Challenges in Aircraft Noise Prediction

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Abstract

This contribution addresses the problem of aircraft noise prediction using theoretical methods. The problem is set in context with the needs at several levels to produce noise characterisation from commercial aircraft powered by gas turbine engines. We describe very briefly the computational model (whilst referring the reader to the appropriate literature), and provide examples of noise predictions and comparisons with measured data, where possible. We focus on the issue of stochastic analysis, which is required when the models rely on inaccurate, uncertain or unknown data. Examples are shown for the turboprop Bombardier Q400 and the Boeing B737-800. The paper finally addresses the challenges facing the development of accurate methods, their use in predicting existing and future aircraft noise. Calculations are shown with the author's own FLIGHT computer program.

Introduction

In recent years, some progress has been achieved in aircraft noise reduction, thanks to a holistic approach that involves improved design at the system level. There is also some limited progress in operational practices, although many new procedures offering noise reduction have been not implemented. At the heart of the problem there is issue of community noise, which remains somewhat volatile: it depends on several factors, including the frequency of movements, the atmospheric conditions and the time of the day. For this purpose, a number of noise metrics have been developed and standardised. These noise metrics are in most cases in integral form and are meant to assign a "noise value" to an airplane trajectory which may last a few minutes. The central problem of this contribution is to address theoretical methods that can be used to predict these metrics, and hence to provide a noise prediction over the complete trajectory. One such method, once properly verified, can be used for a variety of applications, from design to the optimisation of flight trajectories of existing airplanes, to the management of noise zones at major airports. This contribution will highlight the challenges in reaching these goals.

The state-of-the-art in aircraft noise prediction is represented by a number of computer programs that use a variety of measurements (databases) and empirical correlations. These programs are routinely used by airports to carry out basic noise prediction. They include INM [1], developed in the USA, ANCON, developed in the UK [2], and a number of other computer programs used at a national level in Europe [3] and elsewhere. These programs good predictive capability if the operation point falls within the matrix of the database. None of these models have engineering capabilities, and none of them is able to discern between the different sources of noise. By contrast, theoretical methods have been lagging behind, due to the complexities in modelling the full aircraft system, its external environment and the presence of several unknown parameters. The first attempt at this theoretical modelling was done with the computer model ANOPP, which has evolved over a long period of time [4]. In recent years efforts have been devoted by other research groups, who have been able to demonstrate some advances in this field [5].

As often in science and technology, challenges are moving targets; some of them only appear so on closer inspection of results. In this context, we need to consider the availability

of reliable noise measurements. These measurements have to be done in the field, and often offer little quality control. For example, noise measurements are routinely done at community microphones at several airfields around the world, and include secondary effects as background noise, and masking effects from other ground noise. There are very few controlled noise data available in the published literature, as these are costly and often proprietary. All these measurements have to be synchronised with an airplane trajectory, and with several flight parameters. Most databases, as cited, only allow for measurements of position and airspeed gathered from radars; these are

proved to be inaccurate, or not accurate enough to be considered reliable in a theoretical prediction model. Better results are generally obtained by processing the flight records of the FDR (Flight Data Recorder). Aside from the difficulty of obtaining these data from airline operators, when the data do become available, they show other sorts of approximations, such as airplane positions uncertain by as much as two wing spans. One such example is shown in Figure 1 which refers to an arrival trajectory of a Bombardier Dash8-Q400 (Q400). This result is not unusual, and has been verified on other airplanes at different airfields.
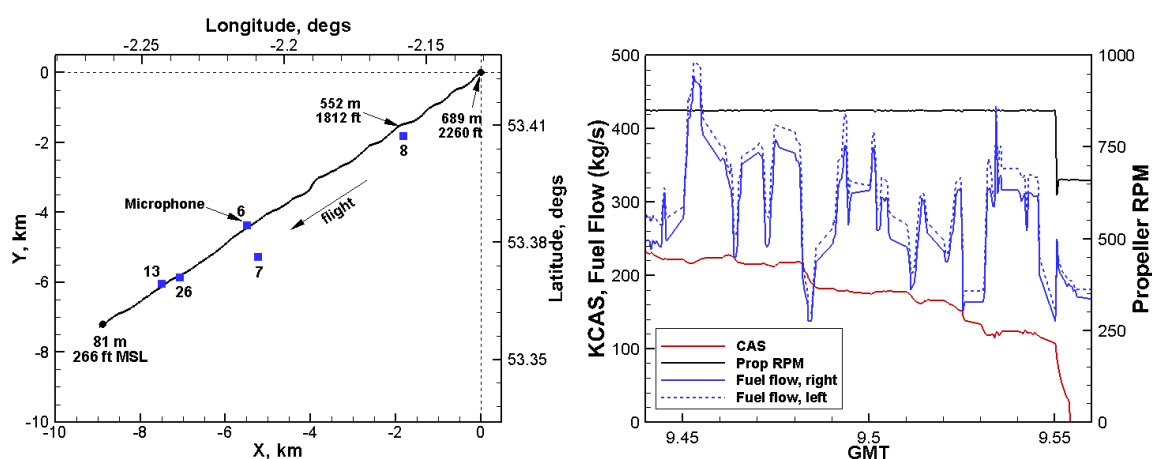

Figure 1: ground track of a Q400 turboprop airplane on arrival (left); selected FDR parameters used in the noise simulation program.

In addition to the flight parameters needed to completely identity the aircraft state and position, there is a need to provide realistic data for the atmospheric conditions which cause considerable changes in the noise signals over the long distance that separates the airplane from the noise receiver (up to several km). Furthermore, ground properties are important in assessing the role of the noise reflection, absorption, refraction from solid boundaries, complex terrain, especially when we deal with grazing flow.

Aircraft Noise Model

The computer model developed for the prediction aircraft noise is briefly discussed in this section. The reader is invited to refer to

the published literature where several features of this model have been documented, for example [6-11]. In these references, additional literature is cited with regards to numerical methods developed and applied. In short, this is a comprehensive model that contains sub-modules for the reconstruction of the aircraft geometry (including gas turbine engines, propellers, if any), for the estimation of masses, inertias, centres of gravity; for the flight mechanics and thermo-structural performance; for the environmental emissions (carbon-dioxide and other combustion by-products); for the flight optimisation (minimum fuel over a specified trajectory; minimum noise on a constrained trajectory), and several other features. The aircraft noise model is built on top of this

software cornerstone. The aircraft noise is split into the determination of the noise sources, and their propagation. The noise sources are associated to the airframe (non propulsive) and to the power plants (gas turbine engines, propellers, auxiliary power units). There is consideration of basic interference effects, such as jet-by-jet shielding, fuselage shielding of engine-propeller noise, and wing shielding of engine noise for the out-of-sight noise sources. The noise signals are collected into a large array of raw sound pressure level $L = L(t, c, f)$, where t is the flight time, c is the noise source component and f is the acoustic frequency in the 1/3 octave band. This raw pressure level is then parsed by the noise propagation module (atmospheric absorption, wind-temperature-ground effects) to provide noise spectra at the receiver $L_{rec} = L_{rec}(t, c, f)$. The latter array is then passed to a signal analysis module to provide noise metrics of interest in the analysis of aircraft noise.

Aircraft Noise Predictions

The types of noise calculations that can be carried out with the FLIGHT model include the following: conventional trajectories on arrival and departures, with allowance for changes in the approach slope (steep glide), continuous descent approach (CDA), noise abatement departure procedures (NADP). The use of FDR flight trajectories allows a more general treatment of the problem, as the aircraft model is forced to follow the trajectory specified by the FDR data.

The noise metrics included in the analysis include both integral and instantaneous quantities. Among the integral quantities, the model provides EPNL (effective perceived noise level), SEL (sound exposure level), TAUD (time-audible). Among the instantaneous quantities, we consider the OASPL (overall sound pressure level, also A-weighted), the PNL (perceived noise level), LAeqT (equivalent continuous noise level), and the awakening probability (based on awakening probability functions).

The effects of the ground are addressed by varying the parameters that define the solid boundaries: the effective flow resistivity, the fluctuating index of reflection (e.g. the atmospheric turbulence level), the inverse effective depth, though not all these parameters are essential.

Wind effects are important. Winds can affect the noise measurements to a degree that certification cannot be guaranteed. Wind not only affects the path of the acoustic waves from the noise to the receiver, but also contributes, via the turbulence level, to create a background noise created by acoustic emission of all surfaces along the boundaries. The FLIGHT program has the capability of predicting wind effects from all directions. One example is shown in Figure 2. This graph shows the effects of tail- and head winds on the predicted sound pressure level (SPL) of a Q400 turboprop during an arrival trajectory. The microphone position was at the standard ICAO point along the flight track. Note the differences in peak SPL and the contribution from the propeller and the main landing gear. No data are available in the technical literature to assess the accuracy of such noise predictions.
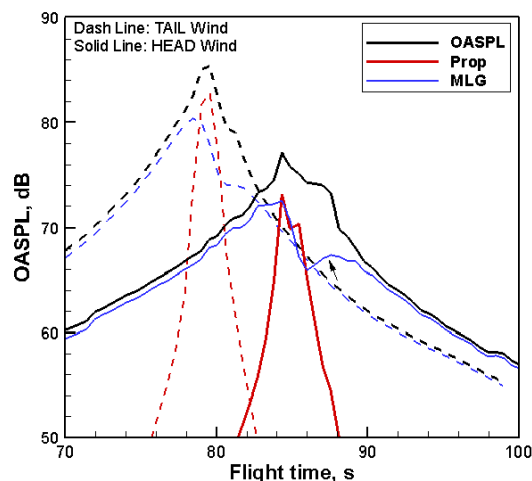

Figure 2: wind effects on a landing trajectory of a Q400 turboprop airplane.

In Figure 3 we show the noise calculations for multiple aircraft movements at an airfield. This case refers to arriving and departing Boeing B737-800 with CFM-56 engines. The flights are separated by 90 s. The graph shows one instantaneous noise map (OASPL), which is in fact a single frame of a video clip automatically generated from the output.
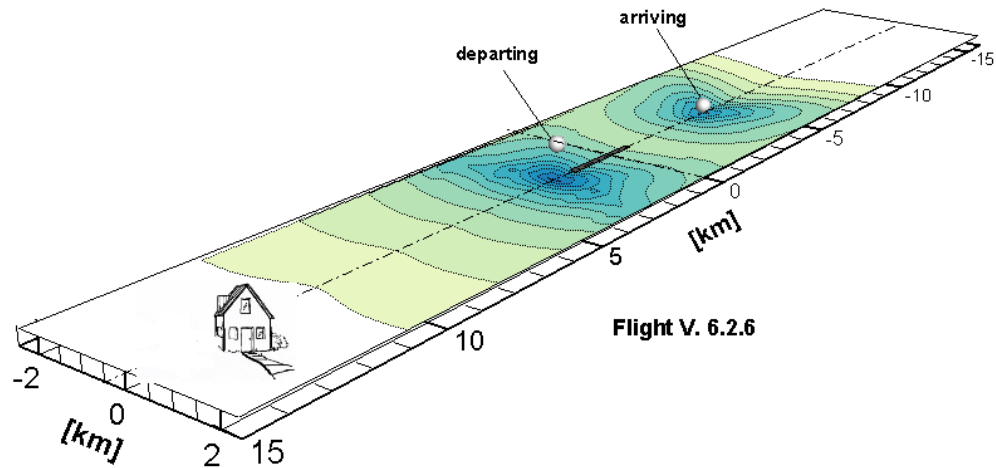
Figure 3: noise prediction from multiple aircraft movements at an airfield. Graph shows OASPL for a departing and arriving Boeing B737-800.

To emphasise the degree of flexibility of a theoretical noise prediction model, we show in Figure 4 the noise signals for an Airbus A319-100 (CFM-56) on landing. The noise is calculated at the standard ICAO reference point. The graph shows the contribution of the main components, including the inlet and exit fan and the landing gear units.
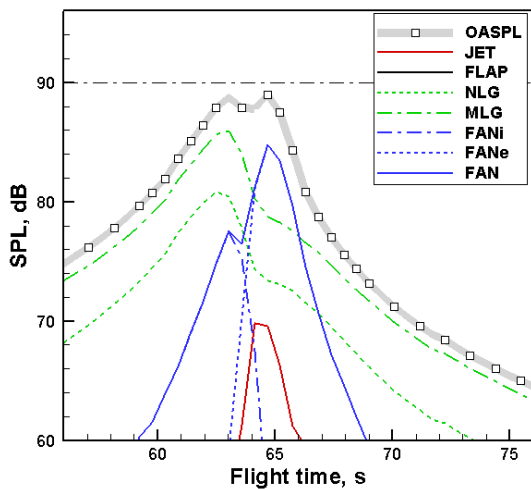

Figure 4: noise breakdown on arrival for the Airbus A319-100, predicted with the computer program FLIGHT.

Role of Stochastic Parameters

The uncertainties in the computer model are associated to five categories: 1.) airframe, 2.) propulsion system, 3.) atmospheric conditions, 4.) aircraft position with respect to the microphones; 5.) ground properties. Thus, we have two contributions associated to the aircraft itself and three contributions depending on external conditions. It is inevitable that with uncertain inputs we must expect approximate results. With this perspective in mind, a sophisticated noise model that is not coupled with accurate external conditions (and the means to predict such effects) is of little use: the overall accuracy is limited by the weakest link in the calculation chain. Thus, a rational strategy must address all these effects at the same time, and allow for the influence of the most important components to be studied in further detail. For this purpose, the aircraft noise model has an in-built facility to produce the statistically most likely values of the noise metrics.

The internal and external parameters p_i are affected by uncertainty $\pm \delta p_i$; the state vector is given as $\bar{\boldsymbol{p}} \pm \delta \boldsymbol{p}$; the use of the average state parameter $\bar{\boldsymbol{p}}$ provides an average noise metric $\bar{L}$. There are up to 40 independent parameters considered in our analysis; due to computational constraints it is not possible to run all the combinations of uncertainties among these parameters. For example, building a response surface corresponding to all the possible combinations of these parameters would require millions of runs. Instead, we consider these parameters in isolation, so that we are able to verify which ones do not affect the final result; among those do have an effect on the noise metric $\bar{L}$, we take a random combination and produce

several more noise predictions. Finally, all the noise predictions arising from all the perturbations and uncertainties in the state parameters are pooled together and a statistical analysis is carried out to produce average values, mean values, standard deviations, and other statistically significant measures.

One such case is shown in Figure 4, which refers to the arrival trajectory of the Q400 turboprop airplane shown in Figure 1. The results show excellent predictions at microphone 6, 13, 26. Microphones 7 and 8

are problematic, and the results show that the comparisons with the measurements are rather poor. In the first place, these measurements were taken as a routine procedure by an international airport. Microphone 8 is on top a building, about 16 m above ground level, shielded by a taller tower; background noise is present in the form of street traffic. Microphone 7 is a green field, about 6 m above the ground, protected by a row of trees, behind a 4-lane highway, about ¾ km from the ground track.
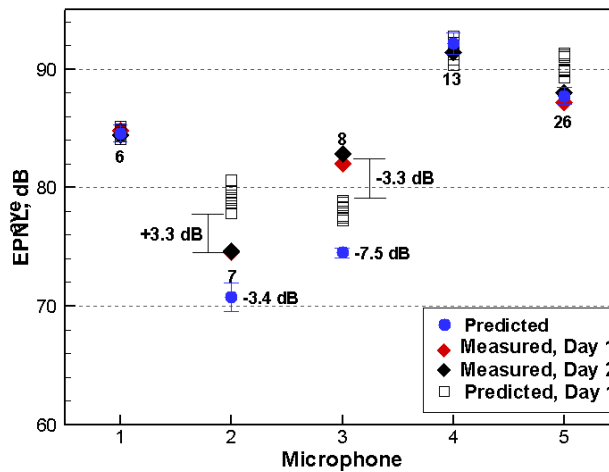

Figure 4: statistical noise prediction for an arrival trajectory of the Q400 turboprop airplane. The named microphones are shown in Figure 1.

he inaccuracy between predictions and measurements could be due to a combination of inaccurate data on both sides; for these two cases, our results cannot be conclusive.

Another category of uncertainty analysis consists in evaluating the contribution of each separate component on the integral noise metrics, for example EPLN. In other words, an error δE on the EPNL of a component leads to a change in the resulting EPNL. It turns out that the error on some components is irrelevant, which is equivalent to discarding

that component from further analysis. Thus, the power of aircraft noise prediction leads to a more systematic investigation of the important noise contributions from the aircraft.

For the nominal case, using default/average parameters, the predicted noise signal at microphone 13 and microphone 8 (as shown in Figure 1) are displayed in Figure 5. With reference to the latter case, here appears to be little correlation between the measured data and the prediction.
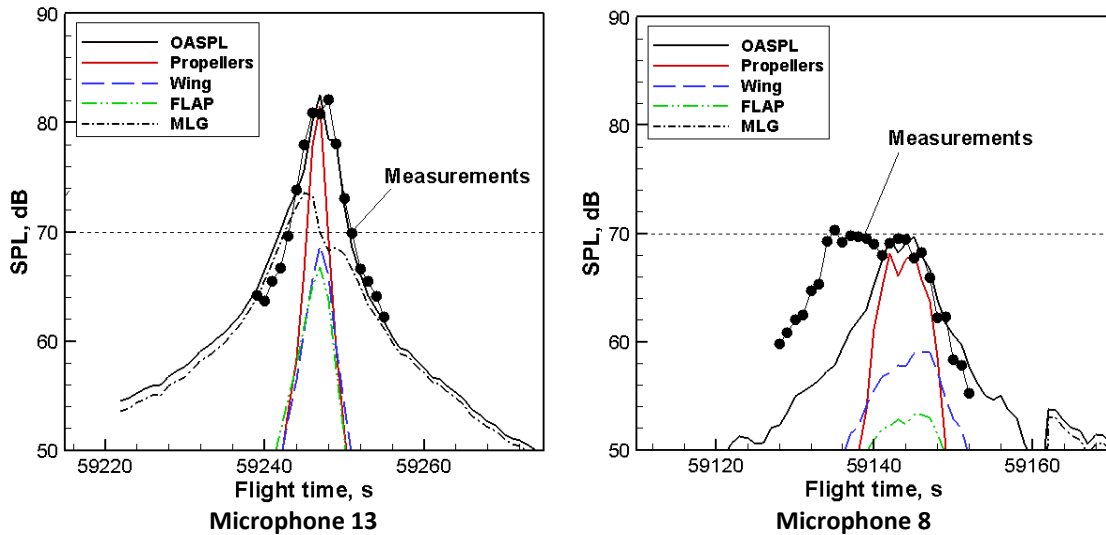
Figure 5: prediction of SPL and comparison with noise measurements taken at an international airfield. The microphones are number 13 and 8 in Figure 1.

Perspectives in Noise Prediction

Considerable advances have been done in the past decade in the development of noise prediction models for selected sub-component. However, several models remain fully empirical. These include in particular the modelling of aircraft noise (high-lift systems, landing gear), several propulsion components (all the rotating machines in the gas turbine engines: fans, compressors, combustors, turbines). These models are coupled with physics-based models for duct acoustics (liners and such), propeller noise, noise propagation. The prediction of the jet noise is also mixed, as it relies on several experimental databases, and are thus limited to the quality of these databases.

This mix of models, all of them with shortcomings of some degree, concurs in the determination of the noise metrics via the concept of component summation. This approach breaks down when interference effects take place. Common examples of interference include cases when one engine/propeller is shielded by the airframe, and therefore is out of the line of sight of the receiver. The way this interference intervenes depends on the impedance of the obstacle, as well as its shape. In the present context, we model fuselage interference and wing interference. Sophisticated models exist in the technical literature to address more general

problems which will be of engineering interest in the future; such cases include over-the-wing engines, wing-body airplanes with engines mounted high, box-wing configurations with engines out-of-sight of the receiver, deeper engine ducts, scarf inlets, and more.

Many forms of noise prediction cannot be properly assessed, due to lack of reliable data. Such cases include full noise mapping over an airfield, wind effects, and effects of ground impedance. However, recent progress in beam-forming techniques has been instrumental in producing advances in noise source characterisation, so that we are now able to assess with greater confidence the role of the major noise sources, both in terms of noise intensity and noise directivity.

Due to requirements at several levels, we must accept some compromise in the degree of sophistication we should consider. For example, the analysis of fan noise, wherein the fan is taken as an isolated component working at few operating points, must be done to a good level of accuracy, especially if the underlying model depends on the geometrical details of the component. Field methods in computational aero-acoustics must be used for this purpose. However, when the fan is encased into a duct, integrated with stator vanes, acoustic liners or other dampers, within the engine, at all operating points, at rapidly variable speed

(from idle to maximum rpm), flight altitude and Mach number, the same prediction methods are not applicable. This is besides the fact that in most cases we have inaccurate component data (blade geometry). In this instance, the challenge is to develop models that are accurate whilst requiring a minimum amount of data; methods that comply with this requirement, out of necessity, lack generality and the capability of predicting the effects of the finer details of the component. The optimal situation has not been addressed in any satisfactory manner; thus, we are left with fan noise models that are too old for the requirements of modern-day high by-pass fans.

Not all noise metrics can be predicted with the same accuracy. The prediction of integral metrics such as EPNL can be realistically achieved within 1dB in particular situations, specifically when the propagation effects are minimal (microphones under the flight path during arrival and departure). The prediction of SEL is more problematic, as the frequency effects, particularly at the low and high end of the spectrum, tend to be inaccurate. Low-frequency effects arise from airframe components; high-frequency (broadband) effects are associated to the engine core components. The prediction of the instantaneous SPL can be done sometimes with a good degree of accuracy, but there no general rule as to when the prediction falls short. Thus, further developments are required that address accuracy over the full spectrum of frequencies.

Conclusions

There exists enormous untapped potential in the prediction of aircraft noise. However, several challenges lie ahead, as pointed out in this paper. The quality of the noise measurements and the availability of real flight trajectory is a major obstacle to progress. On the theoretical side, there is still a gap in prediction capability on several key sub-components, including fan noise (intended as a complete system made of the fan, the stator, the inlet/exit duct, the acoustic liners). Landing gear noise is an important contribution on arrival trajectories. Again, although there is enough physical understanding, there is a shortage of reliable landing gear noise models that can be applied to the context described.

The role of noise propagation has not been addressed with sufficient detail to provide a best-practice guideline on the theoretical models to use. Finally, there is no standard and no agreement as to how best to carry out comparisons between measurements and predictions, and no agreement on the acceptable level of inaccuracy. A good step in the direction of improving noise prediction would be a code-to-code comparison between the most up-to-date prediction models and with noise measurements.

The role of accurate noise measurements is not to be discounted. For a real-life situation we are faced with little control over the quality of the data, in contrast with carefully tuned laboratory measurements. In some of the cases we have examined, it was not even possible to assess the level of uncertainty in the measurements. Hence, statistical analysis is required.

This contribution, with the development of the FLIGHT software platform, has partially addressed some of the gaps in aircraft noise prediction. This platform allows noise calculations in a variety of situations, for both jet-powered and turboprop commercial airplanes, in most flight configurations and with a variety of external steady-state conditions. Calculation times are kept to a level that is compatible with the needs of engineering analysis. This is the same time as the flight trajectory (1-3 minutes) for a case in absence of atmospheric winds; this computing time increases for a turboprop airplane due to the aerodynamic trim required to establish the flight mechanic compatibility. These computing time increase rapidly in the presence of winds, reaching 30-60 minutes with conditional statements, or a few hours otherwise. Noise maps generally require a minimum of 600 grid points, therefore unless additional software optimisation is done, the calculation of a noise map requires 1-2 days, depending on input conditions. The statistical noise prediction briefly described in this paper

requires between 1 and 2 hours per microphone.

Recent developments of the FLIGHT program include the integration of this software platform with global optimisers, including heuristic search methods (particle swarming optimisation) to determine minimum-noise flight paths. Further to that, the software is being integrated with neural networks in order to minimise the noise along three-dimensional flight trajectories requiring several additional free parameters. In fact, as the number of free parameters increases, the computational burden increases exponentially until it becomes unwieldy.

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