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ASSESSMENT OF A SEMI-EMPIRICAL METHOD APPLIED TO PREDICT ACOUSTIC NOISE OF EXTERNALLY BLOWN FLAPS

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Abstract. *A semi-empirical method available in the literature is implemented to predict acoustic noise generated by externally blown flaps. The method is assessed through comparisons between predictions and experimental data for a single stream round jet impinging against flaps at different deflection angles. A sensitivity analysis is also carried out and shows that the method is highly dependent on empirical data, preventing its application to general flap configurations. However, the low computational cost and good agreement with experimental data for the baseline geometry encourage the extension of such methods to assist the design of modern aircraft.*

Keywords: *aeroacoustics, externally blown flaps, semi-empirical prediction methods.*

1. INTRODUCTION

Propulsion Airframe Aeroacoustics (PAA) is an area of study concerned with the noise generated by the integration of aero-engines with the structure of the aircraft, such as the wings, flaps and pylons. The studies in this area have gained importance with the rise of stricter noise regulations. One of the problems that arise with this integration, also defined as installation effect, is due to the interaction of the jet flow, exhausted from the engines, with high-lift devices such as flaps. In this case, the problem is intensified by the close-coupling between the engine and the wing, required to provide sufficient clearance to the ground with the use of large high-by-pass engines (Pott-Polleske, 2011). According to Bondarenko *et al.* (2012), the jet-flap interaction problem affects the design of aircraft and the understanding of this interaction helps developing more efficient and more environmental friendly aircraft.

Although many studies have been carried out in this area, part of the phenomena is still not completely understood and needs further investigation. The prediction of the installation effects is crucial in the aeroacoustic design of aircraft and, due to computational limitations, steady state CFD simulations together with semi-empirical methods play an important role inside the industrial context.

Externally Blown-Flaps (EBFs) are high lift devices commonly used in STOL (Short Take-Off and Landing) aircraft and works by introducing the flaps into the jet flow. This procedure generates extra lift by deflecting the flow and retarding the wing stall, which is enabled by the passage of high speed air through the slots of the wing. However, this type of configuration generates high levels of noise due to the strong interaction of the jet with the structure of the wing. Such a phenomenon was extensively studied during the seventies and some semi-empirical methods were developed in order to predict the noise generation of this mechanism (Clark *et al.*, 1973; Fink, 1978; McKinzie *et al.*, 1976).

McKinzie and Burns (1975) applied the developed semi-empirical method to predict the sound field generated from a jet impinging on a flat and a curved plate and compared the results with experimental data. The aim was to investigate noise generated at the plate trailing edge and reasonable agreement with measurements was found. McKinzie *et al.* (1976) used an improved method, by adding a noise source to account for the lift fluctuation on the flaps, to predict noise of a two-flap EBF. The authors also analyzed the effect of noise suppression devices and a good agreement with experimental data was verified. Finally, McKinzie (1980) applied the method to different geometries and noise suppression devices. The author proposed alternative procedures to obtain required empirical data.

The present study is concerned with the assessment of the method proposed by McKinzie (1980). In EBF systems the flaps are introduced into the jet stream, whereas current aircraft adopt flaps that are less intrusive. Although the installation effect in current aircraft is somehow different from that in the EBF cases, the understanding of methods developed to predict noise of EBFs can be useful in the desing of modern geometries. The aim of this study is to implement a semi-empirical method available in the literature and predict acoustic noise generated by externally blown flaps at different deflection angles. A sensitivity analysis is also carried out to verify the influence of empirical data on noise predictions.

2. THE METHOD

As stated by McKinzie *et al.* (1976), the noise generated in EBFs results from a series of sources, presented in Fig. 1, including: oblique jet impingement, surface scrubbing, jet interaction with the leading and trailing edges, free shear layer mixing over the surfaces of the flaps and inflow over the flaps. The noise generated by the oblique impingement, surface scrubbing and free shear-layer mixing is called impact noise (McKinzie and Burns, 1975). The term inflow noise is used for the source that results from the lift fluctuations caused by the inflow over the wing and flaps. The leading-edge noise is considered to be less important than the trailing-edge noise and is not taken into consideration.

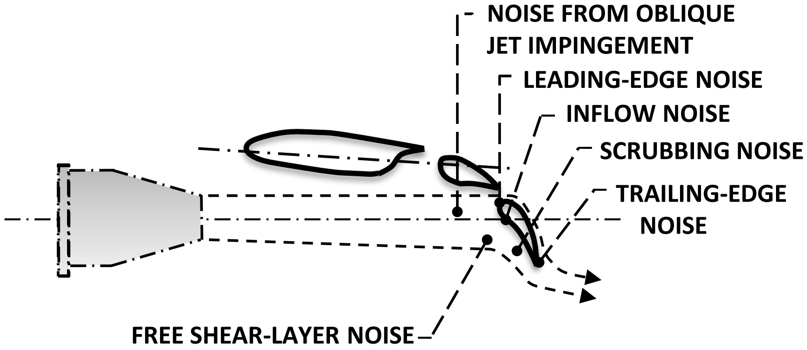


Figure 1: Major sources of noise in externally blown flaps as described in McKinzie *et al.* (1976)

The method proposed by McKinzie *et al.* (1976) considers that these three main sources are uncorrelated, so that they can be combined by superposition. The total impingement overall sound pressure level ($OASPL_{tot}$) is shown in Eq. (1), where the sound field of the impact, trailing-edge and inflow sources are represented by $OASPL_{imp}$, $OASPL_{TE}$ and $OASPL_{inf}$ respectively. The results are provided in the OASPL form for each observer angle and only in the fly-over plane. A brief description of the each source is presented in the following sections.

$$OASPL_{tot} = 10\log\left[10^{\left(\frac{OASPL_{imp}}{10}\right)} + 10^{\left(\frac{OASPL_{TE}}{10}\right)} + 10^{\left(\frac{OASPL_{inf}}{10}\right)}\right] \tag{1}$$

2.1 Impact Noise

The method lacks on a theoretical expression for predicting the sound field from the impact source, as this source mechanism was not completely understood (McKinzie and Burns, 1975). Therefore, for considering this effect, empirical data of Olsen *et al.* (1972) was adopted. This study consisted of a jet impinging on a large flat plate, so the noise field data presented excluded the trailing-edge noise and included the remaining sources: oblique jet-impingement, surface scrubbing, reflection by the surface, free jet mixing and free shear-layer mixing.

Impact noise data available in Olsen *et al.* (1972) and McKinzie (1980) were used in this work and they must be interpolated for different jet velocities. Also, scaling laws must be used to account for different jet diameters and different microphone locations.

2.2 Trailing-edge Noise

Equation (2) is used for calculating the contribution of the trailing-edge noise. The derivation of this expression is based on the jet impingement over a semi-infinite half-plane and its details are described in McKinzie and Burns (1975).

$$OASPL_{TE} = 10\log\left(\frac{W\delta U_m^5}{r^2}\right) + 10\log\left[\cos^2\left(\frac{\psi}{2}\right)\right] + 10\log\left(\frac{1.15\times10^8\alpha^2\rho^2}{c}\right) \tag{2}$$

In Eq. (2), $U_m\,[\mathrm{m/s}]$, $W\,[\mathrm{m}]$ and $\delta\,[\mathrm{m}]$ are the velocity profile data at the trailing-edge and are illustrated in Fig. 2. The first parameter, U_m, represents the maximum mean velocity of the free shear layer at the trailing-edge of the flap. The second, W, is half of the span-wise width of the velocity profile, characterized by the distance between the point where the velocity is U_m and the point where it is half of this value. The last one, δ, is the boundary layer thickness.

Moreover, r is the distance between the observer and the trailing edge, ψ is the angle between the observer and the surface of the flap, α is the normalized turbulence intensity and $\rho\,[\mathrm{kg/m^3}]$ and $c\,[\mathrm{m/s}]$ are respectively the density and sound speed in the vicinity of the trailing edge. The angle φ, in Fig. 2 also defines the observer position, however, this work is only concerned with $\varphi = 90°$, which is relative to the fly-over plane. At last, ψ_N is the angle between the surface of the plate and the jet centerline. The value of α used in this work is 0.1, the same value used in McKinzie and Burns (1975), McKinzie *et al.* (1976) and McKinzie (1980).

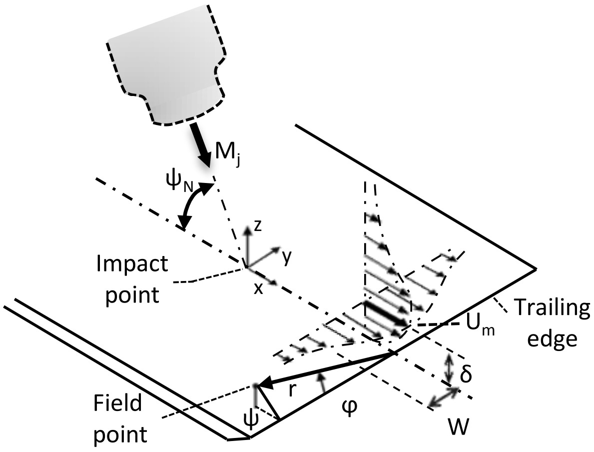


Figure 2: Coordinate system of a jet impinging on semi-infinite half-plane as described by McKinzie and Burns (1975).

2.3 Inflow Noise

According to McKinzie *et al.* (1976), the inflow noise arises from the large scale turbulent structures passing through the flaps. The derivation of the Eq. (3) related to the noise produced by the inflow effect is presented in McKinzie *et al.* (1976). The inflow noise must be calculated for the wing and each flap.

$$OASPL_{inf} = 10\log\left[\frac{(C_L)_\alpha \rho_l U_l^2}{r_{inf}}\right]^2 + 10\log\left(A_c\frac{A}{A_c}\right) + 10\log\left[\frac{A}{A_c}\left(\frac{\pi}{7.559/M_l^2+1}\right)\right]$$
$$+10\log\left(\frac{v'/U_l}{8\pi P_{ref}}\right)^2 + 10\log\cos^2\beta + 10\log\left(0.23 f_r\right) \quad (3)$$

The coefficient $(C_L)_\alpha$ is the effective lift coefficient slope and is actually considered the transfer function between the upwash disturbance v' and the lift response of the airfoil (McKinzie *et al.*, 1976). The local density ρ_l $[\mathrm{kg/m^3}]$, local velocity U_l $[\mathrm{m/s}]$ and local Mach number M_l are assumed as the values at the jet center line at the streamwise position relative to the mid-chord of each flap. The distance r_{inf} $[\mathrm{m}]$ is the distance between the observer and the flap taken into consideration. Also, the angle β is the angle between the resultant fluctuation lift force F_L' and the observer in the farfield. Both the distance r_{inf} and the angle β are represented in Fig. 3. The terms $A\,[\mathrm{m^2}]$ and $A_c\,[\mathrm{m^2}]$ are the actual and ideal correlation area respectively (McKinzie *et al.*, 1976). The term v'/U_l is called the upwash turbulence intensity, P_{ref} $[\mathrm{Pa}]$ is the reference pressure, assumed as $20\,\mu\mathrm{Pa}$ and fr $[\mathrm{Hz}]$ is the characteristic frequency of the fluctuating lift force.

The coefficient $(C_L)_\alpha$ is estimated by Eq. (4) presented in McKinzie *et al.* (1976). It is a function of L', which is the ratio of the turbulence integral scale length l_1 to the airfoil semichord $C/2$. The Eq. (4) is an approximation for $L' \leq 3$.

$$\overline{(C_L)_\alpha^2} \approx 2\pi^2\frac{\ln\left[1,2+\pi^2/(L')^2\right]}{\ln 1.2 + 3\left[\pi^2/(L')^2\right]} \quad (4)$$

The ideal correlation area is considered $\pi l_1 l_2$, the area of an ellipse having a streamwise semixaial length l_1 and a spanwise semiaxial length l_2, however one can consider $l_1 = 3l_2$ (McKinzie *et al.*, 1976). The length l_2 was considered equal to the nozzle exit radius. The actual correlation area is calculated by the product of the effective chord length C of each flap and the lateral correlation length, obtained from the data available in McKinzie (1980).

Finally, the frequency f_r is defined as the ratio of the eddy convection speed U_c to the eddy characteristic scale length δ_e. This parameter can be calculated with the assumptions given in McKinzie *et al.* (1976), shown in Eq. (5). As suggested by McKinzie (1980), the last term of Eq. (3) can only be considered if the flap is sufficiently immersed in the flow and its interaction with the jet ring vortices is considered strong.

$$f_r = \frac{U_c}{\delta_e} = \frac{0.63U_l}{6\pi l_2} \quad (5)$$

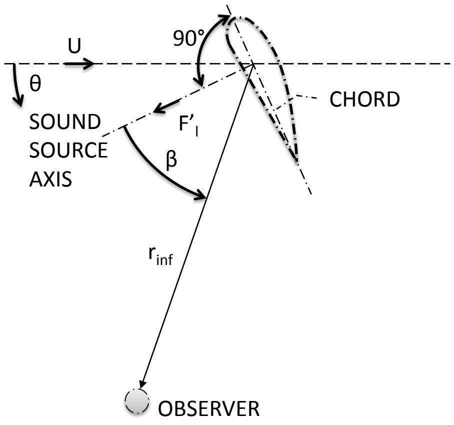


Figure 3: Reference system for the inflow noise calculation (McKinzie *et al.*, 1976).

3. RESULTS

The method was implemented and was applied in a case of a three-flap EBF geometry reported in Hayden *et al.* (1973). The experimental configuration consisted of a single flow jet from a $44.5\,\mathrm{mm}$ diameter nozzle impinging over a three flap $1/15$ scale model. The chords of the wing fixed part and each flaps are approximately, $184\,\mathrm{mm}$, $38\,\mathrm{mm}$, $54\,\mathrm{mm}$ and $73\,\mathrm{mm}$, respectively. Figure 4 shows the model in three different operating conditions : cruise, take-off and approach. For the purpose of analyzing the noise prediction method, the take-off and approach configurations with jet exit velocity of $192\,\mathrm{m/s}$ were chosen.

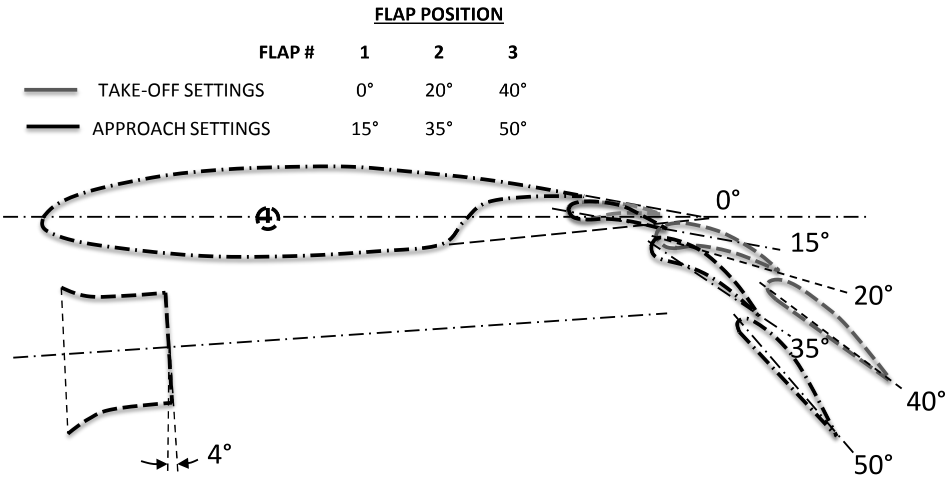


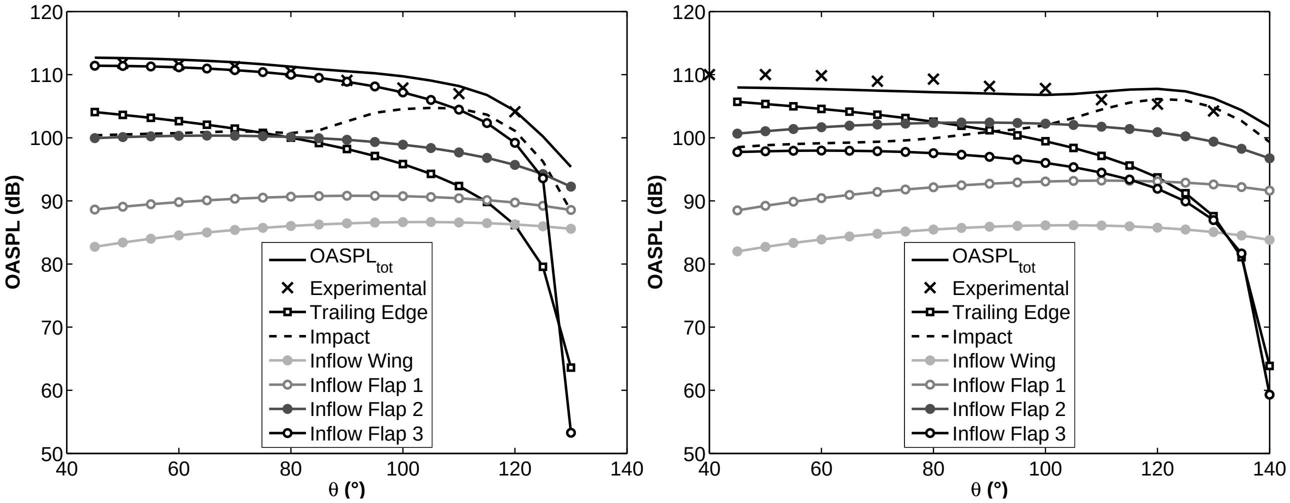
Figure 4: Hayden *et al.* (1973) EBFs configurations.

The empirical velocity profile data required by the trailing-edge noise expression were taken from aerodynamic data available in Hayden *et al.* (1973). The value of $\alpha = 0.1$ was adopted as used in McKinzie and Burns (1975) and McKinzie *et al.* (1976). The distance r and the angle ψ were calculated using geometrical relations.

For the impact noise, the data of Olsen *et al.* (1972) and McKinzie (1980) were used and corrected for the nozzle diameter and measuring distance of the case. Also, the flow turning angle correction was applied, based on McKinzie (1980). Since impact data was not available for the take-off configuration flap angle, the data from 20° and 60° were scaled using the curve available in Olsen *et al.* (1972), which represented the influence of the plate incidence angle. This procedure can obviously introduce more errors in the final result.

Finally, the parameters of the inflow equation were selected following the assumptions made in McKinzie (1980). The upwash turbulence intensity v'/U_l was taken from plots of the axial and radial turbulence intensity available in McKinzie (1980), in the position corresponding to the leading edge of each flap. Both values were corrected according to the Mach number and so the resultant component normal to the airfoil chord was calculated.

The results for the three flap EBF model are shown in Fig. 5a for the approach situation and in Fig. 5b for the take-off. The experimental results of Hayden *et al.* (1973) should be compared with the full line corresponding to the sum of all the sources. The contributions of each different source are shown in the same graphs. As can be seen, the results for the approach situation show reasonable agreement with the experimental data. In this case, the inflow noise associated with the last flap is totally dominant in angles lower than 80°. However, at angles greater than 80° the impact noise also plays an important role. The greater deviations occur in the region were the level of the impact noise rises and can be associated with the uncertainties of the interpolations and corrections applied to the empirical data. The shape of the curve of the experiment is very close to the shape of the curve relative to the inflow noise on the third flat, and this can mean that the method predicted well the noise from the dominant source.



(a) Approach Condition (b) Take-off Condition

Figure 5: Results of the implemented model compared to the experimental data of Hayden *et al.* (1973).

The results for the take-off show good agreement with the experimental data. In this case, the interactions were considered weak for all the flaps in the take-off condition, and as consequence, the inflow noise became less important if compared with the approach case. At angles lower than 70°, the trailing-edge noise is dominant, while in higher angles, the impact source and the inflow over the second flap are more important. One can conclude that the deviations at lower angle could come from the poor prediction of the trailing edge noise, while in higher angles, from the poor predictions of the impact noise due to the corrections and approximations applied. It is important to observe that if the interaction with the last flap was to be considered strong, the inflow noise contribution would rise significantly and the results would show a great deviation from the experiment.

4. SENSITIVITY ANALYSIS OF THE INVOLVED PARAMETERS

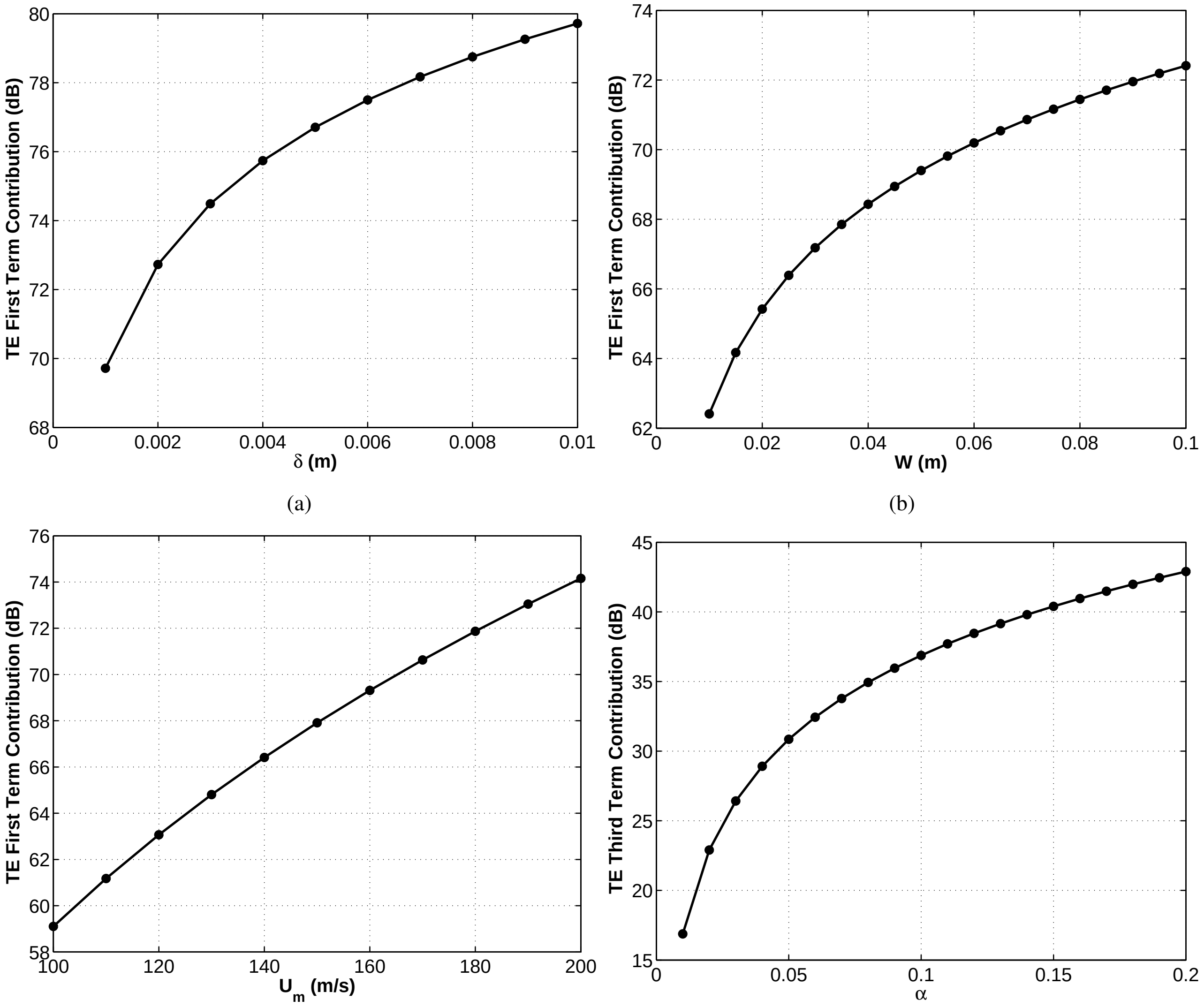
As some of the empirical data used in this work were estimated, interpolated or even obtained from low quality plots, a sensitivity analysis was conducted to evaluate the possible effects of these uncertainties on the results. This study can also help to assess the precision of using CFD for obtaining the flow parameters. The analysis is focused on the inflow and trailing-edge noise, as the impact part is fully empirical.

The variations of the parameters were done by using the same data adopted in the prediction of the noise of the last flap of the approach configuration. This analysis was carried out, varying each parameter of interest alone and leaving the others fixed. Finally, the results of the variations were observed in the terms of the equations relative to each parameter.

Regarding the trailing edge noise, the most influential parameters are the velocity profile data and the normalized turbulence intensity. As can be seen in Eq. (2), the first term of the right-hand side includes the half-span of the velocity profile, the boundary layer thickness and the maximum velocity in the vicinity of the trailing edge. The weight and influence of these terms can be observed in the curves shown in Fig. 6. As can be seen, variations in the value of δ from $1\,\mathrm{mm}$ to $3\,\mathrm{mm}$ can lead to variations of $4\,\mathrm{dB}$ on the results, while the value used in the approach case was $1.5\,\mathrm{mm}$. For the same case, the value of W was $0.08\,\mathrm{m}$ and variations around this value can lead to around $1\,\mathrm{dB}$ of difference. For obtaining the data described above, RANS simulations ends up being a strong alternative.

Another term that showed a significant influence on the results is the normalized turbulence intensity, present in the third term of Eq. (2). The dependence of this parameter is shown in Fig. 6d. McKinzie and Burns (1975) states that this can vary between 0.01 to 0.2, but the value of 0.1 was used in most of the works using this model. The results show that this value must be carefully chosen, as a difference between using 0.075 and 0.125 can lead to $5\,\mathrm{dB}$ of difference.

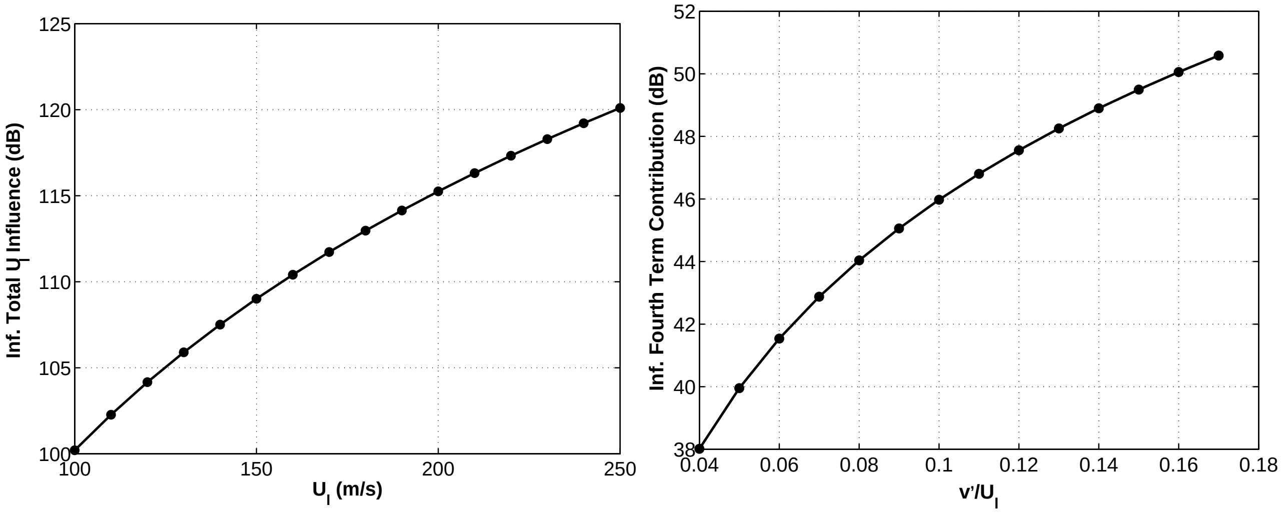
About the Inflow noise, the influence of the upwash turbulence intensity and the local velocity are shown in Fig. 7. As can be seen, variations of 1% can lead to around $1\,\mathrm{dB}$ of difference in the final result. In this case, the use of RANS simulations can be difficult due to the limitations of the turbulent models to precisely predict the jet turbulent field. It



(a) (b)

(c) (d)

Figure 6: Influence of δ (a), W (b), U_m (c) and α (d) variations in the first and third term of the trailing edge noise equation.



(a) (b)

Figure 7: Influence of U_l (a) and v'/U_l (b) variations on the terms of the inflow noise equation.

must be observed that if this source of noise is to be considered, it is important to have turbulence data of high quality and for the nozzle geometry used, as the use of coaxial jets, with pylon or even chevron nozzles can alter the turbulent field. Another point is that the inflow noise can have lost importance as well, since in current single flap geometries the flaps are not so intrusive into the jet flow.

It is worth observing, that in current high-lift configurations, the term of the impact noise may not have the complete physical meaning anymore. In a modern single flap configuration, the jet may not impact directly as it does in an EBF configuration, and so some of the sources represented by the impact noise can have much less importance. So, the data obtained from the same way as the experiment of Olsen *et al.* (1972) may not be used in the analysis of newer configurations.

5. CONCLUSIONS AND DISCUSSION

An analysis of a semi-empirical method developed for predicting the noise generated by Externally-Blown flaps, was conducted in order to assess the possibilities of its application in current project situations. The preliminary results showed reasonable agreement with EBF experimental data. The sensitivity analysis showed that the method is dependent on some parameters that are not easily obtained from current database or CFD simulations. Turbulence intensity values, for instance, are often over predicted by RANS simulations.

Moreover, the impact noise source, which incorporate scrubbing, free-jet mixing, reflection on the surface and other effects, depends entirely on empirical data. The data used for this purpose was taken from Olsen *et al.* (1972), that consisted of a jet impingement over a large plate. These impact data seem to be very specific, since this source includes the jet noise of a single flow nozzle impinging over a flat plate. In a modern single flap configuration, the jet may not impact directly as it does in an EBF configurations, so the sources of noise may be considerably different. Also, the use of coaxial jets, the presence of the pylon and the use of noise control devices like chevron nozzles may require the use of newer data.

Although the limitations discussed above prevent the use of the presented method in current design, the good results obtained with low computational cost encourages the development of new alternatives of semi-empirical methods for the prediction of the jet-flap interaction acoustic field.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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