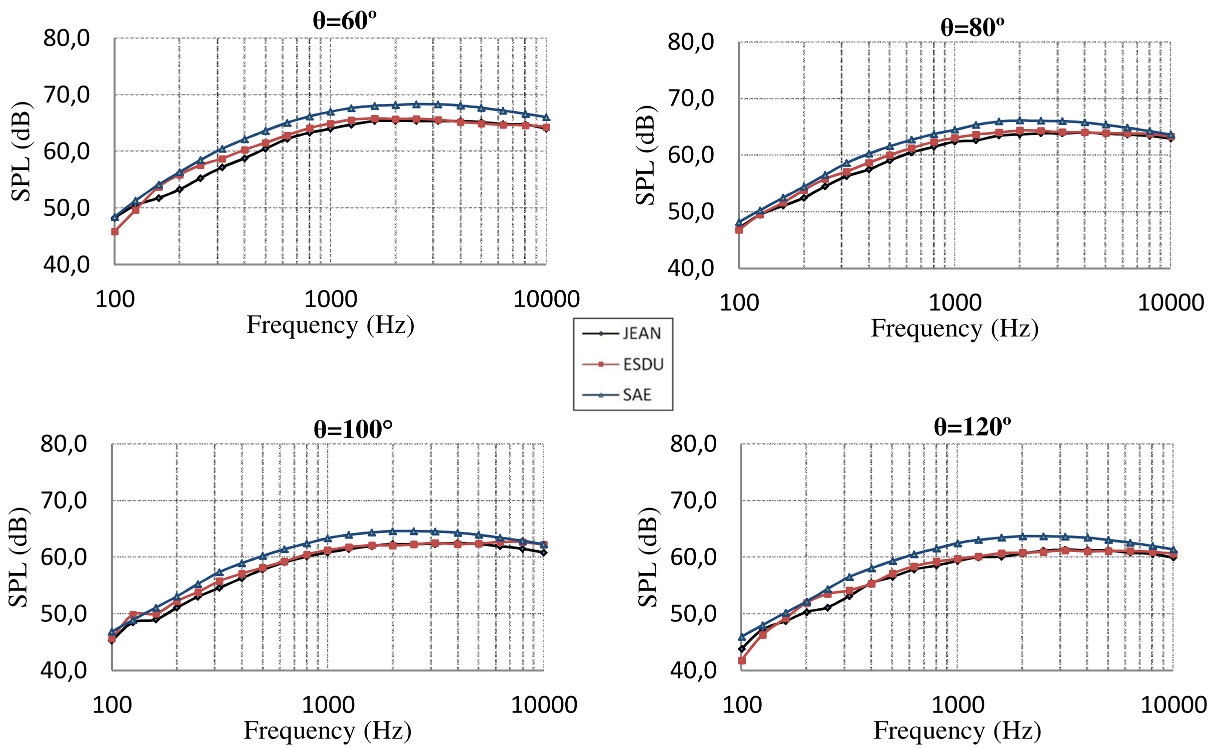

Figure 5. Noise measured for AR=2 and VR=1.

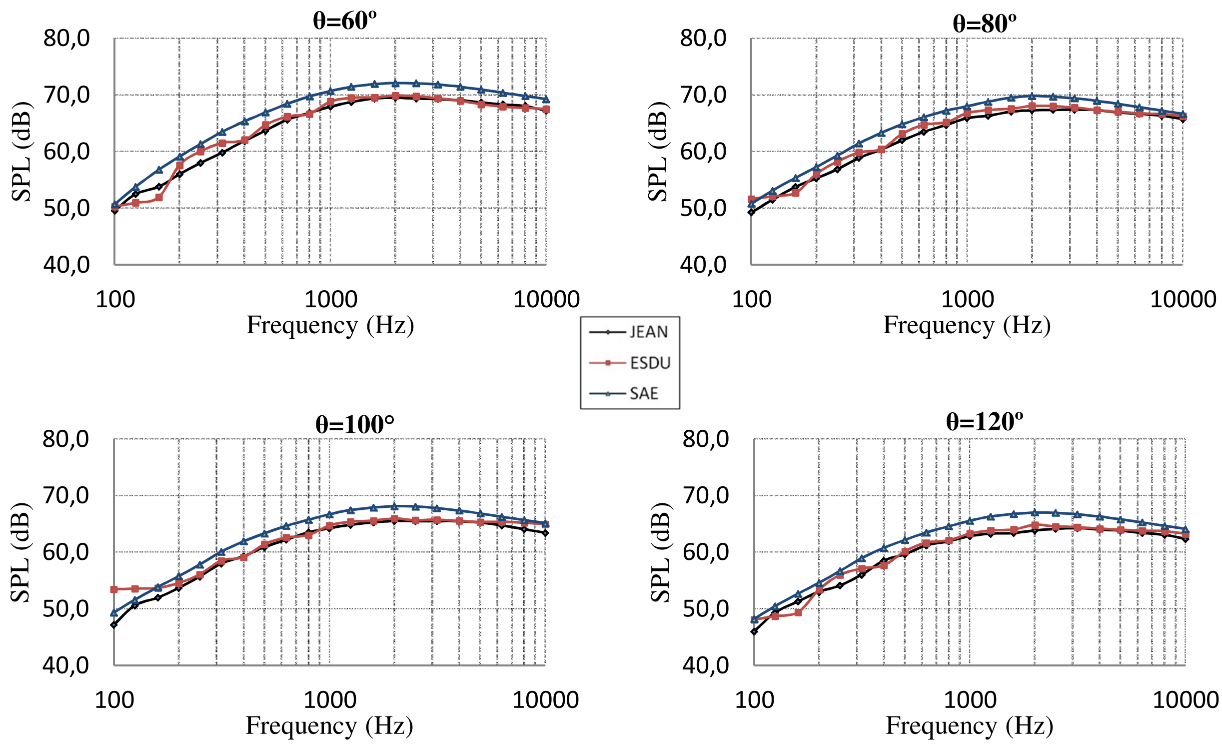

Figure 6. Noise measured for AR=2 and VR=0.79.

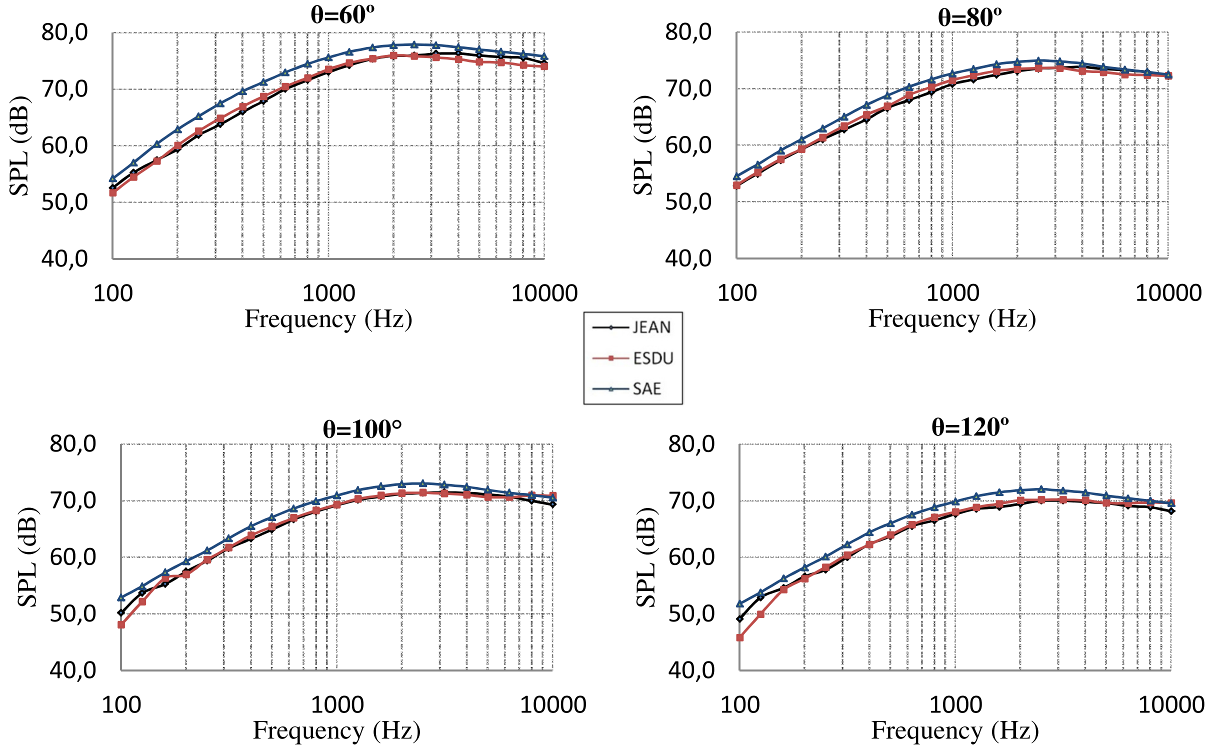

Figure 7. Noise measured for AR=2 and VR=0.63.

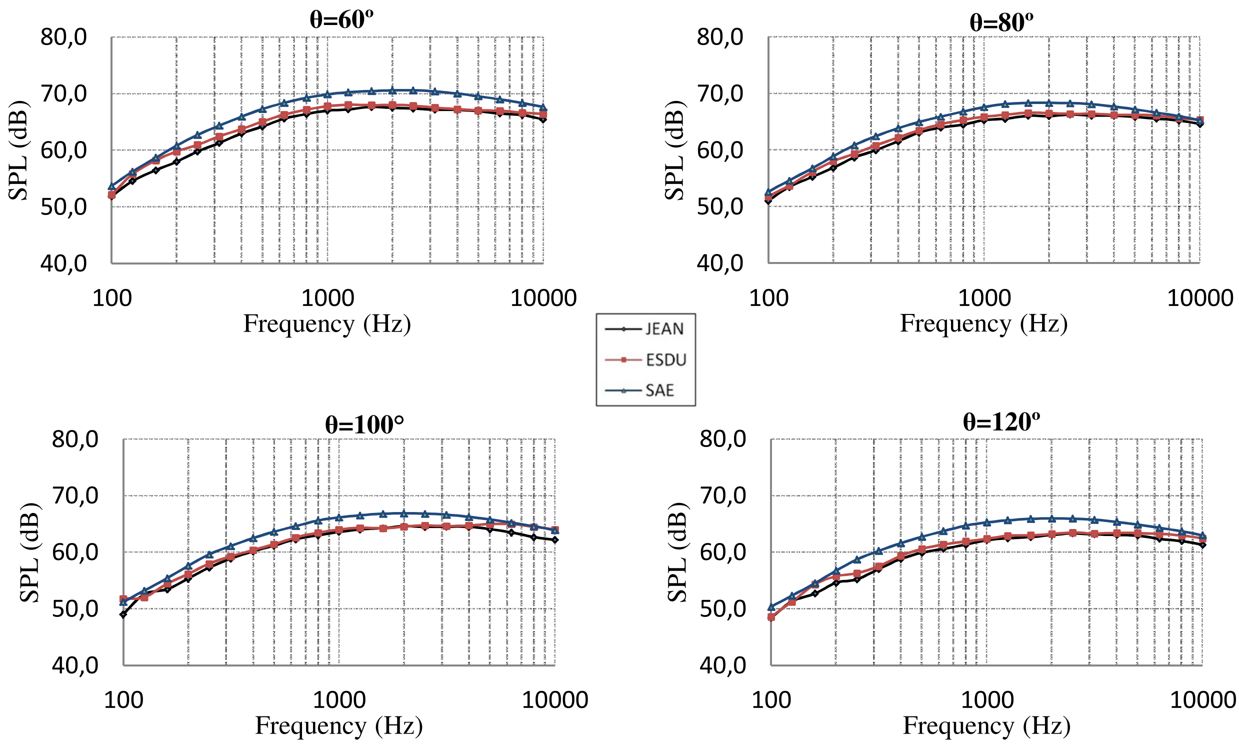

Figure 8. Noise measured for AR=4 and VR=1.

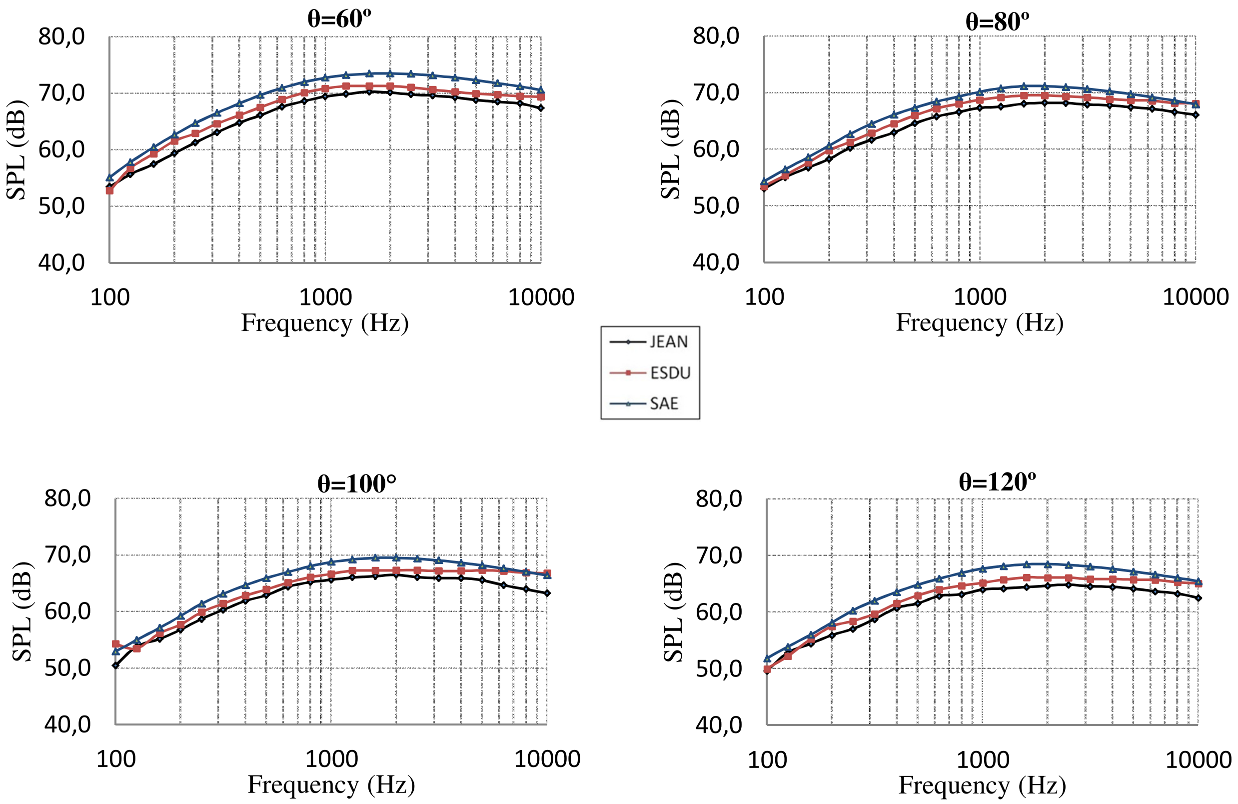

Figure 9. Noise measured for AR=4 and VR=0.79.

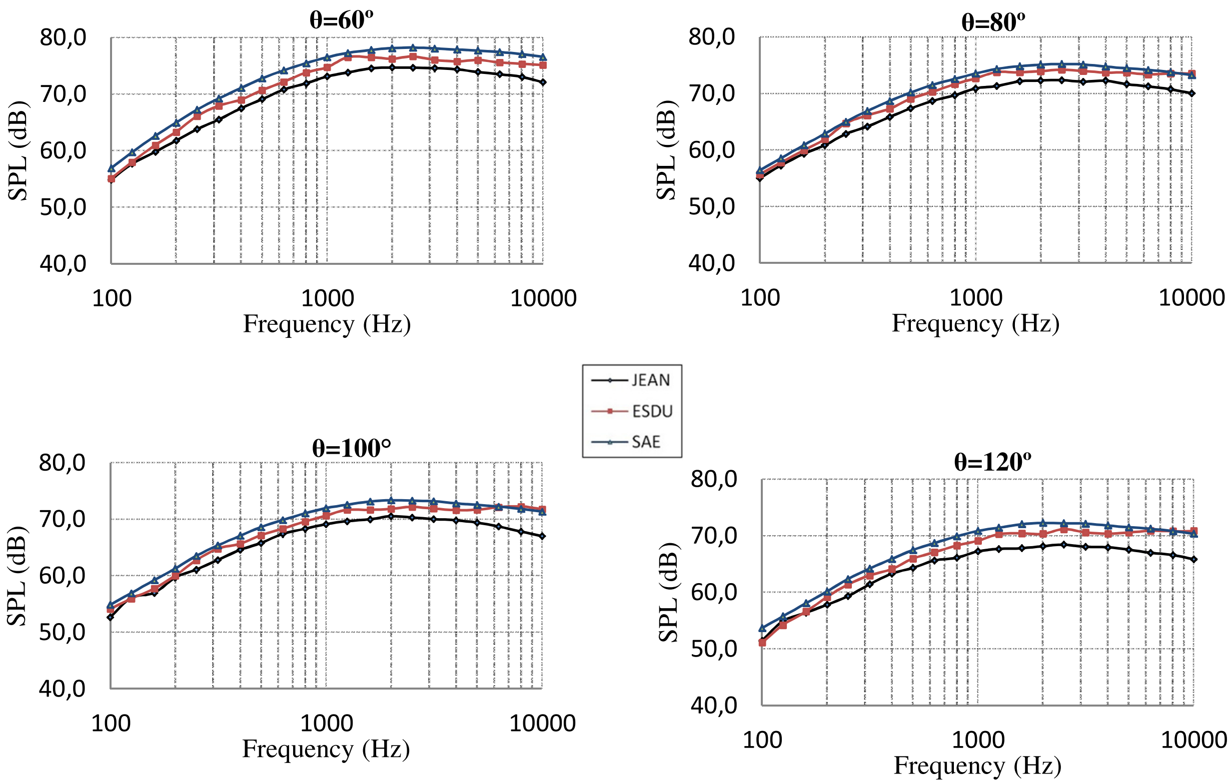

Figure 10. Noise measured for AR=4 and VR=0.63.

In the Tab. 2 the results are expressed in terms of standard deviation values, for each condition analyzed. It is utilized the root mean square error (RMS), through the equations:

$$x(f) = (numerical\ result - experimental\ result)^2 \quad (7)$$

$$RMS = \sqrt{\frac{1}{n}\sum_1^n x(f)} \quad (8)$$

Where n is equals the number of frequency bands of 1/3 octave analysis.

Table 2. Standard deviation values

Condition		Database	60	70	80	90	100	110	120
AR	VR								
2	1.00	SAE	2,63	2,24	1,94	1,90	2,07	11,89	2,44
		ESDU	1,20	0,90	0,72	0,68	0,74	11,55	0,88
2	0.79	SAE	2,60	2,19	2,07	1,97	2,12	2,23	2,33
		ESDU	0,94	0,78	0,88	0,81	1,62	2,10	0,90
2	0.63	SAE	2,37	1,89	1,64	1,50	1,67	1,83	1,94
		ESDU	0,74	0,97	0,54	0,54	0,77	0,82	1,06
4	1.00	SAE	2,68	2,16	1,86	1,74	2,11	2,30	2,55
		ESDU	0,87	0,57	0,61	0,42	0,97	1,11	0,70
4	0.79	SAE	3,17	2,76	2,47	2,41	2,75	2,91	3,06
		ESDU	1,36	1,16	1,32	1,15	1,67	1,88	1,41
4	0.63	SAE	3,38	2,82	2,57	2,48	2,80	3,15	3,38
		ESDU	1,83	1,61	1,83	1,77	2,08	2,59	2,42

In general, it is possible to see that the results of the Four-Source method using the ESDU's database not produce smooth spectra, which was expected. The curves of the SAE method are smoothed, since the database consists of standardized data. And it is important to emphasize that the experiment used as a reference has also some points which oscillates through the frequency range.

The Four-Source method returned results with the expected trends for both databases: slight reduction in sound pressure levels with increasing of angle observer, the SPL increases with decreasing velocity ratio (remembering that the decay parameter is due to increasing the primary jet velocity and the secondary jet velocity remains constant) and when it is increased the area ratio of 2 to 4 the high frequency region of the SPL remains practically unchanged compared to the same conditions of VR. But this is not occurring when the analysis is about the lower frequencies, the SPL is slightly higher in the case of AR equal 4. The excellent results generated by the Four-Source Method are due to the independent study of the areas listed above, so the modification of these parameters can be seen by the model.

Analyzing the data obtained with each database individually, we find that the use of ESDU's data is more accurate for the conditions analyzed. This can be easily seen in Tab. 2, which compared the deviations of the experimental results. The deviation obtained for the first case (AR=2, VR=1) at an angle of 110º is too far beyond the results and it is justified by a given frequency that does not contained in reference JEAN (2003), assigning the value null.

4. CONCLUSIONS

This work shows the influence of the parameters velocity ratio, area ratio and angle observer in the total noise generated by a coaxial jet. The databases used to predict noise on the proposed terms proves the efficiency and relative flexibility of the Four Source method.

In general, the method coupled with the ESDU database was better than SAE to the conditions analyzed. But, an important result does not appear explicitly in this work, that the trend of the ESDU results for extremes Strouhal numbers. As mentioned previously, this method uses extrapolation to calculate results that are outside of its boundaries at the database. Thus, analyzing high and low frequencies or jets at high velocity and large diameters, the results obtained with this database tends to get worse considerably. This can be seen in Almeida (2008), where other conditions for entry and other reference for compare the results (CoJeN) were utilized. The ESDU database also has the disadvantage of limited range for angles of analysis (between 30 and 120º).

These observations justified further work to merge the databases, allowing the method to be more flexible to applications in different conditions.

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