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# A NEW METHOD FOR ESTIMATING COMMUNITY NOISE CHANGES DUE TO AIRCRAFT TECHNOLOGY VARIATIONS

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Future air traffic growth forecasts underline the need for new environmental abatement strategies for aviation, involving, among others, the adoption of new aircraft designs and technologies. Accurately predicting the noise impact of these strategies is therefore a matter of significance. The reliability of existing tools is governed by tradeoffs between parameters such as their fidelity level, their dependance on confidential data, as well as the cost and accuracy of experimental data. This paper proposes an innovative, flexible and simplified method for aircraft noise prediction that by-passes the difficulties of existing models. Based on scenarios where community noise levels are known through existing tools or publicly available databases, the proposed method determines variations resulting from aircraft technology changes, such as the increase of the bypass ratio of a turbofan engine. The method shows promise of being applicable to new designs like the wing body aircraft, whereas, by adapting the input variables, it can also estimate the noise impact of changes at operational level. To illustrate the proposed method, which is part of a wider effort to better understand environmental and economic interdependencies, noise estimations are compared to existing NPD data.

## 1. Introduction

The forecast growth in air traffic highlights the need for additional aircraft noise abatement measures, if environmental aims are to be met [1]. Accurately predicting the impact of potential mitigation strategies is therefore a matter of some significance.

Normally, mitigation measures are either operational or technological changes, which lead to reducing noise levels at the observer point. In turn, these changes translate into variations of aircraft noise source levels, either directly, as a result of technological changes, or indirectly, as a result of trajectory variation.

Existing aviation noise prediction tools are not optimised in promptly forecasting the community noise impact arising from such variations. Most importantly because they aim at delivering absolute noise level values, either by using experimentally obtained noise data, or through semi-empirical mathematical models that besides, often depend on confidential inputs.

The aim of the research reported in this paper is to develop a simple method of estimating community noise variations due to changes in aircraft source levels that bypasses difficulties associated with existing prediction tools. We name the proposed noise prediction method 'FANE'. The crux of FANE, which is currently focused on turbofan-powered aircraft, is that it only uses changes as inputs and returns as output the variation with respect to scenarios where community noise 'base' levels are known. The paper presents the methodology of FANE, illustrates its usability by estimating Noise-Power-Distance (NPD) curves of existing aircraft and discusses its potential.

# 2. Existing noise prediction tools

This section briefly reviews the underlying methodologies of existing noise prediction tools. These tend to fall into two broad groups that we term 'airport' and 'engineering' [2].

## 2.1 Airport noise prediction tools

Airport prediction tools, such as INM [3], use experimentally obtained noise data (typically public NPD databases), to predict the noise arising from mixed fleet operations in terms of average metrics. Hence, they are useful at legislation and commercial level for dealing with the cumulative noise exposure arising from airport operation. Since predictions rely on actual measurements rather than on mathematical models, airport tools can sensibly predict average values of aircraft noise exposure, in a reasonable time. Yet, they are subject to uncertainties, mainly because it is practically impossible to produce experimental datasets for all aircraft-engine pairs and configurations; which poses limitations on their potential regarding contemporary procedures and configurations and technological changes. Another limitation is that airport tools treat the aircraft as a lumped acoustic source and therefore cannot predict noise contribution from individual aircraft noise sources (fan, jet, airframe, etc.), which is useful information for reducing aircraft noise at design level.

## 2.2 Engineering noise prediction tools

Engineering prediction tools, such as ANOPP [4], are motivated by the need of manufacturers to meet certification levels as measured in EPNLdB. They are mathematical models that attempt to simulate the complex aircraft noise generation and propagation mechanisms, whereas they consider the individual sources on the aircraft together with installation effects (such as wing reflection). Individual noise sources are modelled using different methods that can be private or publicly available, such as the semi-empirical ones of Stone [5] for jet noise and Heidmann [6] for fan noise. Private methods are normally more accurate than their publicly available counterparts because they use commercially sensitive data. Which highlights that engineering tools may require confidential inputs if accurate predictions are to be made. Moreover, they often end up handling hundreds of parameters and become extremely sophisticated and time consuming.

# 3. FANE methodology

New noise abatement scenarios are typically associated with known changes in terms of aircraft technology or operations. The underlying concept of FANE is rooted in the fact that rather than seeking absolute values, the new scenario is assessed by determining noise variations with respect to a known 'base' scenario, using as inputs these known technological (or operational) changes.

The difference in philosophies between existing noise prediction tools and FANE is illustrated in Fig. 1. Existing tools would define the absolute noise level of a new scenario 'Sc.1', either through simulation, which may be subject to confidential information, or by employing experimental data (e.g. NPDs) that may be unavailable. In contrast, FANE uses noise levels of a base scenario in combination with estimated variation in noise levels due to technological changes in order to predict the noise impact (i.e. the $\Delta Noise$) of 'Sc.1'. Hence, parameters defining the absolute values become excessive, reducing dependance on confidential data. The few remaining unknown parameters are given approximated values, introducing some tolerable error, which explains why FANE gives estimations and not exact calculations.

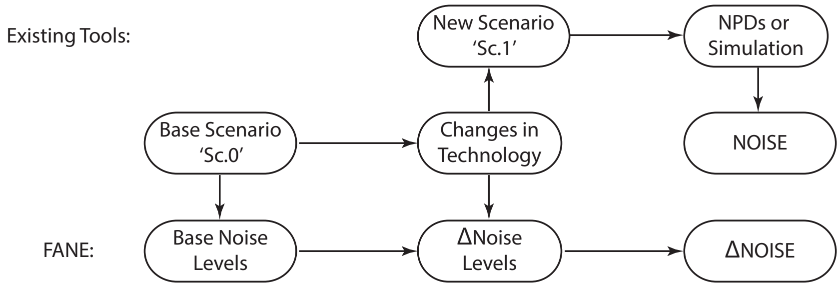


Figure 1: Schematic representation of existing tools and FANE methodology.

### 3.1 Base noise levels

For any aircraft operation (takeoff, landing), FANE requires as inputs the base noise levels of the aircraft, as well as of its individual noise sources. The former is directly acquired from NPD curves that are publicly available for most commercial aircraft and are accessed from resources like [8].

Conversely, very few published datasets exist for the base levels of individual noise sources, with NASA [9] being one of the most descriptive. Still, NASA expresses this data in terms of average levels corresponding to aircraft sizes rather than to specific aircraft models. Data associated with specific aircraft are normally proprietary to manufacturers. Thus, one option is to calculate these levels through engineering tools; yet, this may still require commercially confidential knowledge.

The alternative employed by FANE is to approximate the relative contributions of individual noise sources. These are extracted from the total aircraft noise level and the aforementioned average levels published by NASA, through an empirical technique that uses the number of dominant sources and exploits properties of equal loud sound sources addition. More specifically, starting from the NASA averages and making assumptions based on historical trends and expected technological achievements, it is possible to establish standard noise sources level relationships for each operation. This reveals the probable number of dominant sources per operation. Then:

- If one source is clearly dominating, its level can be assumed equal to the aircraft noise level.
- If two sources dominate, their level would be about 3 dB less than the total aircraft noise level, since addition of two equally loud sound sources results in a higher level of 3 dB.

Since it is practically impossible to create base level relationships for each different aircraft and since experimental data in [9] show that relative source noise levels are influenced by aircraft size, FANE groups aircraft into the size-classes defined by NASA [9] and examines them separately. These size-classes are termed Business jet, Small Twin, Medium Twin and Large quad.

### 3.2 Evaluation of the variation in individual noise sources due to technological changes

The variation of individual aircraft noise sources due to a technology change can be either given directly e.g. from manufacturers, or estimated. This section explains the philosophy behind estimating the variation of individual aircraft noise sources using common semi-empirical methods. FANE treats the aircraft as a lumped noise source consisting only from the significant noise sources, that according to published resources (such as [9]) are the jet, the fan and the airframe.

To illustrate the way of thinking, the jet noise variation relationship is derived next. Starting from Lighthill's acoustic analogy, the following can be written for the jet acoustic power:

$$W_j \propto \rho_j A_j V_j^8 \,. \tag{1}$$

In the Equation above, $\rho_j$ and $A_j$ are the jet density and jet cross sectional area respectively, whereas $V_j$ represents the static specific thrust. Using the definition of gross thrust $F_G$ and introducing an effective velocity to account for the flight speed effects, proportionality 1 becomes:

$$W_j \propto F_G V_e^6 \,. \tag{2}$$

Thus, jet sound power level change due to a change of gross thrust can be expressed as:

$$\Delta Lw_j = 10 \log \frac{F'_G}{F_G} + 60 \log \frac{V'_e}{V_e} \,, \tag{3}$$

where the values corresponding to the condition after the thrust change are denoted with an accent. The advantage of this approach is that Eq. 3 is only dependant on parameters that are either known (e.g. thrust) or can be estimated based on publicly available information.

Due to space constraints, the level changes relationships for the fan and the airframe are presented below, without showing the derivation. With $\mu$ being the BPR, $V_0$ the airspeed and $V_{j,b}$ the bypass jet velocity, Eq. 4 gives the relationship for fan noise variation due to a change of gross thrust, which evolves from the semi-empirical fan noise prediction method of Heidmann [6].

$$\Delta Lw_f = 20 \log \left( \frac{V'^2_{j,b} - V'^2_0}{V^2_{j,b} - V^2_0} \right) + 10 \log \left[ \frac{\left( \frac{\mu'}{1+\mu'} \right) \frac{F'_G}{V'_j}}{\left( \frac{\mu}{1+\mu} \right) \frac{F_G}{V_j}} \right] . \tag{4}$$

The airframe sound power level change due to a change of gross thrust derives from Fink airframe prediction method [7] and NASA ANOPP [4]. It is given by:

$$\Delta Lw_a = 10a \log \frac{G' V'_0}{G V_0} \,, \tag{5}$$

with $a$ taking the value 5 for wings and tails whereas 6 is assigned to flaps and landing gears. The expressions for geometric function $G$ are given in ANOPP [4].

### 3.3 Evaluation of total aircraft noise variation due to variation in individual sources

For any relative position of aircraft and observer, the SPL at an observer located at distance $R$ and direction $(\theta, \phi)$ from an aircraft consisting of $m$ noise sources with power $W_i$ and directivity $D_i(\theta, \phi)$ is obtained by:

$$\mathrm{SPL}(\theta, \phi, R) = 10 \log \left[ \sum_{i=1}^{m} \frac{W_i D_i(\theta, \phi)}{R^2} \right] + C \,. \tag{6}$$

In the equation above, $C$ is a constant related to the ambient conditions. It can be shown that with $m$ being the number of aircraft noise sources, the SPL change resulting from altering the acoustic power of $k$ sources by $\Delta W_i$ is expressed by the term:

$$\Delta \mathrm{SPL} = 10 \log \left[ 1 + \frac{\sum_{i=1}^{k} (\Delta W_i D_i)}{10^{(\mathrm{SPL}/10)} R^2} C \right] . \tag{7}$$

An equation is then derived to describe the sound exposure level change, $\Delta$SEL:

$$\Delta \mathrm{SEL} = 10 \log \left[ 1 + \frac{\sum_{i=1}^{n} \left[ \frac{C \Delta t}{R_i^2} \sum_{j=1}^{k} (\Delta W_j D_{j,i}) \right]}{10^{SEL/10}} \right] , \tag{8}$$

where SEL refers to the aircraft event before any acoustic power changes (i.e. is the base SEL), whereas $n$ is the number of discrete SPL points within the SEL and $\Delta t$ is the time step between them.

Equations 7 and 8 that give total aircraft changes require the noise source changes in terms of acoustic power (i.e. $\Delta W_i$). In contrast, the individual aircraft noise sources changes in Equations 3 and 4 are expressed in dB. Therefore, the level change $\Delta Lw_i$ in dB of each noise source $i$ (jet, fan, etc.) needs to be converted into change of acoustic power $\Delta W_i$ in Watts.

This is achieved by employing the base levels $Lw_i$ of the individual sources $i$ that are obtained through of the techniques presented in Section 3.1. Then, if $W_{ref}$ represents the reference acoustic power ($10^{-12}$ Watts), the change $\Delta W_i$ is given by:

$$\Delta W_i = W_{ref} \left[ 10^{(Lw_i + \Delta Lw_i)/10} - 10^{Lw_i/10} \right] . \tag{9}$$

### 3.4 Summary of inputs required by FANE

Table 1 summarises the necessary input parameters to FANE. Operational parameters are normally known, whereas engine design inputs are publicly available, either from manufacturers websites or from the EASA type certificates [10]. Base level NPDs are freely available in the ICAO ANP database [8]. Lastly, base levels of sources are obtained through the procedure described in Section 3.1.

The engine design parameters are essential in assessing (or estimating) variables in Eqs. 3, 4, 5, that give the sound power level changes of individual sources. Base levels then serve to transform these changes into noise variation of the whole aircraft, with Eqs. 7 and 8.

Table 1: List of inputs to FANE.

| **Engine design** | **Base levels** | **Operational** |
|---|---|---|
| Fan diameter | Base level NPD | Distance (Trajectory) |
| Rated thrust | Base source noise levels | Airspeed |
| Airflow at rated thrust | | |
| Bypass ratio | | |
| Max. low pressure rotor speed (N1,max) | | |
| Max. temperature at the combustor exit (Tt4,max) | | |

## 4. FANE example applications

For the purpose of illustrating FANE capabilities, this Section presents two example applications.

### 4.1 Estimation of individual noise source levels of existing aircraft

The purpose of assessing individual source base levels of existing aircraft is that it enables FANE to investigate the noise impact of technological modifications on existing aircraft, since all remaining inputs in Table 1 are already available. For instance, we can estimate the impact of directly varying the jet noise of an Airbus A320, by say, 5 dB, or indirectly as a result of varying, say, its engine BPR. The detailed procedure for estimating the levels of a small twin aircraft, namely the Airbus A320-232 during takeoff, is described below.

The procedure involves fitting of estimated NPD curves to the published ones. Hence, the process for estimating NPD curves is first outlined. In agreement with the philosophy of FANE, estimated NPD curves derive by adding level changes to a base NPD curve. Most conveniently, the base NPD curve is chosen to be the one representing the lowest thrust setting. Then, for a certain NPD distance, the $L_{A,max}$ NPD point corresponding to a higher thrust setting will be the sum between the level at the base NPD point and the aircraft SPL change obtained with Eq. 7. Regarding the SEL NPD curves change, this is obtained from Eq. 8 and is added to the base SEL NPD to yield the point associated with the higher thrust setting. This procedure is repeated for the remaining NPD distances.

In estimating individual noise source levels of the A320-232 we first use the (freely available) engine design variables listed in Table 1 to estimate parameters required by Eqs. 3, 4, 5. This yields the level change of each source at the different thrust settings associated with the respective NPD curves, which in our example, are the ones of the Airbus A320-232 at takeoff. The keypoint then, is to slightly vary the published average noise levels of NASA [9] for small twin aircraft, until the estimated (with FANE) NPD curves fit to the published ones. Ultimately, the varied source levels that produce the minimum deviation between estimated and published NPD curves can be regarded as the base source levels of the A320-232.

The left plot in Figure 2 compares the published with the fitted $L_{A,max}$ NPD curves for the Airbus A320 during takeoff. The continuous lines refer to the fitted NPD curves while the dashed lines describe the existing (published) data. The base NPD curves are the blue-coloured ones that represent the lowest thrust setting. Table 2 lists the resulting (due to fitting) estimated base source levels for the A320-232, along with the average noise levels published by NASA for small twin aircraft at takeoff certification conditions [9].

For illustrating capability of FANE in estimating the impact of modifications on existing aircraft, the right hand plot of Figure 2 shows estimated NPD curves (represented by the lines with a cross) for a modified (non-realistic) A320-232, termed hypothetical A320, that has engines with larger BPR. The base levels used were the estimated ones for the A320-232 in Table 2. Further parametric studies can be carried out (e.g. further increase BPR or manually vary individual source levels).

Table 2: Average noise levels (dB) for small twin aircraft at takeoff certification conditions and estimated base levels for the A320-232 and the B737-400.

| Aircraft | Fan Inlet | Fan Dis. | Core | Turbine | Jet | Airframe |
|---|---|---|---|---|---|---|
| Small twin (average) [9] | 73.3 | 80 | 75.3 | 40.8 | 81.8 | 77 |
| A320-232 | 73.02 | 80.57 | 73.89 | 40.47 | 80.57 | 74.77 |
| B737-400 | 76.58 | 89.32 | 80.75 | 42.76 | 85.32 | 80.44 |

Table 2 also lists the estimated base source levels for the B737-400, to highlight that it is the relationships between sources that we are interested in, not the absolute values. Both A320-232 and B737-400 are small twin aircraft, yet according to the NPD data in the ICAO ANP database [8], the latter is noticeably noisier (about 8 dB at takeoff). Hence its individual source levels tend to be higher.

### 4.2 Estimation of B737-800 NPD curves based on those of B737-400

To display the noise impact assessment of a technological change with FANE, for a non-hypothetical case, we estimate takeoff NPD curves of the Boeing 737-800 using as base aircraft its predecessor, the Boeing 737-400. The individual source levels for the base aircraft (the Boeing 737-400) are listed in Table 2; they derive through the same procedure as for the A320-232. The estimated curves (continuous lines) for the Boeing 737-800 are compared to the published ones (dashed lines) in Fig. 3. The base NPD curve, which is the one associated with the lowest thrust setting of the Boeing 737-400 is represented with the crossed orange line.

## 5. Discussion and potential uses of FANE

This paper demonstrated that base levels of individual aircraft noise sources can be accurately predicted with FANE, enabling fast noise parametric studies for existing aircraft, i.e. fast noise impact assessment of technological changes. This capability was displayed through two examples; first, by

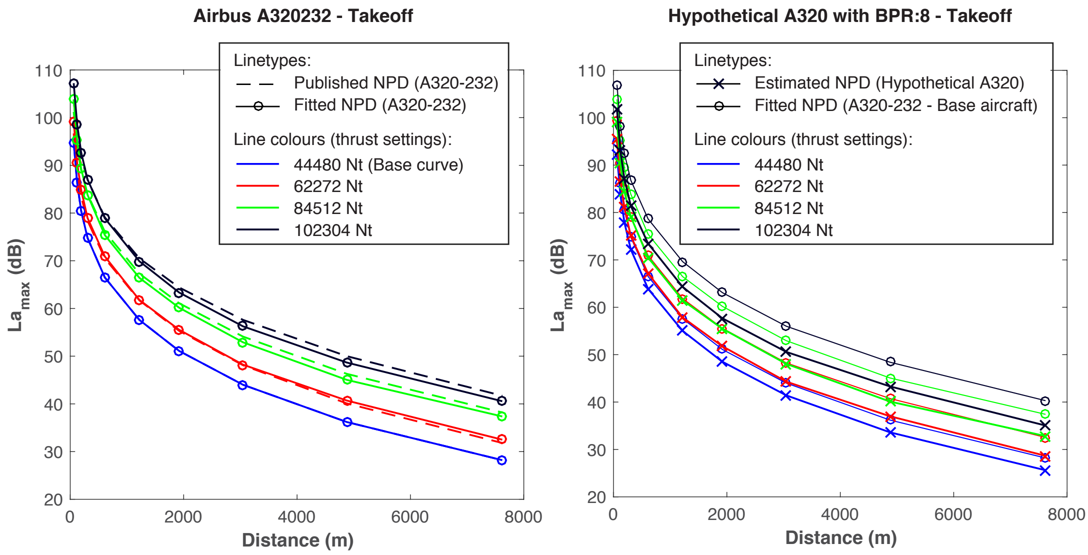


Figure 2: Comparison between published and fitted NPD curves for the Airbus A320 at takeoff (left) and estimated NPD curves for an hypothetical A320 that uses engines with BPR = 8 (right).

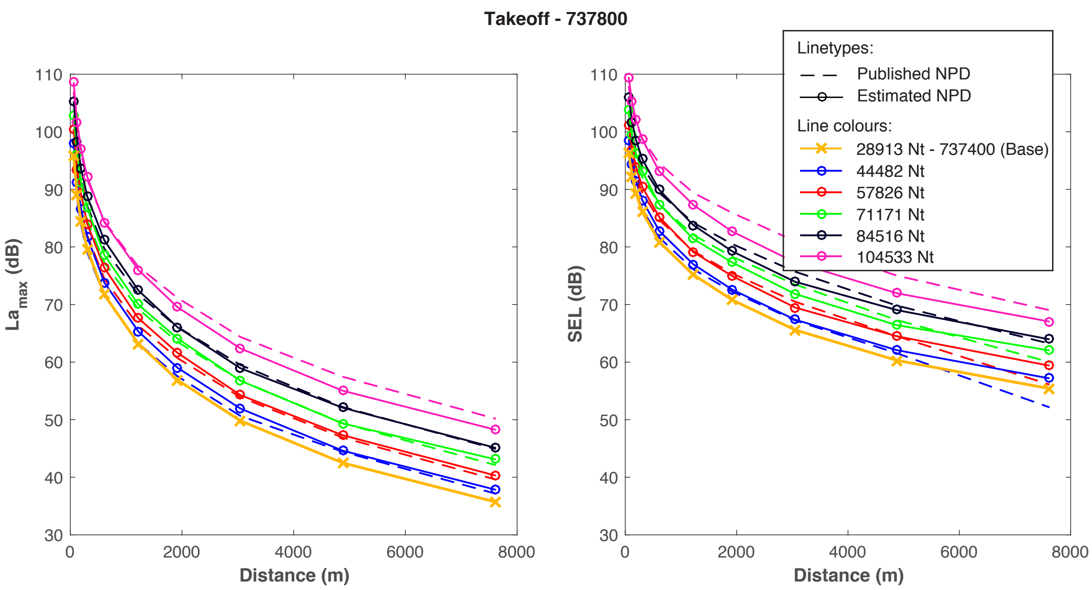


Figure 3: Comparison between estimated and published NPD curves for the B737-800 at takeoff. Base level NPD curve is the one representing the lowest thrust setting of the B737-400.

estimating the A320-232 individual source levels, which then enabled estimating NPD curves for an hypothetical, modified A320-232; and second, by estimating NPD curves of the B737-800 based on its predecessor, the Boeing 737-400.

Figure 2 corresponds to the first example; the right hand plot illustrates the predicted with FANE, noise reduction after increasing the engine BPR of an A320-232. Generally, increase in BPR reduces aircraft noise at takeoff [11], so the trend observed in Fig. 2 is the expected one. Yet, the amount of predicted level decrease is probably unrealistic, since the example is simplified, aiming at demonstrating FANE's capabilities on parametric studies. A realistic BPR increase would be normally associated with additional changes that would further influence the aircraft noise variation.

Figure 3 displays the good agreement achieved between estimated and published $L_{A,max}$ NPD curves for the B737-800. Regarding the SEL NPD curves, although error remains small, the agreement is somewhat worse, especially at the highest NPD distance (around 8000 m). This will be further investigated, but it must be noted that the published NPD curve has an odd steepness increase from distance 5000 m onwards.

At both examples, the curves associated with the highest thrust settings show the biggest deviation. This could be related to the fact that during NPD measurements aircraft need to maintain a standard airspeed of 160 knots. Doing so at high thrust settings possibly requires the (further) deployment of high-lift device, which ultimately increases the total noise. In which case, FANE predictions are underestimated as this possible change in high-lift device setting is omitted.

Moreover, Eq. 7 and 8 involve the source directivities $D_i$. At the current stage, FANE uses the directivity data included in NASA ANOPP [4], for all aircraft. Overall, this has not produced significant error in terms of NPD curves estimation. However, more accurate $D_i$ may be required in predictions related to operational changes.

Further capabilities of FANE include estimation of noise changes due to alterations on existing operations and optimisation of new aircraft designs. An example relevant to operational changes is the noise impact estimation of a steeper final approach. In that example, the base scenario would be the conventional approach whereas the changes would involve both piloting factors (e.g. change of thrust) as well as trajectory change. Regarding the optimisation of new aircraft designs, FANE could, for instance, investigate the optimum (in terms of noise) number of engines on an aircraft with a distributed propulsion system, provided that some base levels for a basic configuration are given.

## REFERENCES


1. UK Department for Transport (2013). *UK Aviation Forecasts 2013*. [Online.] available: `https://www.gov.uk/government/publications/uk-aviation-forecasts-2013`.

2. Synodinos, A. P., Self, R. H., Flindell I. and Torija, A. J. Estimating variation in community noise due to variation in aircraft operations, *Proceedings of the 10th European Congress and Exposition on Noise Control Engineering (EURONOISE)*, Maastricht, Netherlands, 31 May - 3 June, (2015).

3. Boeker, E. R., Dinges, E., He, B., Fleming, G., Roof, C. J., Gerbi, P. J., Rapoza, A. S., and Hemann, J. Technical Report FAA-AEE-08-01, Integrated Noise Model (INM) Version 7.0, (2008).

4. Zorumski, W. E. Technical Report NASA TM-83199, Parts 1 and 2, Aircraft Noise Prediction Program: Theoretical Manual, (1982).

5. Stone, J. R., Krejsa, E. A., Clark, B. J. and Berton, J. J. Technical Report NASA TM-215524, Jet Noise Modeling for Suppressed and Unsuppressed Aircraft in Simulated Flight, (2009).

6. Heidmann, M. F. Technical Report NASA TM-X- 71763, Interim Prediction Method for Fan and Compressor Source Noise, (1979).

7. Fink, M. R. Technical Report FAA- RD-77-29, Airframe Noise Prediction Method, (1977).

8. Eurocontrol Experimental Centre (2016). *The Aircraft Noise and Performance (ANP) Database*. [Online.] available: `http://www.aircraftnoisemodel.org`.

9. Kumasaka, H. A., Martinez, M. M. and Weir, D. S. Contractor Report NASA CR-198298, Definition of 1992 Technology Aircraft Noise Levels and the Methodology for Assessing Airplane Noise Impact of Component Noise Reduction Concepts, (1996).

10. European Aviation Safety Agency EASA (2016). *EASA Type Certificates (TCDS)*. [Online.] available: `https://www.easa.europa.eu/document-library/type-certificates`.

11. Zaporozhets, O. and Tokarev, V., *Aircraft Noise: Assessment, Prediction and Control*, Spon Press, (2011).