Estimation of Flight Phase Specific Jet Aircraft Parameters for Noise Simulations

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Recent aircraft noise calculation methods separate engine and airframe noise components to provide accurate single-flight noise predictions. General noise mapping, such as legal compliance calculations, usually relies on position data as the only available input. Therefore, more advanced input variables of engine and airframe noise models require estimation based on position data. We present a methodology to estimate aircraft's configuration and engine rotational speed for jet airliners from position data. The problem is split into a statistical evaluation of the aircraft's configuration, and a flight phase specific modelling of engine rotational speed. The modelling is validated using flight data recorder data, both as relative deviations of the estimation with respect to the reference and in terms of its acoustic impact on noise contours. The latter gave receiver level deviations of less than 0.2 dB for 85% and of less than 0.6 dB for 95% of the areas affected by departures, as well as of less than 1 dB for 95% of the areas affected by approaches. Major differences (above 0.6 dB) mostly occur in areas with low relevance for noise contours for scenarios. With a few modifications based on local procedures, the models are applicable to other airports.

I. Introduction

AIRCRAFT noise generation can broadly be separated into engine and airframe noise sources. For commercial jet aircraft, engine noise comprises engine jet and fan noise, whereas airframe noise comprises components from the fuselage, landing gears, high-lift elements and speedbrakes [1]. While engine noise is largely dominant for departures, airframe noise has a considerable share in the overall noise generated for approaches, as the engines are in idle conditions for most of the initial approach. Departing aircraft generally apply a thrust reduction in both initial and continuous climb phases—an accurate noise calculation for a single flight event considers this reduction. For approaches, the flap and landing gear schedule is of increased importance, as airframe noise components become dominant compared to engine noise components for large portions of the event [2]. Alternative approach procedures change the relative importance of either component, as the configuration schedule and the inferred thrust requirements vary [3].

Recently, sonAIR, an aircraft noise calculation model accounting for engine and airframe noise sources was

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developed [1] and has been transferred into a service tool [2]. Noise emissions are computed based on a set of input parameters capturing the physical characteristics of the noise sources. sonAIR considers the directivity, the engine power (through the proxy of engine rotational speed $N1$), the properties of aeroacoustic sources (through the Mach-Number Ma and the air density ρ), the aircraft configuration (through the landing gear, the flap handle and speedbrake positions) as well as interactions between these variables. Instead of engine power or engine thrust, sonAIR uses $N1$. For modelling, $N1$ can be determined acoustically in the absence of flight data recorder (FDR) data. Recently, it has been shown that acoustically determined $N1$ data improve results for best-practise aircraft noise calculation models, by taking account of the amount of thrust reduction for departures [4]. The use cases of sonAIR range from the development and optimization of low noise approach procedures to general noise mapping applications. As real world trials are extensive and costly, noise reduction measures are often investigated using simulations, . An exemplary comparison between continuous descent approach (CDA) and low-drag/low-power (LD/LP) approach procedures using sonAIR was shown in [1].

Whereas for procedural optimizations input parameters for the engine and airframe noise models are usually defined by the scenarios, general noise mapping applications rely on an estimate of these quantities. Often, only position data such as radar or Automatic Dependent Surveillance - Broadcast (ADS-B) data are available. Air traffic management (ATM) requires radar data to follow accuracy requirements. A study of uncertainties in aircraft noise calculations determined standard uncertainties of 133 m (436 ft) laterally and of 27 m (89 ft) vertically for radar data in Switzerland [5]. A study by the German Air Navigation Service Provider (ANSP) showed that ADS-B data are generally subject to smaller uncertainties than radar data, but present the challenge that the uncertainties are created by the on-board sensors of the aircraft rather than by an on-ground detection [6]. Thus ADS-B data quality varies between aircraft. In addition to position data, airports sometimes provide lists of movements containing additional flight information, such as aircraft and engine type, aircraft identifiers (e.g. registration numbers), destination or maximum and actual takeoff weights.

Reference documents for the calculation of aircraft noise, such as ECAC Doc 29 [7], ICAO Doc 9911 [8] or BADA [9], give some guidance on performance calculations in addition to basic engine and aerodynamic data. These tabulated values, however, are available for selected aircraft (i.e. combinations of aircraft and engine type) only, and the documents contain merely general advice on necessary modifications to account for realistic operational procedures, such as thrust reductions. Some previous efforts have gone into estimating engine thrust from position data [10, 11], but to the authors' knowledge, no robust method has been derived so far.

This contribution presents a methodology to estimate the engine rotational speed $N1$ and aircraft configuration from position data, based on training data. The estimation of the aircraft's configuration uses a statistical approach, while the estimation of $N1$ relies on a flight phase specific modelling approach. This allows for the application of $N1$ - and configuration-dependent noise calculation programs to general noise mapping calculations. Contrary to current best-practise programs, such as FLULA2 [12] or AEDT [13], operational measures that affect noise contours, such as departure thrust de-rates, are reproduced.

II. Methods

A. Statistical evaluation of aircraft configuration

An aircraft's configuration state, in terms of landing gear retraction or extraction and flaps retraction or extension, is defined by the configuration schedule and depends on the aircraft operator's procedures. To an external observer of the aircraft's trajectory, changes in flap extension and in thrust are not distinguishable. The identical trajectory is achievable by different combinations of flap deflection, thrust setting and angle of attack. The aircraft's equations of motion have no unique solution. In theory, a change in flap extension should be noticeable in the aircraft's acceleration profile. The aircraft's angle of attack, however, is a hidden variable. In addition, the position signal is subject to significant uncertainties, requiring smoothing in order to obtain usable derivatives. This leads to non-robust and often erroneous results if the configuration state of an aircraft is determined by means of observation of the position signal and its derivatives.

The configuration state is not arbitrary, but depends on fixed schedules and conscious decisions by the (auto)pilot. We assume that altitude over ground h and calibrated airspeed v_{CAS} are the major factors of influence for the configuration schedule. As local wind conditions are not readily available, airspeed is considered as proportional to $v_{GS} \cdot \sqrt{\sigma}$, where v_{GS} denotes the aircraft's ground speed and σ the temperature ratio between the local and the reference air temperature. Thus, the configuration estimate is formulated as a classification problem,

$$\{h, v_{GS} \cdot \sqrt{\sigma}\} \rightarrow \{\text{flap handle, landing gear}\} , \quad (1)$$

the flap handle and landing gear positions being predicted by the combination of h and $v_{GS} \cdot \sqrt{\sigma}$. The use of speedbrakes is not predictable in the same way. For the estimation of the landing gear position, a binary classifier is sufficient (two classes: landing gear extended or retracted), whereas the estimation of the flap handle position requires a multiclass classifier (e.g. five classes for an A320: approach flap handle positions 0,1,2,3,4), such as a series of binary classifiers.

B. Flight phase specific modelling of $N1$

We use flight phase specific modelling for the estimation of $N1$. Efforts to first calculate engine thrust from the equations of motion, then converting thrust to $N1$ proved to be unreliable and highly dependent on position data quality. Inputs such as aircraft mass, aircraft configuration, atmospheric and weather conditions, and position derivatives have to be estimated. Then, appropriate performance and aerodynamic coefficients, provided by available databases, for instance ANP [14] or BADA [9], are required. $N1$ is calculated from thrust using conversion parameters and equations, such as equation B-3 from ECAC Doc 29 Vol. 2 [7]. These databases contain a limited number of aircraft types (aircraft type – engine type combinations) and the availability of the coefficients varies between entries. Crucially, recent aircraft—B787 and A350, to name only two—usually lack conversion parameters. In addition, the conversion equation

is only valid for departures, as the quadratic $N1$ -dependency leads to non-physical thrust elevations for low $N1$.

Here, a more robust technique overcoming these challenges by a flight phase specific modelling of $N1$ is presented. Figure 1 shows a sample of departures and approaches of an A333 aircraft (A330-300 with TRENT772B engines), as well as the arrangement in flight phases for modelling (data provided by Swiss International Air Lines for Zurich and Geneva airports). Departures are divided into an initial climb phase at flexible takeoff power and a continuous climb phase at de-rated climb power with either departure flap settings or flaps fully retracted. Approaches are divided into initial and final approach phases. These flight segments are separated by transition phases. The criteria for separation chosen in our implementation are given in section II.B.6.

Fig. 1 Sample $N1$ profiles of A333 events and arrangement into flight phases.

For modern commercial jet aircraft, departures usually occur with reduced takeoff power, either using flexible or de-rated thrust. While the thrust reduction increases the fuel consumption, as the engines are most efficient at higher altitudes, the reduced engine maintenance costs have led to the adoption of this practise [15]. After an initial climb phase with takeoff thrust at constant speed, thrust is reduced to continuous climb thrust after the cutback altitude. The climb thrust generally does not correspond to the maximum available climb thrust either, but is de-rated as well. At this stage, two types of procedures are common [16], falling in the category of ICAO noise abatement departure procedures (NADP). The first is of the type ICAO NADP-1, and in a first phase uses the available thrust for maximum gain in altitude close to the airport, while speed is kept constant up to a some altitude. Thereafter thrust is used for both altitude and speed gain (at lower climb angle) until the required speed for climbing to cruise altitude is reached. The second is of the type ICAO NADP-2, and uses thrust for both gain in altitude and speed (at a lower climb angle than an NADP-1 profile), until the required speed for climbing to cruise altitude is reached. The data considered in this contribution stem from Zurich and Geneva airports. All departures are therefore of the type ICAO NADP-1, with a mandated cutback altitude in Switzerland of 457 m (1 500 ft) above ground level (AGL).

Ideally, the initial approach phase occurs with engines mostly in idle conditions. In practise, some thrust elevations

are needed, by ATM requirement to account for busy air traffic (speed restrictions, horizontal segments) or due to local wind conditions. As observed in Figure 1 (b), the thrust elevations can occur over the whole altitude range of the initial approach, but values overall cluster around the $N1$ range characteristic for engines in idle (around 30%). It is therefore assumed that, in most cases, large parts of the approach occur in idle, before thrust is increased in the final approach stage. In the final approach phase, the approach is stabilized and occurs at constant speed and under a fixed glide angle.

1. Flexible takeoff

If airspeed and climb angle are constant in the initial climb, aircraft thrust is a function of aircraft mass and climb behavior,

$$F = f(m \cdot \cos \bar{\gamma}, m \cdot \sin \bar{\gamma}) , \quad (2)$$

where F denotes the aircraft's thrust, m the aircraft's mass and $\bar{\gamma}$ the mean climb angle. Equation 2 is obtained by simplification of the general force balance equation B-20 from ECAC Doc 29 Vol. 2 [7] following the assumptions. Equation B-3 from ECAC Doc 29 Vol. 2 [7] links thrust to the engine rotational speed $N1$. For a given altitude, thrust is a quadratic function of $N1$ and has a linear dependency on temperature. The velocity-dependent term is usually small compared to all other terms. It is further assumed that the linear $N1$ term can be neglected, leading to

$$N1_{h=h_i}^2 \propto F_{h=h_i} , \quad (3)$$

and

$$N1_{h=h_i}^2 \propto T_{h=h_i} , \quad (4)$$

where $N1$ denotes the engine rotational speed, T the surrounding air temperature, and h_i a considered altitude slice. The pressure ratio δ and density ratio θ mostly correlate with altitude and are therefore neglected. As a temperature dependency is included, the atmospheric influence is still expected to be considered. The combination of equations 2, 3 and 4 yields the ansatz for the flexible thrust takeoff,

$$N1_{h=h_i}^2 = a_0 + a_1 \cdot m \cdot \cos \bar{\gamma} + a_2 \cdot m \cdot \sin \bar{\gamma} + a_3 \cdot T_{h=h_i} , \quad (5)$$

where a_i denote the linear regression coefficients obtained for given altitude levels. The regression is established for a number of discrete altitudes leading up to cutback altitude. An alternative equation can be built using ground roll S_{GR} and the basic balance of forces on ground. The liftoff thrust is given by $F_{LO} = m \cdot \frac{1}{2} \cdot \frac{v_{LO}^2}{S_{GR}}$, assuming that the liftoff

speed is proportional to the aircraft speed in the initial climb ($v_{LO} \propto v_{IC}$), leading to

$$N1_{h=h_i}^2 = a_0 + a_1 \cdot \frac{m^2}{s_{GR}} + a_2 \cdot T_{h=h_i} . \quad (6)$$

As ground roll is usually not trivial to determine, e.g. for long runways with multiple possible break-release points, with increasing uncertainty of position data close to the ground, equation 5 is preferred and has been found to provide better estimates overall.

Actual takeoff mass is often an unknown for aircraft noise modellers. Therefore, in addition to the mass-dependant model formulation in equation 5, a mass-independent formulation is established. Following the recommendations by ECAC Doc 29 Vol. 2 [7], the squared initial climb speed v_{IC}^2 is used as a proxy for the aircraft's mass. In this case, equation 5 translates to

$$N1_{h=h_i}^2 = a_0 + a_1 \cdot \overline{v_{GS,IC}^2 \cdot \sigma} \cdot \cos \bar{\gamma} + a_2 \cdot \overline{v_{GS,IC}^2 \cdot \sigma} \cdot \sin \bar{\gamma} + a_3 \cdot T_{h=h_i} , \quad (7)$$

where in the absence of wind data, the calibrated airspeed again equates to $v_{GS} \cdot \sqrt{\sigma}$ (c.f. section II.A). The temperature ratio σ cannot be neglected from this equation, as, while its instantaneous value mostly correlates with altitude, it is part of a term that considers an average value over an altitude range. The term $\bar{\sigma}$ does not depend on the current altitude slice h_i .

2. De-rated climb

For modern jet aircraft, climb thrust is generally de-rated, following the reasoning discussed in section II.B.1. Depending on the aircraft type, one or more de-rates are available [15]. For instance, the A320 aircraft (A320-200 with CFM56-5B engines) has one climb de-rate, while the A333 (A330-300 with TRENT7 engines) has two. These de-rates are visible as distinct and clearly separated clusters in the $N1$ profiles. Figure 2 shows $N1$ distributions for flight samples of A320 and A330 aircraft at $h = 3\,000\text{ m}$ (9 843 ft) above mean sea level (MSL). While $N1$ values cluster around a single value for the A320, two clusters are observed for the A333.

The variance inside the de-rate classes is due to air temperature differences (Figure 3). The triangular shape of the dependency reflects the limitations of engine performance with increasing temperature [15]. As outside temperature rises, the engines require elevated $N1$ levels to deliver the same amount of thrust. This increase is limited to prevent the turbines from overheating, causing $N1$ to fall off after this critical temperature. The ansatz for the de-rated climb thrust follows this temperature dependency and its characteristic shape. It is applied per de-rate class and per altitude slice,

$$N1_{h=h_i} = a \cdot |T_{h=h_i} - b| + c \quad \text{per class } k , \quad (8)$$

Fig. 2 $N1$ distributions at 3 000 m MSL. Only aircraft in clean configuration are shown.

Fig. 3 Variance inside the de-rate classes, explained by temperature variations.

where $T_{h=h_i}$ denotes the air temperature at altitude h_i , and a , b , c denote the fitting parameters. The fits are built separately for extended and retracted flaps. We consider two factors for the discrimination between de-rates for those aircraft types that have multiple de-rates: aircraft mass m and relative increase in energy $\Delta E/m$ through gain in altitude or in speed between two time points t_1 and t_2 ,

$$\Delta E/m = 0.5 \cdot (v_{GS,2}^2 - v_{GS,1}^2) + g \cdot (h_2 - h_1) . \quad (9)$$

For good classification performance, the time points cannot be too close in time (as differences in power add up over time leading to more clearly defined boundaries). We chose $t_1 = t(h = 1\,500 \text{ m AGL}) = t(h = 4\,922 \text{ ft AGL})$ and $t_2 = t_1 + 5 \text{ min}$. As the aircraft gains speed, drag forces increase, causing the balance $\Delta E/m$ to drop with rising airspeeds,

leading to a slight imbalance in equation 9 depending on whether energy is used for climb or for acceleration. Again, models are built once considering aircraft mass explicitly, and a second time considering v_{IC} as a proxy. The separation is done via linear binary classification, as shown exemplarily in Figure 4 for the two climb de-rates of the A333. The coloring of the plane is dictated by the classification results, whereas the coloring of the data points is determined manually as shown in Figure 3.

Tapering de-rates for washout to maximum climb thrust are not modelled. Multiple levels of tapered de-rate may be possible, e.g. options for slow and fast tapering [15]. Tapering occurs at altitudes that are not relevant for noise contours around airports, and can be neglected.

Fig. 4 Separation boundary for the A333 to discriminate climb de-rates achieved by linear classification.

3. Initial approach

The initial approach ideally occurs with engines mostly in idle. Local $N1$ elevations are often necessary, for instance due to ATM requirements, but are difficult to model (c.f. section II.B). The receiver areas affected by the initial approach segment are far from the airports, and local $N1$ variations have little influence on the noise contours. Therefore, a median $N1$ profile over altitude is sufficient,

$$N1_{h=h_i} = \text{median} (N1_j(h = h_i)) , \quad (10)$$

where the index j denotes the pool of available training events. The obtained median profile as a function of altitude is close to the $N1$ range for engines in idle conditions (c.f. section III.C.2).

4. Final approach

For the final approach, thrust is increased to stabilize the aircraft on a constant speed, constant angle glide path. The thrust increase occurs after the full configuration of the aircraft, generally by 305 m AGL (1 000 ft AGL) at the latest, as

recommended by the FAA for instrument approaches. The variations in $N1$ mostly depend on factors such as aircraft angle of attack and local wind conditions that are not easily observable from position data. Nonetheless, the range of $N1$ is bound by some boundary conditions: the aircraft is fully configured and on a constant speed glide path (i.e. in a narrow airspeed range), using a power setting corresponding to the aircraft's configuration. Again, a median $N1$ profile over altitude is considered sufficient, equalling to equation 10.

5. Model implementation

As discussed in section II.B, flights are segmented into flight phases. For modelling, tight limits, i.e. large transition phases between segments, are set, such that only segment specific data are contained in the respective models. The limits would need adjustment if models were built with data from different airports, i.e. if cutback altitudes differ or the procedures vary. In the initial climb, data are considered between 100 m AGL (328 ft AGL) and 400 m AGL (1 312 ft AGL). In the continuous climb with takeoff flap configuration, data are considered between 700 m AGL (2 297 ft AGL) and 1 000 m AGL (3 281 ft AGL), whereas in the continuous climb with clean configuration, data are considered above 1 000 m AGL (3 281 ft AGL). The initial approach segment contains the data where the aircraft is not yet fully configured, whereas the final approach contains data below the stabilization altitude of 305 m AGL (1 000 ft AGL). Some flights have to be qualified as outliers and excluded for modelling. Examples are flights containing unaccelerated horizontal flight segments during the climb phase, with an associated drop in $N1$, or flights that switch de-rates, e.g. going from de-rate 2 to de-rate 1.

The model expressions (equations 5, 7, 8 and 10) are formulated as regressions for specific altitude levels. For pre-processing, the data are sampled as a function of altitude using a sampling distance of 10 m (33 ft) in an altitude range of $h \in [0; 5\,000 \text{ m AGL}]$ ($h \in [0; 16\,404 \text{ ft AGL}]$). After the fitting parameters are determined (as a function of discrete altitude levels), they are stored in a vector and smoothed using linear fits as a function of altitude. The sampling rate is defined by the altitude step. In addition to the model parameters (equations 5, 7 and 8), maximum and minimum values of $N1$ (as a function of altitude, too) are retained.

6. Practical notes and handling of transition segments

The application of the models in practise, i.e. the estimation of configuration and engine rotational speed from position data, requires a segmentation of individual flights into flight phases. In the initial climb, data are considered below 430 m AGL (1 411 ft AGL). The cutback is required to occur at 457 m AGL (1 500 ft AGL) in Switzerland. In the continuous climb with flaps extended or retracted, data are considered above 600 m AGL (1 969 ft AGL). The initial approach is the segment, where the aircraft is not yet fully configured, whereas the final approach is the flight segment below the stabilization altitude of 305 m AGL (1 000 ft AGL). Transition segments are introduced in-between the regular flight phases by interpolation, generating smooth and continuous transitions over time (c.f. exemplary data

in section III.C.2). Here, the data are resampled and interpolated over the altitude using a sampling distance of 10 m (33 ft) in an altitude range of $h \in [0; 5\,000 \text{ m AGL}]$ ($h \in [0; 16\,404 \text{ ft AGL}]$). As parameters are estimated, it is verified that the maximum and minimum values for $N1$ are satisfied. If values fall outside these bounds, they are corrected to the minimum or maximum value. It is assumed that outliers, e.g. flights not adhering to the standard procedures or based on erroneous position data, are considered well enough through this minimum and maximum value check, and that no data need to be filtered out.

III. Results and validation

We show exemplary model implementations, resulting model fits and validation results for two aircraft types, the narrow-body A320 (A320-200 with CFM56-5B engines) and the wide-body A333 (A330-300 with TRENT7 engines).

A. Input dataset

FDR data were provided by Swiss International Air Lines. The data were not randomly selected but such as to contain extreme value combinations for aircraft weight and atmospheric conditions. Flight events are available for both Zurich (ZRH) and Geneva (GVA) airports, for a selection of air routes, i.e. for different runways in terms of length and operational concept. Table 1 contains the available flights by aircraft type, amounting to about 300 flights per aircraft type, 150 flights each for departures and approaches. Individual flights are 800 s long, and contain variables such as $N1$, aircraft configuration state, atmospheric and wind conditions, and aircraft orientation.

Table 1 Number of events with FDR data for modelling and validation.

Type	Departure		Approach	
	GVA	ZRH	GVA	ZRH
A320	60	84	59	87
A333	58	85	59	87

A validation requires independent modelling and validation datasets. Each of the following sections detail the respective split of the dataset into modelling and validation datasets.

B. Statistical evaluation of aircraft configuration

For the classification of aircraft configuration, classifiers are built separately per aircraft type and procedure. The multiclass classification is implemented using error-correcting output codes models (ECOC) using support vector machine (SVM) binary learners. The entire dataset is provided as input, with 10-fold cross-correlation predicting the model accuracy. The classification yields the generalized classification errors given in Table 2.

For departures, the classification error is small for both the estimation of the landing gear (less than 0.25%) and flap handle position (less than 2.5%). For approaches, the landing gear position is associated with a low error (less

Table 2 Generalized classification error for configuration estimation.

Type	Departure		Approach	
	flap handle	landing gear	flap handle	landing gear
A320	2.49%	0.09%	16.25%	3.65%
A333	2.39%	0.21%	15.35%	4.37%

than 4.5%), while there is a considerable error in the flap handle estimation (up to 16.25%). The latter is likely due to the fact that intermediate flap handle positions do not deviate much from each other, and can thus be used at similar flight conditions. An investigation into the misclassifications confirmed that mislabellings mainly occurred for the flap handle position pairs 0/1 and 2/3. Figure 5 shows the decision boundaries for the A320 as obtained by the classifier. For departures, the flap schedule mainly depends on speed, while landing gear position mostly depends on altitude, whereas for approaches, configuration changes occur based on a combination of altitude and airspeed, reflecting a variation in the configuration schedules.

Fig. 5 Decision boundaries and predicted classes for the configuration classification of an A320 aircraft.

Table 3 Mean R^2 for model fits.

Type	Initial climb		Continuous climb flap handle 2		Continuous climb flap handle 0	
	w/ m	w/o m	CLB1	CLB2	CLB1	CLB2
A320	0.81	0.73	0.95	—	0.95	—
A333	0.69	0.66	0.72	0.92	0.87	0.93

The acoustic influence of errors of misclassifications is assessed by the following reasoning: considering configuration through a statistical evaluation as a function of altitude and airspeed is equivalent to establishing emission models that do not consider configuration explicitly, but contain variables dependent on altitude and airspeed (such as the air density ρ and the Mach number Ma). It has been shown that these models work similarly well as models considering configuration explicitly for noise calculations [2]. Therefore, it is assumed that the acoustic impact of the misclassifications given by Table 2 is also minor, at least for the application at ZRH and GVA airports.

Aircraft configuration is determined by a statistical evaluation. Only aircraft operations corresponding to the specific schedules contained in the modelling dataset (i.e. reflecting the operation of Swiss for ZRH and GVA airports) can be estimated (c.f. section IV). In practise, for instance, the predicted departure flap schedule is only correctly estimated for ICAO NADP-1 airports.

C. Flight phase specific modelling of N1

The FDR dataset is separated into modelling and validation datasets. Thus, the validation data are independent of the modelling data. In this validation, only the quality of the $N1$ estimation is assessed. All other variables, for instance atmospheric conditions and configuration, are considered as given. The labels w/ m and w/o m used in a number of the subsequent tables and figures, indicate whether aircraft mass has been considered as input. The labels CLB1 and CLB2 denote de-rated climb classes.

1. Model validation

Two thirds of the data are used for modelling, one third for validation. Events are randomly assigned to either dataset.

The model fits for the initial and continuous climb phases are evaluated in terms of mean R^2 values (Table 3). The mean R^2 values are computed as the mean over all discrete altitude fits (c.f. section II.B.5). The initial climb mostly provides good fits (with R^2 over 0.65), whereas the explanatory value of the models is excellent for the continuous climb (with R^2 over 0.7 and up to 0.95). The quality of the fits without knowledge of aircraft takeoff mass is close to that of the fits using a direct input of aircraft mass, with slightly improved R^2 if aircraft takeoff mass is available. The model for the A333 underperforms that for the A320 in all flight phases.

Validation yields the boxplots shown in Figure 6. The values contained are the mean relative deviations over the

respective flight segment per flight. In other words, one data point in the boxplot is the mean relative deviation between the reference and the estimated $N1$ over the entire segment for a single flight. For the initial climb, relative deviations of up to 5% can occur, with most deviations being under 2%. For the continuous climb segment, deviations are smaller, with less than 1% relative differences. In the initial and final approach segments, the relative deviations can be as large as 20%. $N1$ is typically three to four times larger in the departure segments compared to approach segments – therefore the absolute deviations cannot be directly compared between flight phases. Furthermore, the acoustic impact of the deviations is of varying importance. Differences in $N1$ for approaches impact noise contours less than those for departures, as departures are dominated by engine noise, whereas approaches contain major airframe noise contributions. In addition, the shape and extend of noise contours are generally defined by the far field of departures. Therefore, a good estimate in this area (i.e. continuous climb) promises good estimates of noise contours (cf. section III.C.2).

As the events in the dataset were specifically chosen such as to contain extreme events, we expect that a random flight event would yield values inclining towards mean values, and perform better on average than the validation events presented here. In that regard, the present validation corresponds to a worst-case scenario in terms of flight event selection.

2. Acoustic validation

For noise calculations, the exposure level at selected receiver points is the value of interest. A validation should therefore consider the acoustic impact of relative deviations in the $N1$ estimate. Errors in the $N1$ estimation are only relevant, if the resulting noise levels and contours are affected. The acoustic validation helps to link the scale of the observed deviations in the $N1$ estimation to their acoustic impact.

We use the service application of sonAIR [2] for the noise calculations. The dataset is split such that per aircraft type, one departure and one approach route for ZRH are singled out as validation data. All other data are used to build the models. The models used for this acoustic validation are thus different from the ones built in section III.C.1, as the split between modeling and validation data differs. The routes used as validation data are designated as F16 (departure on runway 16 in ZRH) and Q34 (approach to runway 34 in ZRH). The modelling dataset contains all other departure and approach routes from GVA and ZRH (including other departures from runway 16, although on a different route, and no approaches to runway 34), but no flights from routes F16 or Q34 in ZRH. Thus, the validation gives a measure of the predicting quality for routes unknown to the model. The simulation is repeated for three scenarios. First, a reference simulation with full FDR data, second, a simulation with estimated $N1$ using aircraft takeoff mass, and third, a simulation with $N1$ estimation without aircraft takeoff mass. The estimation of $N1$ is based on trajectories from FDR data (position and atmospheric data).

Figure 7 contains the results of the $N1$ estimation. For departures, both the models considering takeoff mass explicitly and the models without takeoff mass capture the variation in the initial climb adequately. Extreme cases

(a) Departure

(b) Approach

Fig. 6 Relative $N1$ deviations between estimated and reference values for A320 and A333 aircraft, boxplots per flight segment.

however, are sometimes under- or overpredicted (mostly the very high and very low power A333 departures). For the continuous climb, the variation in $N1$ due to temperature is nicely captured, and the de-rates for the A333 are perfectly estimated. This particular set of A333 departures contains only flights in the lower de-rate for most of the continuous climb segment, likely due to the destinations served using route F16, combined with the ample runway length of runway 16 (3 700 m = 12 139 ft). Outlier events, such as flights where the de-rate is changed mid-flight or where an unaccelerated horizontal segment in the climb leads to a drop in $N1$ are not captured. For approaches, the assumption of an initial approach mostly in idle leads to large local underestimations for single events. The final approach segment shows considerable variation, too. The transition segments lead to smooth transition between flight phases, that overall reproduce the original data well. For instance, observing the transitions between initial climb and continuous climb with flaps 2, as well as the transition between continuous climb with flaps 0 to continuous climb in clean configuration, the variation in time (local curve slope) is well captured. The transition segment between the initial and final approach phases shows more variation when compared to departures, but produces transitions that are

appropriate for the considerable variation in the real $N1$ data. The majority of the transition segments in this area feature slopes that are very comparable to the underlying data. This indicates that the delimitations of the segments and the interpolation of the transitions is appropriate. As this dataset was explicitly chosen such as to contain extremes, a bundle of random flights is expected to give better performance than the validation flights shown here.

Fig. 7 Reference (red) and estimated (blue) $N1$ of the validation events.

The noise simulation uses a digital terrain model with a sampling of $25 \text{ m} \times 25 \text{ m}$ ($82 \text{ ft} \times 82 \text{ ft}$) assuming grass as land cover. Results are calculated on a $150 \text{ m} \times 150 \text{ m}$ ($492 \text{ ft} \times 492 \text{ ft}$) grid. The simulated flights are combined into average A-weighted exposure level $\bar{L}_{AE}$ footprints [5],

$$\bar{L}_{AE} = 10 \log \left(\frac{1}{m} \sum_{i=1}^m 10^{0.1 L_{AE,i}} \right), \quad (11)$$

where $L_{AE,i}$ denotes the L_{AE} of flight i for a total number of m flights on the specific route. Figure 8 shows the generated

footprint noise contours as well as footprint differences between the estimated and reference simulations. The flight tracks are shown in pink coloring, noise contours are shown in gray coloring (dashed lines for reference and solid lines for estimation) in the range between 60 dB and 130 dB, spaced in 5 dB intervals. Footprint differences are categorized into seven classes: under -1 dB, between -1 dB and -0.6 dB, between -0.6 dB and -0.2 dB, between -0.2 dB and 0.2 dB, between 0.2 dB and 0.6 dB, between 0.6 dB and 1 dB, and above 1 dB. Footprint differences outside the 60 dB contour are omitted. The noise contours for the calculation with FDR data (dashed gray lines) are mostly covered by the contours for the calculation with the estimated parameters (solid gray lines), and are therefore hardly visible for most of the images.

Fig. 8 Comparison of computed $\bar{L}_{AE}$ footprints between reference and estimation noise calculations of the validation events.

For departures (Figure 8 (1a), (1b), (2a), (2b)), the areas close to the airport are subject to local differences larger than 0.2 dB, due to the over- or underestimation of extreme events (c.f. Figure 7) in the initial climb. For instance, the estimation for the A333 with takeoff mass (Figure 7 (2a)) fails to capture a number of high power events at the top of the scale, which is reflected to the slight underestimation of levels (of up to 0.6 dB) in the near field of the airport. On the other hand, the estimation for the A333 without takeoff mass (Figure 7 (2b)) fails to capture a number of low

power events at the bottom of the scale, which is reflected to the slight overestimation of levels (of up to 0.6 dB) in the near field of the airport. The far field (after cutback) shows little differences, with most areas in the -0.2 dB to 0.2 dB class. The overestimation of levels (of up to 0.6 dB) at a ground distance of around 15 km (9.3 mi) from the airport is likely due to the events featuring a drop in $N1$ during the continuous climb (due to phases of unaccelerated horizontal flight). The latter are expected to be of lower altitude than the average flight. When they are assigned a regular (non-dropping) $N1$ value, the affected regions are overestimated. The area behind the runway, at the back side of the aircraft, is overestimated (by over 1 dB) because the takeoff phase on the runway is not modelled, but irrelevant for noise calculations. Flights serving the runway's other direction (in this case, departures on runway 34) will mask this effect.

For approaches (Figure 8 (1c), (2c)), the areas close to the airport (final approach) show little deviations (mostly less than 0.2 dB, with a few areas with up to 0.6 dB in deviations) in the footprints. Again, the area at the end of the runway is overestimated, but irrelevant for noise contours in a scenario. As exposure levels contain multiple air routes, the differences are masked. In the far field, larger differences of up to 1 dB are observed, due to the modelling assumption of an initial approach in idle. Nonetheless, these deviations occur at distances larger than 30 km (18.6 mi) from the airport, and do not impact noise contours of scenarios, as they are below relevant exposure levels.

Noise contours are disproportionally influenced by certain flight phases. The shape of the noise contours in the far-field are mostly influenced by the continuous climb. The near-field of the airport is dominated by the initial climb. Approaches play a lesser role if they geographically overlap with departures, but can be significant in areas exposed to approaches mainly. Then, mostly the final approach segment is of relevance for the noise contours.

The visual observations are confirmed in Table 4 by an evaluation of the relative frequency of which areas (inside the 60 dB contour) are part of the receiver level classes. Departures have 85% of the areas with less than 0.2 dB and 95% with less than 0.6 dB deviations. The remaining 5% mostly concern areas right next to the runway, irrelevant for scenario noise contours. No significant differences can be observed between estimations using the aircraft's actual takeoff mass and estimations without this information. Approaches have 95% of the areas with less than 1 dB deviations. It is interesting to note that the underestimation of approaches in the initial approach phase is more pronounced for the A320 than for the A333. For these approaches to Q34, the A333 generally manages to implement the approach with engines in idle more closely and frequently than the A320. This could be due to the fact that approaches of wide-body aircraft to runway 34 in Zurich mostly occur during the first hour of day-time operations (06 – 07 h), while the narrow-body aircraft are more evenly spread across the day. Most of the larger deviations (above 0.2 dB) occur right next to the runway, or at distances of over 30 km (18.6 mi) from the airport, and, again, are deemed irrelevant for scenario noise contours.

Table 4 Statistics of sound exposure level differences (relative frequencies of which areas are part of receiver level difference classes), for levels above 60 dB.

Level classes [dB]	A320	A320	A320	A333	A333	A333
	F16 (w/ <i>m</i>)	F16 (w/o <i>m</i>)	Q34	F16 (w/ <i>m</i>)	F16 (w/o <i>m</i>)	Q34
< -1	0%	0%	5%	0%	0%	0%
[-1; -0.6[	0%	0%	21%	0%	0%	0%
[-0.6; -0.2[	0%	6%	33%	10%	0%	13%
[-0.2; 0.2[	86%	84%	35%	84%	85%	85%
[0.2; 0.6[	13%	10%	5%	5%	11%	1%
[0.6; 1[	1%	0%	0%	1%	1%	0%
≥ 1	0%	0%	0%	1%	3%	0%

IV. Discussion

A. Summary

Estimating the aircraft configuration and engine rotational speed on a flight-by-flight basis allows to represent the operational conditions accurately for noise calculations, and to apply recent aircraft noise calculation programs, such as sonAIR [2], to general noise mapping applications. Current best practise programs, such as FLULA2 [12] or AEDT [13] do not account for configuration and thrust variations for single flight events. Starting from version 3b, AEDT allows users to specify engine de-rates, but provides no methodology for determining the amount of de-rate, nor does it recommend the use of the data for standard calculations. Contrary to complex aircraft noise calculations such as ANOPP [17], SIMUL [18] or PANAM [19], *N1*- and configuration-dependent noise calculation models can be used based on position data alone, using the estimation methods presented here, and can be applied for general noise mapping applications. Validation showed good agreement of our estimations compared to reference FDR data, with little deviations in sound event levels at receiver areas relevant for noise contours. Our method allows the consideration of important operational variables, such as thrust reductions, for accurate noise mappings, even if only position data are available.

B. Limitations

Some considerations about the generality of the presented methods are appropriate. The estimation of configuration through statistical evaluation leads to the mapping of local procedures. Therefore, the application to airports and airlines using different departure procedures (e.g. departures of type ICAO NADP-2 instead of ICAO NADP-1) will yield erroneous configuration schedule estimates. Similarly, alternative approach procedures (e.g. LD/LP instead of CDA) change the flap schedule and would need separate modelling and further insights about the operations. In this case, the applicability of the models to other airports and airlines than those with similar procedures is restricted. The modelling of *N1*, on the other hand, is not procedure-dependent, and can be applied at other airports and for any airline. For

instance, the determination of the de-rate considers both gain in energy through acceleration and through altitude. We assume that the cutback altitude can be determined. In general, the cutback altitude can be left open to operators, often between 244 m AGL (800 ft AGL) and 457 m AGL (1 500 ft AGL). For high-precision position data, the cutback is visible in the altitude profile as a dent. For low-precision data, it could be necessary to estimate the cutback altitude statistically. For approaches, $N1$ is considered as a median in both the initial and final approach stages. The final approach stage is expected to be unaltered with alternative approach strategies, whereas a steeper or continuous descent might require further thrust corrections to $N1$. As long as the initial approach mostly occurs in idle, the models should be applicable to other scenarios. To summarize, in order to apply the model at different airports, special care needs to be taken with respect to the configuration schedule. The latter should be determined for the largest carrier of each aircraft type at the respective airport. The estimation of $N1$ is expected to be robust with respect to other procedures and to be able to consider the inferred changes.

In this contribution, the implementation and validation was presented for two aircraft types, the narrow-body A320 (with CFM56-5B engines) and the wide-body A333 (with TRENT7 engines). For the application to a full scenario, it is not sufficient to model only two aircraft types. Flight events at the airport in question can be condensed down to a list of acoustically relevant aircraft types. In order to successfully estimate flight parameters for each of these aircraft types a corresponding model must exist. Aircraft with different engine options need to be modelled separately for each engine type. Another consideration is the quality of the models. High-quality models consider a generous amount of diverse events featuring a number of variations in the input parameters, e.g. variations in temperature or in take-off mass. Capturing a large number of diverse events is mostly a challenge for models based on acoustically determined $N1$ data. If an aircraft type is used by one operator only, on a limited number of destinations, a low number of flights are recorded, and there tends to be less variation in the flight parameters.

C. Outlook

In the present validation, atmospheric conditions were accepted as given, and wind implicitly included in the models. As temperature actually is an important influence parameter for most of the estimations for the departure $N1$ estimation, the influence of calculations using available data sources or international standard atmosphere should be looked into in a future study.

Ideally, the parameter estimation of configuration and $N1$ can be build in synergy with the emission models. Users of these emission models should be provided with a corresponding parameter estimation. The presented methodology was exemplarily demonstrated using A320 and A333 aircraft, for which FDR data were provided for modelling. FDR data, however, can be hard to get access to. In practise, $N1$ -dependent emission models can be created using acoustic $N1$ determination [1, 20]. In this case, the models generally have a slightly reduced accuracy, as the determination of $N1$ in itself is subject to uncertainties and aircraft configuration is not available. Nonetheless, it has been shown

that these models work well in practise [2]. The methods for $N1$ estimation shown in this contribution are applicable to these models too. As a main challenge, training data are not continuous over larger altitude ranges, but restricted to areas in the vicinity of the acoustic measurements. Thus, the modelling parameters need considerable inter- and extrapolation. Configuration data are usually missing. The modelling in itself then needs some modifications. For approaches, the moment where the aircraft reaches full configuration needs to be estimated, e.g. under the assumption that it occurs at some altitude or velocity, based on information of a similar aircraft type or by an informed engineering guess. For departures, the cutback altitude (if not prescribed by officials) and the change in flap handle position must be determined similarly. Previous efforts for flight phase detection can be found in the literature [21, 22] and could serve as a starting point for further work.

V. Conclusion

We presented a methodology to estimate flight phase specific jet aircraft parameters from position data using training data. The aircraft configuration state is determined using a statistical evaluation over altitude and airspeed data. The engine rotational speed is determined through a flight phase specific modelling approach. This allows the use of configuration and $N1$ -dependent emission models for general noise calculations, where only position data are provided as input.

Our method is robust, does not require high quality input data, e.g. no second derivatives of the position signals are needed, and contains upper and lower bounds for dealing with outlier events. Models performed equally well for situations with unknown aircraft weight. Our methodology is applicable to situations where only acoustically determined $N1$ data are available and is expected to give similar results to the ones shown in this paper.

Validation for a narrow- and a wide-body aircraft showed standard classification errors for the configuration estimation of up to 2.5% for the flap handle position for departures, up to 0.25% for the landing gear position for departures, up to 16.25% for the flap handle position for approaches, and up to 4.5% for the landing gear position for departures. Relative deviations in $N1$ were up to 5% for the initial climb (both for cases with and without information about aircraft mass), up to 1% for the continuous climb and up to 20% for both initial and final approach. The acoustic impact of these deviations was assessed. 85% of the areas affected by departures had receiver level deviations of less than 0.2 dB; 95% of the areas affected by departures had receiver level deviations of less than 0.6 dB. 95% of the areas affected by approaches had receiver level deviations of less than 1 dB. Most of the areas affected by deviations above 0.2 dB are situated either at large distances from the airport or in immediate vicinity of the runway, where the differences are insignificant for relevant noise exposure levels.

Acknowledgments

This research was funded by the Swiss Federal Office of Civil Aviation. We would like to thank Swiss International Air Lines for providing the modelling and validation data.

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