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Component-based Model for Flap Noise Prediction

Yi Jiang*

China Aerodynamics Research and Development Center (CARD C)

A Filippone[†]

The University of Manchester

A component-based model is proposed for flap noise prediction to be used in the context of a comprehensive framework for aircraft noise. The flap noise are decomposed into three distinct acoustic contributions: trailing-edge contribution, low and high frequency side-edge contribution. Except the side-edge noise, the trailing-edge noise is recognized as a comparable contribution in the flap noise. Functions and parameters are derived for the energy conversion efficiency, the normalized spectra and the acoustic directivity. Applications of the model are shown for typical flap noise predictions, which include an isolated Airbus A320 flap, a half-span Fowler flap and a flap in a high-lift wing. It is demonstrated that the model proposed is suitable for aircraft noise prediction, with experimental data well predicted.

Nomenclature

A	=	amplitude of normalized spectra
B	=	parameter defining normalized spectra
c	=	chord length of flap
c_0	=	speed of sound
d	=	span of flap
D	=	directivity factor
f	=	frequency
F	=	normalized spectrum
h_s	=	characteristic length for side-edge component
h_t	=	characteristic length for trailing-edge component
L_c	=	characteristic length, flap noise prediction
L_{SL}	=	characteristic length, low frequency side-edge
L_{SH}	=	characteristic length, high frequency side-edge
L_T	=	characteristic length, trailing-edge
L_{ref}	=	reference chord for flap noise
M	=	Mach number
N	=	Mach number power law
N_{SL}	=	Mach number power law, low frequency side-edge component
N_{SH}	=	Mach number power law, high frequency side-edge component
N_T	=	Mach number power law, trailing-edge component
p	=	acoustic pressure
p_{SL}	=	low frequency side-edge component of acoustic pressure
p_{SH}	=	high frequency side-edge component of acoustic pressure
p_T	=	trailing-edge component of acoustic pressure
P	=	component-specific feature
P_{SL}	=	low frequency side-edge component feature
P_{SH}	=	high frequency side-edge component feature
P_T	=	trailing-edge component feature
q	=	lower power index in normalized spectra
R	=	radial distance of far-field microphone

*Computational Aerodynamics Institute, P.O. Box 211, Mianyang 621000, PR China. Email:

[†]School of Mechanical, Aerospace, Civil Engineering, AIAA Senior Member. Email:

S	=	typical area of flap surface
St_0	=	Strouhal number where the spectrum achieves maximum
U	=	mean flow velocity
$\mathbf{x}$	=	far-field coordinate vector
β	=	flow energy conversion efficiency
β_0	=	parameter defining flow energy conversion efficiency
δ	=	flap angle
γ	=	coefficient of atmospheric absorption
Δ	=	Doppler factor
θ	=	emission angle in flyover plane
μ	=	parameter defining normalized spectra
ρ_0	=	mean air density
σ	=	upper power index in normalized spectra

I. Introduction

Airframe noise is a major contributor to the overall sound level of an aircraft during final approach and landing [1]. High-lift systems, fully deployed in most approach and landing configurations, include leading edge slats and trailing-edge flaps. These systems show comparable levels of aerodynamically-generated noise [2, 3]. The trailing-edge flap system is the subject of this investigation. Specifically, this paper presents a new low-order method to be used within the context of comprehensive aircraft noise prediction of single trajectories, multiple take-off and landings, noise footprints, and more. These applications may require thousands to million of airframe noise calculations, something that cannot be practically achieved with high-order methods (computational fluid dynamics, CFD, and computational aero-acoustics, CAA). Another aspect of the problem is that in many cases the exact geometry of the configuration is unknown, which makes it impossible to produce a sufficiently accurate prediction model using high-order field models.

Therefore, there is a need to improve our noise prediction capabilities with methods that couple some physics with basic geometrical configurations. The approach to be followed, then, is to extract as much information as possible from the physics of a generic configuration, understand the noise production mechanisms, derive low-fidelity models and then apply these models to a chain of noise predictions for an end-to-end engineering process.

Pioneering work in this area was performed by Fink [4], who proposed a simple, entirely empirical model, to predict the noise from airframe components on the basis of a very limited number of parameters. Empirical tools for the prediction of airframe noise have been developed more recently [5, 6] on the basis of large experimental and numerical databases of aircraft noise. These data are available for understanding the basic mechanisms of noise generation and for calibrating low-order prediction models.

A fundamental understanding of the airflow around a flap is required before developing a low-order method for flap noise. Wind-tunnel experiments and CFD are two common tools to investigate the airflow. The vortex roll-up at the flap side-edge and its noise generation mechanisms have been comprehensively recognized from a series of experimental and numerical studies [7–14]. A double vortex structure is mainly responsible for aeroacoustic noise radiation at the flap side-edge. The vortices in the double vortex system are formed by unsteady shear layers shedding from the suction and pressure sides at the side-edge. These vortices eventually merge to a single vortical structure on suction side of the flap. The unsteady shear layers have been recognized as the main mechanisms responsible for flap side-edge noise. Supported by a stability analysis made by Streett *et al.* [7] and wind tunnel measurements conducted by Choudhari *et al.* [10], the shear layer instability mechanism contributes to broadband side-edge noise.

While noise from flap side-edges has been the focus of numerous studies, trailing-edge noise from the flap has received less attention. However, trailing-edge noise has been well recognized in several studies [15–21]. Trailing-edge noise should certainly be included in flap noise models. It is worth noting that the focused trailing-edge component here in the flap noise is radiated in the flow condition of high angles of attack caused by deployed high-lift systems. In particular, Brooks & Schlinker [16] described the trailing-edge noise mechanisms in some detail. At high angles of attack, this noise mechanism is similar to that of a bluff body; the separated flow near the trailing-edge gives way to large-scale separation causing the airfoil to radiate noise. Although the trailing edge component is important, it is usually neglected in empirical prediction of the flap noise. Only addressing the side-edge noise, Guo proposed an empirical model for flap noise prediction [22]. Rossignol developed this model by choosing appropriate parameters for the characteristic velocity and length scales [13].

Considering the basic noise mechanisms of flap noise described above, a component-based model can be developed for flap noise prediction. In the component-based model, the flap noise is decomposed into several components. This decomposition is inspired by the component-based concept of Dobrzynski *et al.* [23], which has been further used to develop a component-based model for airframe noise prediction [13, 22, 24, 25]. Based on a rational decomposition consistent with the flap noise mechanisms, the component-based model in the present study is derived by adopting the scaling laws from the theory of aerodynamic noise generation. This model has a general trend described by the inverse fourth power law of convective amplification [26–30]. The modified power law proposed by Rossignol [13] is employed, since the sixth power law of the Mach number is unsuitable for flap noise prediction.

We propose a noise decomposition into three domains: the low frequency side-edge component, the high frequency side-edge component, and the trailing-edge component. The trailing-edge component is generated by vortex shedding from the flap trailing-edge. The vortices at the side-edges are responsible for the broadband side-edge noise, which is decomposed into the low frequency component and the high frequency component. Rossignol [13] decomposed the broadband side-edge noise into low- and high frequency components to develop an empirical model for flap noise, but the trailing-edge noise component is not considered. After the decomposition, the normalized spectrum, the flow energy conversion efficiency and the directivity factors are fitted on the basis of experimental data. The capability of the model is examined by applying it to the noise prediction for various flaps, including an isolated A320-type flap, a half-span Fowler flap and a flap in a high-lift wing model.

II. Prediction model

According to the concept of noise decomposition, the far-field acoustic pressure of a flap shown in Figure 1 can be expressed as

$$\langle p^2 \rangle = \langle p_{SL}^2 \rangle + \langle p_{SH}^2 \rangle + \langle p_T^2 \rangle, \quad (1)$$

Fig. 1 Illustration and nomenclature of a flap geometry.

where the subscripts SL , SH and T , respectively, indicate the low frequency side-edge component, the high frequency side-edge component, and the trailing-edge component. By starting with the Ffowcs-Williams-Hawking equation [27] and applying scaling laws [24], the acoustic pressure can be written as

$$\langle p^2 \rangle = \frac{(\rho_0 c_0^2)^2 e^{-\gamma R} S}{R^2 \Delta^4} \{P_{SL} + P_{SH} + P_T\} \quad (2)$$

where $S = c \cdot d$ is the reference surface area of the flap and $\Delta = 1 - M \cos \theta$. The features common to all three components have been factored out and component-specific ones are represented by the quantity P , with respective subscripts for the three components. These latter factors are defined by

$$P = \beta M^N D(\theta) F(St) \quad (3)$$

The power factor is $N = 6$ according to the scaling laws [24]. However, this simple integer is unsuitable for the flap noise prediction. The power is $N_{SL} = 5.5$ for low frequency side-edge component and $N_{SH} = 6.5$ for high frequency side-edge component. For the trailing-edge component, the power is set to $N_T = 5.5$, which is in good agreement with the fitted result 5.4 and 5.6, respectively provided by Cozza *et al.* [31] and Ewert *et al.* [32], based on CFD solutions and experimental data. To close the prediction model, we also need to formulate the normalized spectrum $F(St)$, the flow energy conversion efficiency β and the directivity factor $D(\theta)$.

A. Normalized spectrum

The normalized spectra are defined in terms of the Strouhal number St

$$St = fL_c/U \quad (4)$$

In Eq. 4, L_c is the characteristic length dominated by the noise mechanism. As discussed earlier, the two structures, i.e. vortices rolling from side-edges and the trailing-edge are mainly responsible for the flap noise radiation. Since vortices from trailing-edge are linked to the trailing-edge component of the flap noise, the characteristic length of this component is given by

$$L_T = h_t L_{ref} \quad (5)$$

where, L_{ref} is a reference chord length, and h_t is a parameter to control the position of the spectral peak. The constraints defining the position of the spectral peak are given in Eqs. 8 and 9. The quantity L_{ref} is affected by anything dominating the noise mechanism, such as porous edge and edge geometry. In this model, we choose $L_{ref} = 0.48$ m and $h_t = 0.12$ for a non-porous and blunt edge. The values of these two parameters are determined to complete the construction of the normalized spectrum. The characteristic lengths of the two components of the side-edge noise are the same, which can be written as

$$L_{SL} = L_{SH} = h_s L_{ref}, \quad (6)$$

where $h_s = 0.15$, approximately corresponding to the starting position of the vortices rolling from the side-edge. The h_s is also proposed for a non-porous and blunt edge based on experimental data.

With characteristic lengths (5) and (6), the Strouhal number can be calculated for each separate component, then the normalized spectrum is obtained from a general form

$$F(St) = A \frac{St^\sigma}{(B + St^\mu)^q} \quad (7)$$

The spectrum $F(St)$ achieves a maximum at the Strouhal number

$$St = St_0 \quad (8)$$

with two conditions [24],

$$\begin{aligned} A &= (q\mu/\sigma)^q St_0^{q\mu-\sigma}, \\ B &= \{(\mu q/\sigma) - 1\} St_0^\mu. \end{aligned} \quad (9)$$

Once the empirical constants q , μ , σ and St_0 are given by fitting with experimental data, the normalized spectra are determined. These parameters are given in Table 1. An illustration of three normalized spectra is plotted in Figure 2 for the nearly full-scale flap of the Airbus A320 [13], as a function of frequency in a range between 100 Hz and 10,000 Hz. These spectra are designed to represent the two main sources, i.e. vortices from the trailing-edge and from side-edges.

B. Energy conversion efficiency

The energy conversion efficiency β describes the transition between airflow and noise generation. The conversion efficiency can be derived by matching predictions with experimental data for the three spectral components. Our understanding of the flap noise is that the far-field SPL increases with the deflection angle δ . This basic principle can be validated by experimental data [11, 13]. With this in mind, we propose a model of the conversion efficiency for the low frequency side-edge component and trailing-edge component

Table 1 Parameters of the normalized spectra.

	For P_{SL}	For P_{SH}	For P_T
St_0	0.8	4.0	1.6
σ	4.0	3.0	5.0
μ	2.5	1.5	2.1
q	2.6	4.2	5.2
A	2.02	2188.36	938.65
B	0.36	8.80	3.18

Fig. 2 Illustration of the normalized power spectral density.

$$\beta = \beta_0 e^{1.1\sqrt{\delta}}, \quad (10)$$

and for the high frequency side-edge component

$$\begin{cases} \beta = \beta_0 e^{\delta/4} & \delta < 30^\circ \\ \beta = \beta_0 e^{1+13\delta/60} & \delta \geq 30^\circ \end{cases} \quad (11)$$

Table 2 Energy conversion efficiency parameters.

	For P_{SL}	For P_{SH}	For P_T
β_0	1.25×10^{-10}	2.5×10^{-10}	1.25×10^{-10}

where β_0 is an empirical constant. The values of β_0 are given in Table 2 for the three spectral components. Note that β for the high frequency side-edge component is a piecewise function dependent on the deflection angle δ . This function is used to represent the influence of the flap deflection on vortex rolling from the side-edges. At low deflection angles the vortices remain near the flap surface, whilst large flap deflections lead to an earlier lift-off of the vortices [13]. In order to discern the variation of high frequency noise due to flow feature variation, a deployment angle of 30° is chosen as a separation point for the piecewise function (11). Figure 3 displays the increments of side-edge noise level as a

function of deployment angle δ ; the increments are relative to the SPL at $\delta = 20^\circ$. Note that the level of high frequency component increases quicker with δ .

Fig. 3 Increment of side-edge noise due to deployment angle.

Fig. 4 Directivity factor for all the three spectral components.

C. Directivity factor

Due to the limited availability of experimental data, the directivity model will be presented only for emission angles in the flyover plane; on this plane the emission angle θ is measured from the downstream direction of the flight path, as illustrated in Figure 1. Test data have shown that the flap noise in the flyover plane has a directivity pattern varying only gradually with the emission angle [33]. The direction of maximum noise emission is roughly aligned with $\theta = 90^\circ$ in the flyover plane, according to some experimental observations [34, 35]. Furthermore, in some experimental data [33], we noted that the difference is about 1 dB between the SPL at $\theta = 90^\circ$ and at $\theta = 30^\circ$. Thus, a directivity factor is proposed for all three components as

$$D(\theta) = 1 + 0.6 \sin \theta \quad (12)$$

The directivity factor is shown in Figure 4. This factor is fitted from experimental data [33] in $30^\circ < \theta < 150^\circ$. The applicability of this directivity factor needs further validation for the emission angles beyond the range of

the experimental data. Moreover, the directivity factor is proposed from experimental data with frequencies $100 \text{ Hz} \leq f \leq 10,000 \text{ Hz}$.

III. Numerical tests

A. A320-type flap

The first case considered in our validation exercise is an isolated flap model — a nearly full-scale Airbus A320 geometry. This model has a chord length of 0.48 m, and a span length 0.4 m. The corresponding measurements were conducted by Rossignol *et al.* [13]. In this experiment, the distance between the flap model and the microphones was 0.6 m.

In the experiment, the flap and the microphones were both fixed, therefore the predictions are performed with the convective amplification removed, $\Delta = 1$. The flow conditions for the predictions are $c_0 = 340 \text{ m/s}$ and $\rho_0 = 1.18 \text{ kg/m}^3$; no atmospheric absorption is included.

Figure 5 displays the predicted solutions for different deployment angles at $M = 0.18$ and $\theta = 90^\circ$ with the corresponding experimental data. The three components of the noise spectra are shown at all flap angles. It can be gleaned that the role of the high frequency component becomes increasingly important as the deployment angle is increased. This phenomenon can be explained by the fact that the flap noise at high deployment angles is dominated by the vortices from the side-edges. To validate the power law of Mach number dependence, Figure 9 shows the solutions for different Mach numbers with a deflection angle 25° . A good fit of the measured data is obtained with the power law $N_{SL} = N_T = 5.5$ and $N_{SH} = 6.5$.

Fig. 5 Theoretical predictions at increasing deployment angles at $\theta = 90^\circ$ and $M = 0.18$. Experimental data from Ref. [13].

B. Fowler flap

The second flap model considered is a half-span Fowler flap with a chord length of 0.12192 m and span 0.4572 m. This model was tested in a quiet flow facility by Brooks *et al.* [11]. In that experiment, flaps with different edge geometry were measured. Since the present prediction model is proposed for a flat edge, we will only consider the corresponding experimental data. This flaps was further investigated by Hutcheson *et al.* [12] in the context of noise directivity. In all these experiments, the distance between the model and the microphones was 1.524 m.

Fig. 6 Noise predictions for Fowler flap at $\theta = 90^\circ$; experimental data from Ref. [11].

Atmospheric absorption is ignored in this case, and the convective amplification is removed due to the fixed location of the flap and the microphones in the experiment. The flow conditions for the numerical results are $c_0 = 340$ m/s and $\rho_0 = 1.18$ kg/m³. Figure 6 shows the solutions for the deployment angles of 29° and 39° , an emission angle $\theta = 90^\circ$, and flow Mach number $M = 0.17$. The predictions are in good agreement with experimental data. For the directivity factor, the numerical predictions are further compared with experimental data of Hutcheson *et al.* [12]. The comparison is carried out at four angles in the flyover plane, as shown in Figure 7. While most of the noise is very well captured by the model, the predicted solutions are rather inaccurate when the emission angle is $\theta = 73^\circ$.

C. Flap in high-lift wing model

A flap model attached to a high-lift wing is chosen to test the capability of the prediction model, although the prediction model has been derived for an isolated flap. Aeroacoustic measurements were performed for a high-lift wing with a half-span flap by Rossignol [13], where the detailed geometry of the high-lift wing was described. This flap has the same profile geometry as the A320-type case in section III.A, but with a chord length of 0.12 m and a 0.4 m span. To utilize the prediction model for this flap, the atmospheric absorption and the convective amplification are removed. Flow conditions for the predictions are $c_0 = 340$ m/s and $\rho_0 = 1.18$ kg/m³. For the present prediction, the distance between the flap model and the microphones is set to 0.6 m.

To improve the agreement between experiments and prediction, an effective flap deployment angle is used to replace the nominal deflection δ . This effective angle was also introduced by Rossignol [13] to empirically predict the flap noise. An effective deflection angle must be considered, because the influence of other elements of the high-lift wing system on the flow features of the flap.

Rossignol determined the effective angle based on linear extrapolation of the lift coefficient. The effective angles were about 5 to 6 degrees lower than the nominal flap deflection angle. In the same vein, we defined effective angles 17° (corresponding to $\delta = 25^\circ$) and 26° (corresponding to $\delta = 34^\circ$). Figure 8 shows the Mach number effect of the flap noise at $\delta = 34^\circ$. An acceptable agreement is found between the predictions and experimental data, though not as good as the case shown in Figure 9.

This behaviour indicates that the influence of other elements in the high-lift wing system on the flow feature of the flap have not been fully represented. The effect of deployment angle on the flap noise is demonstrated in Figure 10 at $M = 0.15$. The prediction at $\delta = 25^\circ$ is better than that at $\delta = 34^\circ$. This result may be explained by the fact that the flow features of the flap are affected more significantly by other parts of the high-lift system at higher deployment angles.

Fig. 7 Acoustic directivity for deployment angles of 29° and 39°; experimental data from Ref. [12].

Fig. 8 Mach number effect in a high-lift wing at $\delta = 34^\circ$; experimental data from Ref. [13].

IV. Conclusions

A component-based model was proposed for flap noise prediction by decomposing the flap noise into the low frequency side-edge component, the high frequency side-edge component, and the trailing-edge component. At high angles of attack caused by deployed high-lift systems, the trailing-edge component in the flap noise is linked to the vortex shedding from trailing-edge. Supported by experimental data and theoretical analysis in the literature, the vortices rolling from side-edges are seen to be mainly responsible for the low- and the high frequency side-edge component.

The model presented in this paper has been used to predict noise radiated from various typical flap configurations,

Fig. 9 Predictions for different Mach numbers at $\delta = 25^\circ$; experimental data from Ref. [13].

Fig. 10 Deflection effect at $M = 0.15$; experimental data from Ref [13].

including an isolated A320-type flap, a half-span Fowler flap and a flap in a high-lift wing model. The predictions have shown a satisfactory agreement with the corresponding experimental data. The effect of Mach number and deployment angle on the flap noise has been well predicted. The directivity factor needs to be further validated since it was inferred from experimental data in $30^\circ < \theta < 150^\circ$.

The noise model was proposed for a flap with a non-porous and blunt edge. The influence of installation effects on flow features needs further examination. More data are required to further investigate these effects, and only modifications of deployment angles were adopted for the flap in a high-lift wing case to account for them. A further line of investigation requires a more detailed exploration of the wing-flap interaction, and a better understanding of the effective flap deflection angle.

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