SINGLE-STREAM JET NOISE PREDICTION UTILIZING EMPIRICAL METHOD FOR A TURBOJET ENGINE

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Abstract. *Research is carried out aiming at the design, manufacture, testing and development of high performance gas turbines. This work deals with noise prediction for new engines, having in mind the fulfillment of the ever-increasing environmental concerns. Both analytical and empirical methods are being developed at the Center for Reference on Gas Turbine (ITA). These methods may be combined with performance and design computational programs to assess the noise generated by each gas turbine component and the total engine noise, at the very beginning of the engine design process. In this work only empirical method for single-stream jet noise prediction is pointed out. The single-stream jet empirical prediction method is based on the ESDU Item 98019, for the calculation of the one-third octave band sound pressure levels and overall sound pressure level (OASPL), which depend on the directivity index, the observer position and on the engine performance data. The one-third octave band sound pressure levels are estimated and compared with results from open literature. The method is also used to predict the single-stream jet noise radiated by a new turbojet at two different conditions: firstly, the effect of the observer position on SPL for the engine operating at steady design rotational speed and secondly, the effect of the engine rotational speed on single-jet noise radiation. The results are shown in terms of the SPL and OASPL, being compatible with the noise produced by similar engines. Since the engine has not run yet, measured noise is not still available for the sake of validation. The engine operating conditions were calculated using a high fidelity engine simulator developed to provide the data used in this study. No attenuation was considered in this work.*

Keywords*: noise prediction, gas turbine, single-stream jet noise, empirical method*

1. INTRODUCTION

In the past 30 years, many studies have been carried out to investigate the relationship of different noise sources on environment and population annoyance. Factors such as increasing the world population economic power and the unregulated airline market growth increased the demand of new aircrafts. Experts predict that more intense aircraft traffic in the future, resulting in demands that exceed the current capacity of airports, and the necessity of expansion of the airports system. The General Accounting Office of the United States, GAO, reported that the noise generated by aircraft is of major concern among 29 from 50 noisiest U.S airports.

The noise generated by aircraft engines near the airport has great impact on the environment, with serious economic consequences. The first subsonic jets generation was extremely noisy due to high velocity of the exhaust gas. Current studies, using the mixing jets techniques within the engine, indicate a moderate contribution to reduce the aircraft noise. Recently, stringent regulations and specific requirements of some airports have encouraged large number of new suppressing noise technologies, requiring efforts of the aircraft manufacturers to incorporate such technologies to mitigate the engine noise (Rolls-Royce, 1996). As an example of this trend, the radiated noise from Boeing 737-700 at takeoff conditions is one-third of the equivalent produced in 1965. Figure 1 shows the noise levels reduction for several aircrafts. Although not updated, the trends shown by the Fig.1 did not change so far.

Government regulations usually act on the quality control or create economic incentives as policy, aiming at improvement of incentives for airlines that use quieter aircrafts. The U.S. airports, for example, have the authority to impose tax on the airlines and invest these resources on the development of new projects to reduce aircraft noise. A majority of European airports also collect fees from airports and from airlines in order to stimulate the reduction of noise. Generally, those rates increase according to the noise levels and, sometimes, also based on the weight of the aircraft. In addition, the U.S. and some European countries have adopted other strategies to reduce noise near airports, such as curfews, special airways and operational restrictions (Girvin, 2009).

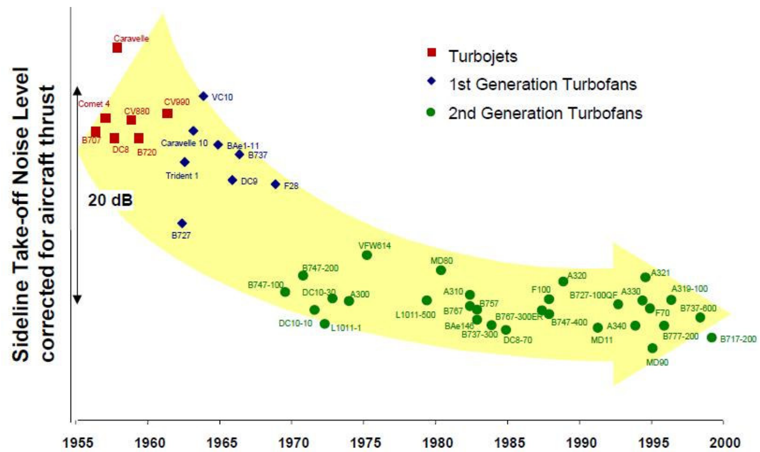


Figure 1. Progress in Noise Reduction (Kors, 2004).

The noise prediction using empirical methods is being pursued as means to support gas turbine design parameter definition at the engine design phase. Santos *et al.* (2005) and Santos (Santos, 2006) have addressed successfully this subject. The results encouraged the continuation of the research at the Center for Reference on Gas Turbine at ITA.

The basic components of a turbojet engine are compressor, combustor, turbine and jet, as shown in Fig. 2.

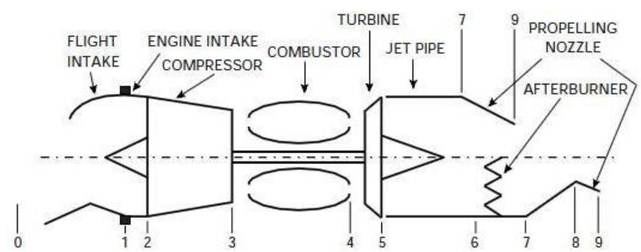


Figure 2. Conventional turbojet, and afterburning turbojet with con-di nozzle (Walsh and Fletcher, 2004).

In a turbojet, air enters in the engine at the intake duct and passes through the rotors and stators of the compressor, where the air pressure and the temperature are increased. The combustor is responsible for the increase of the gas temperature, using burnt fuel. The temperature at the turbine inlet also influences strongly the engine thermal efficiency. The gas generated by the combustor passes through the turbine and produces power to drive the compressor. The temperature and pressure of the gas are reduced during the expansion process. The blades may be cooled in order to keep the temperature at the metal surface within acceptable operation limits. After expansion in the turbine, the gases go to the jet pipe. The jet pipe is a duct that turns the annular flow exiting the turbine into a fully circular flow in the nozzle. The nozzle accelerates the gasses to produce thrust. Afterburner may also be uses to produce even higher gas speed (Boyce, 2002).

The turbojet is small and light. It produces high thrust due to the high exhaust gas velocity. However, the high flow speed causes high-radiated noise, making the turbojet practically not suitable for civil aircrafts. Turbofans are used instead for most civil transportation.

1.1. Single-stream jet noise

The main difficulty to predict the jet noise is due to the lack of a general theory that describes the fluctuations that occur in turbulent jets. During the 70s, Lighthill studied the basic mechanisms involved in the sound generation, concluding that the jet noise intensity is proportional to U_j^8 ("Eighth power law"). Analytical improvements to the Lighthill's theory were developed mainly regarding the jet movement and the convective mean flow effects (Goldstein, 1973).

It is known that for a high Reynolds number air jet issuing from a convergent nozzle with a uniform velocity into a quiescent fluid, there are three distinct regions between the jet and the environment, as shown in Fig. 3. As the jet issues from the nozzle, an annular mixing region forms between the jet and its surroundings. The flow in this region becomes turbulent within about one-half jet diameter downstream. It then spreads linearly into both the jet and the surrounding atmosphere until it fills the entire jet at four, or perhaps five, diameters downstream. Near the nozzle discharge, small vortices are emitted, which are responsible for the high frequency noise. Also in this region, interaction levels and radiated sound power are high (Goldstein, 1976). The flow within the conical region bounded by the turbulent flow remains laminar; hence, this region is called the potential core. The boundary of the jet-mixing region is not straight as shown in Fig. 3. Once the mixing region fills the jet its uniform growth ceases and it evolves differently as it passes first through a transition region and finally, at about eight diameters downstream, into a region of self-preserving flow, called fully developed region. In the fully developed region, large vortices are emitted, which are responsible for the radiation of low frequency noise.

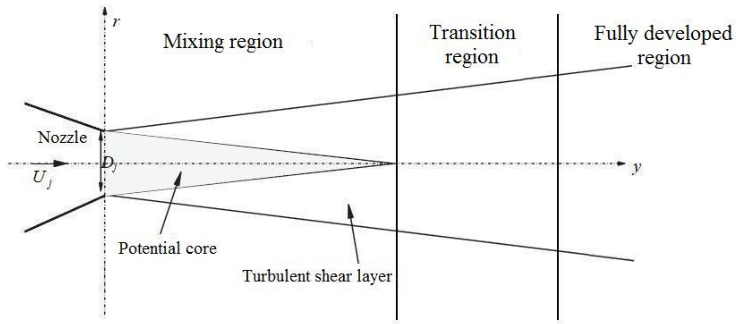


Figure 3. Jet noise structure (Goldstein, 1976).

In subsonic jets, the small-scale turbulence is believed to be the dominant source of noise. Even though large-scale coherent turbulent structures and instability waves have been observed in a wide range of Reynolds numbers, these structures are not effective aeroacoustic sources. However, they play a crucial indirect role on the jet noise generation, by enhancing the turbulent mixing and the consequent jet spreading (Casalino, 2008). The characteristic subsonic jet spectrum shows a peak occurring around 1000 Hz, predominating the broadband noise.

In supersonic jets, even though direct empirical evidence is difficult to be achieved, large-scale coherent turbulent structures and instability waves are believed to be very effective aeroacoustic sources. Furthermore, when shock waves are present in the jet, the interaction between the turbulent boundary layer and the shocks generate a associated-shock broadband noise. The propagation of shock waves in the upstream can excite instabilities in the boundary layer through receptivity mechanisms on the nozzle edge (Tam *et al*, 2009). In addition, the broadband spectrum is increased, with peaks of frequency caused by aerodynamic shocks due to the presence of additional noise sources (Almeida, 2009).

1.2. Single-stream jet noise prediction method

The jet noise prediction model is based on the method proposed by ESDU Item 98019 (ESDU, 1998). The program normalizes the data for nozzle exit area, radial distance and atmospheric pressure. At the same time, normalization by a term $80\log_{10}\left(\mathrm{U_j}/\mathrm{c_0}\right)$ is also carried out to adjust the data for gross parameter variations and present a "flatter" surface for interpolation/extrapolation. The normalization is performed according to the relationship

$$SPL_{Normalized} = SPL - 10.\log_{10}\left(\frac{A_j}{r^2}\right) - 20.\log_{10}\left(\frac{P_0}{101325}\right) - 80.\log_{10}\left(\frac{U_j}{c_0}\right) \tag{1}$$

where $SPL_{Normalized}$ depends on $\log_{10}\left(U_j/c_0\right)$ and $\log_{10}\left(T_{js}/T_0\right)$, with the jet static temperature expressed in Kelvin.

However, two limiting factors can lead to erroneous results. The first is that the Strouhal number, which in the study is expressed by $\log_{10}\left(f.D_j/U_j\right)$, must fall between -1.5 and 1.5; the second is that the noise levels must be only predicted for angles between jet exit and observer position varying in the range $0° \le \theta \le 170°$.

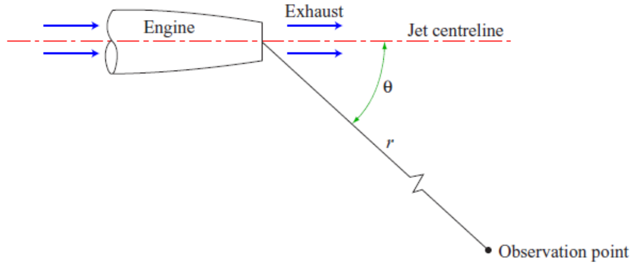


Figure 4. Directivity at jet noise prediction method (ESDU, 1998).

2. RESULTS

A computer program written in FORTRAN has been developed for the calculations. This program fulfills the requirements of integration with the high fidelity gas turbine simulator program (Bringhenti, 1999, 2003), so that it is possible to estimate the engine noise at any operating condition. In addition, a new engine that is being designed can be analyzed, as far as noise is concerned, and eventually design changes might be incorporated to cause noise reduction. Existing engine can also be analyzed to investigate if changes might be made to reduce noise.

In this section, the turbojet noise prediction results are discussed. The turbojet project (Fig. 5) is a partnership with industry. Design thrust is five kN, core mass flow is 8.34 kg/s and design rotational speed is 28150 rpm. Engine data and ambient conditions are shown in Tab. 1.

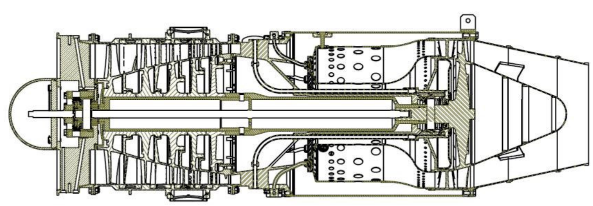


Figure 5. Turbojet engine cross-section (Courtesy TGM Turbines).

Table 1. Turbojet and ambient conditions.

Ambient static pressure, P_{S0} (Pa)	101325	Speed of sound, c_0 (m/s)	340.0
Ambient static temperature, T_{S0} (K)	288	Ambient air speed, U_0 (m/s)	0.0
Compressor rotational speed, N (rpm)	28150	Expansion ratio, P_{T4}/P_{T5}	2.13
Combustor total temperature, T_{T4} (K)	1173	Jet nozzle diameter, D_j (m)	0.1975
Overall pressure ratio, P_{T3}/P_{T2}	5.00	Speed ratio, U_j/c_0	1.66
Ambient air density, ρ_0 (kg/m3)	1.22	Temperature ratio, T_j/T_{S0}	2.97

Firstly, it will be determined the single-stream jet sound pressure levels from 20 Hz to 20 kHz for distances of 6, 8 and 12 meters and $45° \le \theta \le 120°$. After this it will be calculated the single-stream jet overall sound pressure level, OASPL, for the same observer position. The OASPL is determined by the following equation

$$OASPL = 10.\log\left[\sum_{i=1}^{n} 10^{\frac{SPL_i}{10}}\right] \qquad (2)$$

where SPL_i is the one-third octave band sound pressure level at frequency band *i*.

The Fig. 6, 7 and 8 show SPL spectra from jet noise radiated on different observation points. After the analysis, may be noted that the frequency peaks occurred into range 1 kHz – 1.5 kHz, with broadband noise predominance, corroborating with the literature. The broadband spectra are increased as the observation angle decreases. As expected, the minimum predicted values occurred at r = 12m and $\theta = 120°$, and the maximum at r = 6m and $\theta = 45°$, for all distances between jet exit axis and observation point. Also, changes in spectrum shape have been perceived when observation angle is increased, with a "smooth" trend, both higher and lower frequencies. This fact shows the strong influence of directivity of the noise source on sound pressure levels.

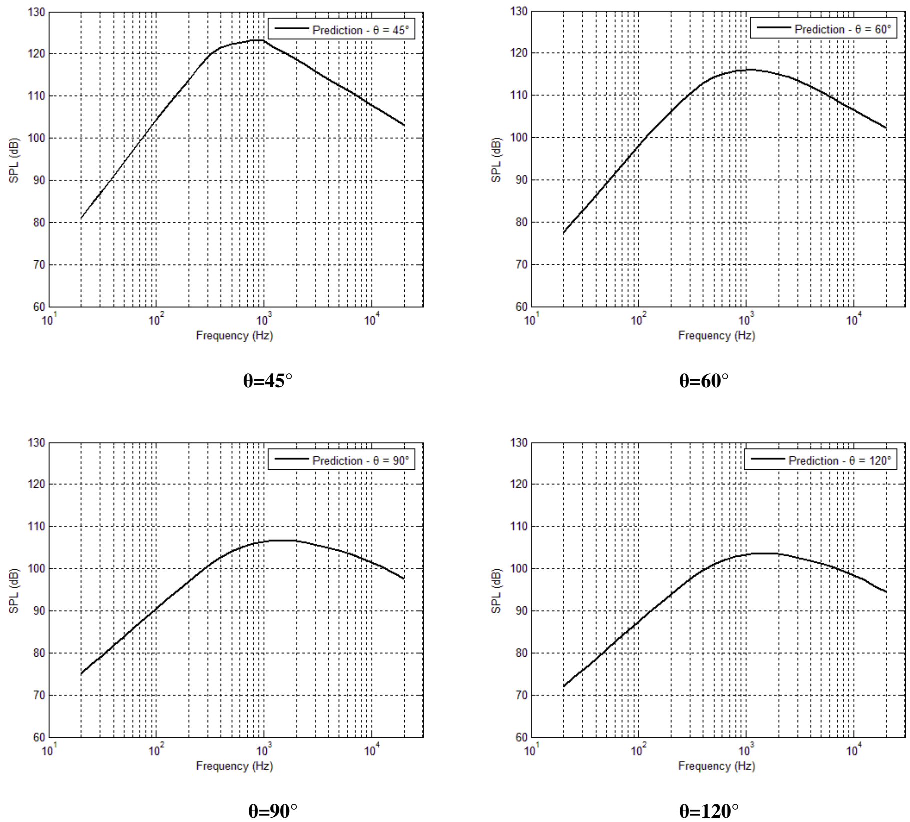


Figure 6. Single-stream jet spectrum – U_j = 564 m/s, T_j = 856 K and r = 6m.

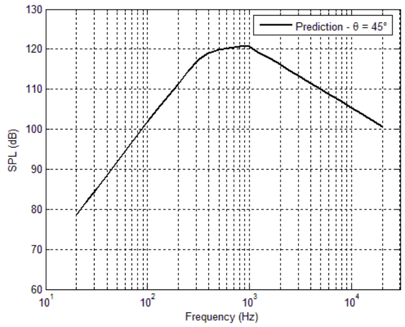
For all cases, the SPL frequency peak for 45º and 60º occurred on 1 kHz and for 90º and 120º, the maximum predicted values were around 1.5 kHz.

It is evident that there are two distinct regions on spectra: between 20 Hz and 1-1.5 kHz, the noise levels increase and; between 1-1.5 kHz and 20 kHz the levels decay. However, this decay of the noise levels at higher frequencies are lesser pronounced than the increase of the noise levels at lower frequencies. At the noisiest case of single-stream jet, when r = 6m and $\theta = 45°$, the variation of SPL between 20 Hz and 1 kHz was equal to 42.1 dB; on the other hand, at the higher frequencies (1 kHz – 20 kHz) the variation was 19.5 dB. Also, at r = 12m and $\theta = 120°$, the spectrum showed that the variation of SPL values between 20 Hz and 1 kHz was 31.3 dB while the values between 1 kHz and 20 kHz declined 8.9 dB. This showed that as the distance and observation angle from single-stream jet is increased, the sound pressure levels tend to "flatten" the spectrum.

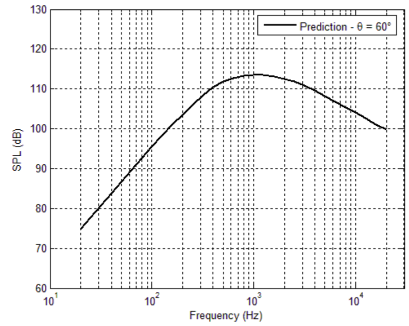
The Fig. 6 shows the SPL spectra from r = 6m. As observed, the maximum predicted SPL occurred at 45º, whose value was equal to 123.3 dB. When the observation point was in $\theta = 60°$, the frequency peak was 116.4 dB and, for 90º and 120º, the frequency peaks were, respectively, 106.6 dB and 103.9 dB.

The SPL predictions for 8 meters are indicated on Fig. 7. Such as occurred at r = 6m, SPL reached the maximum value on observation angle of 45º (120.7 dB). When the angles increased for 60º, 90º and 120º, the SPL predicted values had a greatly decay, whose results were, respectively, 113.6 dB, 104.5 dB and 101.3 dB. The results showed that variation between peaks at 45º and 120º varied 19.4 dB.

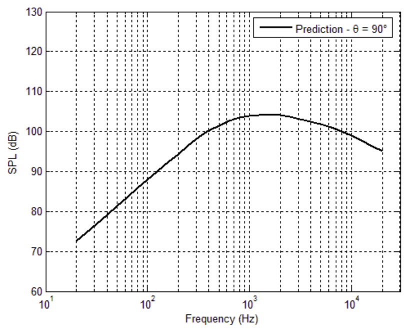
For distance equal to 12 meters, the SPL values were the minors among all, as expected. The levels for 45º, 60º, 90º and 120º were 117.4 dB, 110.5 dB, 101.2 dB and 97.9 dB. The levels reduction between 45º and 120º frequency peaks was of 19.5 dB (practically the same result obtained at r = 8m).



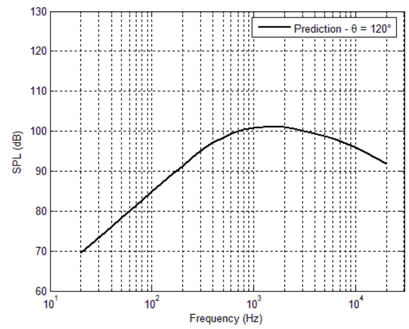
θ=45°



θ=60°

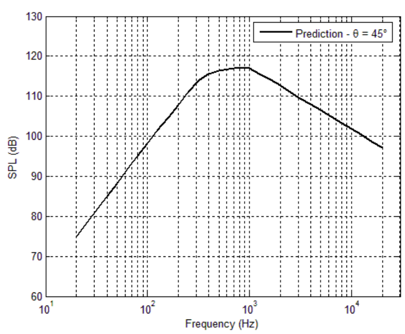


θ=90°

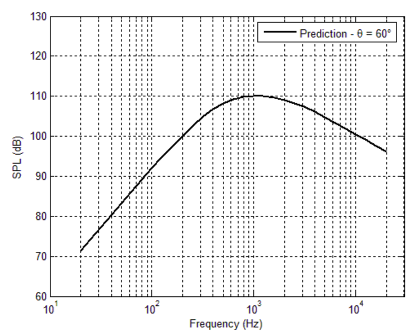


θ=120°

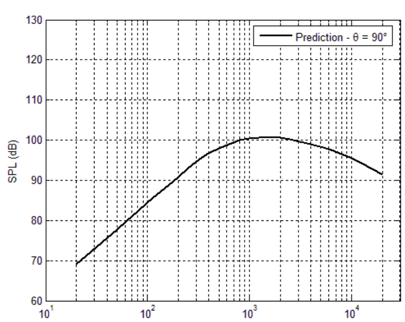
Figure 7. Single-stream jet spectrum – $U_j = 564$ m/s, $T_j = 856$ K and r = 8m.



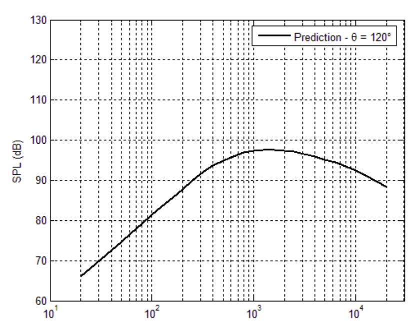
θ=45°



θ=60°



θ=90°



θ=120°

Figure 8. Single-stream jet spectrum – $U_j = 564$ m/s, $T_j = 856$ K and r = 12m.

The OASPL single-stream jet noise results show a sharp decaying as increases the angle between the observer and jet exit axis. The highest levels occurred in $\theta = 45°$ for all distances, whose values were equal to 131.9 dB, 129.6 dB and 126.0 dB. The variation of overall sound pressure level for all distances was over 17.0 dB, which was more pronounced within the range $45° \leq \theta \leq 75°$ (approximately 11.0 dB between the extremes of these range). On the other hand, the minimum predicted values occurred at $\theta = 120°$ and OASPL predicted for 6, 8 and 12 meters was, respectively, 114.3 dB, 112.1 dB and 108.4 dB. Figure 9 shows the results.

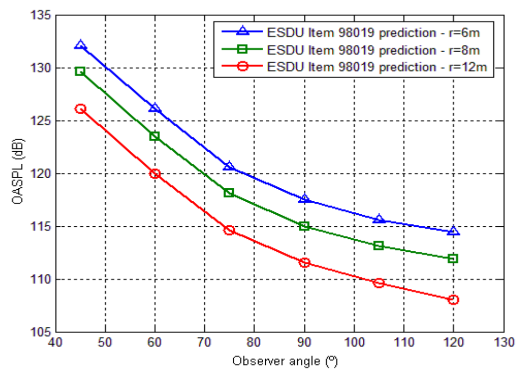


Figure 9. Single-stream jet noise prediction at constant rotational speed equal to 28150 rpm.

To foresee the noise radiation at part speed, the range from 60% to 100% design rotational speed was chosen and a discussion of the results for $\theta = 45°$ and $\theta = 90°$, and r = 8 m follows.

The Tab.2 shows the results at off design point engine operation. Values of jet velocity and static temperature had a greatly increase according to the engine rotational speed was increased.

As observed in Fig.10, the jet noise is strongly dependent of the engine rotational speed as well as the directivity of source. This fact indicates that the jet temperature and velocity are two important parameters for single-stream jet noise analysis.

When $\theta = 45°$, OASPL values increased more intensely than $\theta = 90°$. The variation between 19705 rpm and 28150 rpm was equal to 17.7 dB at $\theta = 45°$ and, at $\theta = 90°$, this variation was 12.1 dB, indicating that predicted curves for $\theta = 45°$ and $\theta = 90°$ did not have the same behavior.

Table 2. Jet conditions at off design point engine operation.

Engine rotational speed [RPM]	Jet Velocity [m/s]	Jet static temperature [K]
19705	333	638
22520	398	657
23928	441	680
25335	492	711
26743	536	770
28150	564	856

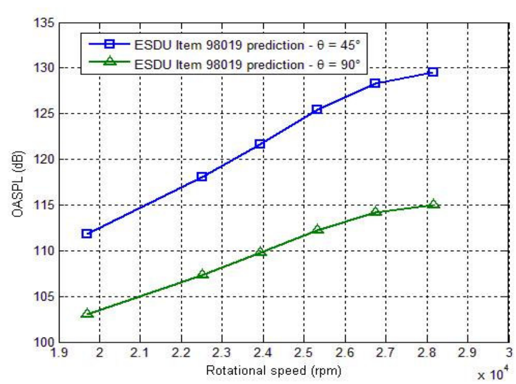


Figure 10. Relationship between turbojet rotational speed and single-stream jet OASPL – r = 8m.

REFERENCES

Rolls Royce. "The jet engine". 5th. edition [S. l.: s.n.], 1996. 292p.
Girvin, R. "Aircraft noise-abatement and mitigation strategies". Journal of Air Transport Management, v.15, p.14-22, 2009.
Kors, E. "Significantly lower community exposure to aircraft noise". In: AIAA/CEAS AEROACOUSTIC CONFERENCE, 10., Proceedings… Manchester, UK, 2004.
Santos, G. D. F., Barbosa, J. R., Pilidis, P. "Analysis of Turbofan Empirical Noise Prediction Methods". In: AIAA/CEAS Aeroacoustic Conference, 11., Proceedings… Monterey, California, 2005.
Santos, G. D. F. "A Methodology for noise prediction of turbofan engines". 2006. 302 f. PhD Thesis – Instituto Tecnológico de Aeronáutica, São José dos Campos, Brasil, 2006.
Walsh, P.P.; Fletcher, P. "Gas turbine performance". Blackwell Science Ltd, Second edition, 2004.
Boyce, M. P. "Gas turbine engineering handbook". Houston: Gulf Publishing Company, Second edition, 2002.
Goldstein, M.; Rosembaum, B. "Effect of anisotropic turbulence on aerodynamic noise". Journal of the Acoustical Society of America, v.54, p. 630-645, 1973.
Goldstein, M. E. "Aeroacoustics". New York: McGraw-Hill, 1976.
Casalino, D.; Diozzi, F.; Sannino, R.; Paonessa, A. "Aircraft noise reduction technologies: a bibliographic review". Aerospace Science and Technology, v.12, p. 1-17, 2008.
Almeida, O. de. "Aeroacoustics of dual-stream jets with application to turbofan engines". 2009. 346 f. PhD Thesis – Instituto Tecnológico de Aeronáutica, São José dos Campos, 2009.
Tam, C. K. W.; Pastouchenko, N. N.; Viswanathan, K. "Broadband shock noise from dual stream jets". Journal of Sound and Vibration, v.324 (2009), p. 861-891, 2009.
ESDU. Engineering Science Data Unit. "Computer based estimation procedure for single-stream jet noise". [S.1.]: ESDU, 1998 (ESDU Data Item 98019).
Bringhenti, C. "Gas Turbine Steady State Performance Analysis" (in Portuguese), 1999. MSc Thesis – Instituto Tecnológico de Aeronáutica, São José dos Campos, 1999.
Bringhenti, C. "Variable geometry gas turbine performance analysis". 2003. PhD Thesis – Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil, 2003.

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