Fly-over noise measurements and simulation for a turboprop aircraft

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ABSTRACT
The study of aircraft noise started in earnest in the 1960s, however, the validation of comprehensive noise models for existing commercial aircraft using well-defined experimental data have since produced modest advances. Considerable focus appears to have been placed on aircraft conceptual design, with relatively little effort considering aircraft currently in use, for which we believe there is a growing need. This study investigates the fly-over noise from a commercial turboprop aircraft, using noise measurements taken both on airport departure and approach for the validation of noise simulations. Predictions are carried out using a software system described elsewhere in the literature. It is shown that, for the examples considered, predicted overall noise levels such as SEL and EPNL display modest agreement, and are within 4.3dB/EPNdB of measured values. One-third octave band analysis shows discrepancies to be due to a general under prediction at low to mid frequencies. Through an analysis of noise source subcomponents, the most likely candidates are identified for which an alteration in the model best improves agreement. By applying these alterations – in particular, by increasing the contribution of the landing gear and airframe noise – an average error in one-third octave band SPL of less than 3.2dB is achieved.

Keywords: Aircraft noise, Aircraft operations, turboprop airplane

1. INTRODUCTION

The study of aircraft noise is a mature subject that continues to grow, and is becoming increasingly more important with the expansion of airports, increase in traffic and the development of human activities near airports. Existing holistic aircraft noise prediction techniques tend to focus on large scale environmental predictions through noise database models such as INM [1], or on predictions made at the conceptual stage through multi-disciplinary optimisation [2]. More comprehensive aircraft noise prediction is currently done at a number of organisations, including NASA (U.S.) [3] and DLR (Germany) [4], using various versions of programs, some of which use interfacing with other software (for example, flight mechanics, propulsion system, numerical optimization), in order to be able to predict noise from real-life flight trajectories.

This paper considers a comprehensive model [5; 6] akin to those described above and investigates the fly-over noise from a commercial turboprop aircraft, comparing simulations to measurements. These measurements were taken within the vicinity of Manchester International Airport, UK, and were obtained at locations along both approach and takeoff flight paths. The focus of this report is the Bombardier (previously de Havilland Canada) Dash 8 400 series (DHC-8) – a twin-engine, medium

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range, turboprop airliner. Representative flight trajectories have been obtained from the onboard Flight Data Recorders (FDRs) of previous DHC-8 flights for use as inputs to the model. Previous validation for this aircraft has been carried out using data obtained from a number of airport noise monitoring stations. This study differs, however, in that both overall noise level and 1/3rd octave band measurement data were acquired. This allows for a more detailed and comprehensive analysis. In addition, the capturing of manned measurements (compared with automated noise monitoring equipment measurements) means that the reliability in both aircraft / unwanted noise discrimination and in aircraft identification is improved. By studying the variation of measurements and predictions with both time and frequency, the noise source components that make up the prediction model are assessed to determine the most likely source of discrepancy between the two.

2. MEASUREMENT DETAILS

2.1 Procedure

Measurements were obtained through the use of a Brüel & Kjær 2250 Sound Level Meter (SLM); a Class 1 SLM conforming to international standard IEC 61672-1:2002 [7]. The SLM was mounted on a tripod, with the microphone positioned at a height of 1.2m above ground level. To minimise any directivity effects the microphone was orientated parallel to the ground, with the diaphragm of the microphone positioned approximately parallel to the flight path. Measurements were operated manually: each measurement was started by the operator on sight of a distant approaching aircraft, the operator then leaving the SLM for the duration of the noise event. The first and last few seconds of each measurement (when the operator was moving away from and toward the SLM) are hence ignored. Measured values were logged with a time increment of 1 second, using the 'slow' setting (1 second integration time). For each time increment both overall and 1/3rd octave band (12.5Hz-20.0kHz) Sound Pressure Level (SPL) values were stored.

2.2 Locations

Measurements were taken at two locations: one on approach (APP) and one on departure (DEP). Their locations are summarised in Table 1 and are illustrated in the maps of Figure 1, and in the photograph of Figure 2 (departure location). The measurement locations were situated (approximately) directly underneath the flight path. Departure measurements were taken close to the end of the runway 2 (23L/05R) landing/takeoff lights, with aircraft heading west taking off from runway 2 (23L). The approach measurements were taken to the east of the airport approximately 1.6km from the end of the runway, with aircraft arriving from the east and landing on runway 1 (23R).

Note: the latitude and longitude (WGS84) coordinate values in Table 1 have been estimated using Google Earth software [8]. The altitude of the microphone at each location given is the altitude Above Mean Sea Level (AMSL), estimated from a ground level height also obtained from Google Earth.

### Table 1: Measurement location details

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude (degrees)</th>
<th>Longitude (degrees)</th>
<th>Approximate altitude AMSL (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEP</td>
<td>53.32696</td>
<td>-2.32098</td>
<td>55</td>
<td>End of runway 2 (23L/05R) landing/takeoff lights; grassland surrounded by farm fields</td>
</tr>
<tr>
<td>APP</td>
<td>53.37219</td>
<td>-2.23798</td>
<td>67</td>
<td>Middle of field; grassland; approximately 80m away from nearby single carriageway</td>
</tr>
</tbody>
</table>

2.3 Aircraft identification

For each measured noise event a photograph was taken of the aircraft passing overhead. This allows the aircraft registration to be obtained and the aircraft identified. An example of this is shown in Figure 3, showing a DHC-8 on approach; the registration (withheld) is located on the underside of the left wing. Where the registration is positively identified, measurements are referred to as verified DHC-8 plane passes. When aircraft could not be identified by their registration the likely aircraft type was
judged on a general inspection of photographs and/or notes taken during measurements. Measurements of aircraft identified by this method are referred to as an unverified DHC-8 plane pass. Fortunately, since the DHC-8 is the only FlyBe propeller aircraft operating out of Manchester airport this aircraft type can be easily identified, even if the registration is unclear. This was the case for each of the measurements detailed in this report. For these measurements the aircraft type is known, but the specific aircraft is not. This, therefore, is only an issue if the FDR data for the flight was required.

Figure 1: Departure measurement location, DEP (left, blue), Approach measurement location, APP (right, blue), nearby airport noise monitoring locations, NMT (red) and approximate straight aircraft takeoff/landing trajectory (green lines); images taken from Google Earth [8]

Figure 2: Photograph taken at the departure measurement position (DEP)
2.4 Weather conditions

Meteorological data was obtained from online data records taken from a weather station at Manchester Airport [9]. This data consists of half hourly recordings of the air temperature; wind speed and direction; atmospheric pressure and the relative humidity. During the measurements conditions were dry and settled, with a variable amount of cloud cover. A wind speed of 5-8mph (≈ 2.2-3.6ms⁻¹) from an (approximate) average southerly direction was recorded, along with a temperature range of 3-9°C, an atmospheric pressure range of 1012-1015mbar and a relative humidity range of 75-93%.

2.5 Background noise

For both measurement locations a representative background noise measurement was taken when no aircraft and/or unusual additional noise sources were audible. These measurements were at least one minute in duration. Approximate background noise levels of 45.6dB(A) and 49.5dB(A) were obtained for the departure and approach measurement locations respectively. One-third octave band data is shown graphically in the proceeding results section. These values provide an approximate noise floor for the measured aircraft noise values.

3. PREDICTION MODEL

3.1 Prediction routine

Predictions have been obtained using FLIGHT Version 5.9.4 – a multidisciplinary software platform for the prediction of aircraft flight performance, environmental emissions and noise. Key features modelled by the software include: full geometric configurations; mass properties; prediction of configuration aerodynamics; propulsion systems (including auxiliary power unit); thermo-structural analysis; aircraft trim; and more. The program has been documented in a number of publications [5; 6]. Predictions include 1/3rd octave band SPL values (50Hz-10.0kHz), as well as several overall noise level measures. In addition a breakdown of the SPL due to individual noise source components (subcomponents of the model) is also obtained for further analysis.

3.2 Flight operational data

Flight operation data for the specific flights measured here is currently unavailable. Previous representative data however have been obtained, and these may be used to provide an approximation of the flight operations. This data has been taken directly from the FDRs of DHC-8 aircraft, both on approach and departure from Manchester Airport, during flights in March 2012. The use of this data is seen as appropriate as the measurements were taken during similar conditions and at locations close to the airport (where deviations in trajectory and flight operations are small). Along with a number of other flight operational measures, the information includes positional data tracking the trajectory of the aircraft. The positional data is given in the form of latitude/longitude (WGS84) coordinates logged once every four seconds and the barometric and radio altitude stored once a second. Example raw flight data has been used to create input flight operation files, with one exception – a slight offset was
applied to the trajectory of the aircraft on approach. This was to ensure that the aircraft used in the model passed directly over the measurement position, as was observed during the measurements.

4. MEASUREMENT RESULTS

4.1 Summary of captured measurements

A summary of the captured noise measurements is given in Table 2 below. All unverified DHC-8 plane passes were identified as FlyBe propeller driven planes, of which no other types operate from Manchester Airport, and so these are essentially verified. Also included is a summary of the overall noise levels obtained for each measurement. These include the Effective Perceived Noise Level (EPNL) and the Sound Exposure Level (SEL) - measures of the total sound level; and the maximum un-weighted SPL ($L_{\text{max}}$) and maximum A-weighted SPL ($L_{\text{Amax}}$).

Table 2: Summary of the captured aircraft noise measurements and overall noise levels

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Start time (GMT, hh:mm:ss)</th>
<th>Verified / unverified</th>
<th>Noise levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start time (GMT, hh:mm:ss)</td>
<td>Verified / unverified</td>
<td>EPNL (EPNdB)</td>
</tr>
<tr>
<td>Location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEP</td>
<td>08:45:15</td>
<td>Verified</td>
<td>83.3</td>
</tr>
<tr>
<td></td>
<td>08:47:09</td>
<td>Verified</td>
<td>83.1</td>
</tr>
<tr>
<td></td>
<td>08:48:44</td>
<td>Unverified</td>
<td>82.7</td>
</tr>
<tr>
<td></td>
<td>08:57:33</td>
<td>Verified</td>
<td>88.3</td>
</tr>
<tr>
<td></td>
<td>09:03:28</td>
<td>Verified</td>
<td>87.2</td>
</tr>
<tr>
<td></td>
<td>09:13:18</td>
<td>Verified</td>
<td>89.6</td>
</tr>
<tr>
<td>APP</td>
<td>11:43:54</td>
<td>Unverified</td>
<td>89.2</td>
</tr>
<tr>
<td></td>
<td>11:57:38</td>
<td>Verified</td>
<td>88.6</td>
</tr>
</tbody>
</table>

Note: the shaded lines above represent the two measurements selected for comparison with predictions in the proceeding section (see below).

5. COMPARISON WITH PREDICTION

Where specific examples are shown, the following measured values are taken from the final verified DHC-8 plane pass on departure, and from the one verified DHC-8 plane pass on approach. Given that other measurements were available the departure choice is, to some extent, arbitrary.

5.1 A-weighted SPL time history

Figure 4 shows a comparison between the measured and modelled A-weighted SPL with time on departure (left) and approach (right). The dark blue lines signify the selected measurements (see above) while the light blue lines in the background represent the remaining measurements for reference. The time variable in each case is relative to the approximate time at which their respective peak value occurs. Also included for reference is the average background noise (obtained from measurements). A summation of the modelled SPL and the measured background noise is given, providing an empirical fix to the prediction to compensate for the ambient noise present at each of the measurement locations.

On departure, the predicted peak A-weighted SPL ($L_{\text{Amax}}$) quite closely matches that obtained from the measurement, exceeding it by 1.2dB. Away from the peak, the model tends to under predict the A-weighted SPL, suggesting an under prediction in the level of low frequency content in the measured signal. This trend is also seen in the remaining measurements. The overall result for this measurement is a shortfall in the predicted EPNL of 1.2EPNdB and in the SEL of 2.2dB, though both lie within the range of measured values given in Table 2.

On approach the agreement with the measured SPL is not quite as good. The prediction very closely
matches the measured envelope shape, though is approximately 4dB lower in level. This correlates with the discrepancies observed in the overall noise levels, with a shortfall in the predicted $L_{\text{Amax}}$ (maximum A-weighted SPL), EPNL and SEL of 3.7dB, 4.3EPNdB and 4.2dB respectively. Again, a similar trend is seen in the additional measurement.

![Comparison between the measured and predicted A-weighted SPL with time on departure (left) and on approach (right); additional measurements shown in light blue in background](image)

In general, the agreement between predicted and measured values is okay, though could be improved; on departure the peak SPL is well predicted though disagreement in envelope shape is seen, whilst on approach the envelope shape is well predicted though there is a shortfall in overall noise level. On departure closer agreement is seen in the EPNL than for the SEL – a trend that has been observed in previous FLIGHT comparisons with airport monitoring station noise data. This (as with the difference seen in envelope shape) therefore implies that the discrepancy is due to the frequency content of the predicted/measured signals. This, for both approach and departure, is considered below.

### 5.2 Octave band SPL time history

To investigate the discrepancies between predicted overall noise levels, the $1/3^{rd}$ octave band data may be studied. Figure 5 shows the modelled and measured $1/3^{rd}$ octave band SPL with time for the approach measurement above, though combined into octave bands for ease of viewing. The remaining measurement is not shown for clarity, though as with Figure 4 (right), a very similar trend is seen. A brief comparison of the measured and modelled values may be summarised as follows:

- At very low frequency (125Hz and below), particularly in the 63Hz octave band, the model can be seen to significantly under predict the SPL, though this is partially due to the level of background noise. Agreement is slightly improved in the 125Hz octave band where the peak measured value is more closely matched. The SPL predicted away from this peak value however is under predicted. Note: the SPL at these frequencies, unless very high, will be less crucial when predicting any of the single figure metric values as their contribution tends to get weighted out.

- In the remaining frequency range (approximately 250-8.0kHz) agreement is generally good, particularly in terms of envelope shape, though with a slight under prediction in absolute level on the order of up to 5dB.

The trend on departure is similar to that on approach outlined above. This is illustrated by the ‘maps’ of Figure 6 – each a form of spectrogram which show the $1/3^{rd}$ octave band SPL ($y$ axis) with time ($x$ axis) for the measured (left) and modelled (right) cases respectively. These display the changing frequency content of the SPL signal with time and help to show the overall trend – in particular a general under prediction at low frequency. This pattern is also observed with the additional measurements (not shown).
Figure 5: Comparison between the measured and predicted octave band SPLs with time on approach

Figure 6: Measured (left) and predicted (right) maps of $1/3^{rd}$ octave band SPL with time on departure
One significant difference from the approach measurement is due to an apparent tonal noise source: the propeller. This, as would be expected for a turboprop aircraft, is one of the dominant noise sources on takeoff. At first glance the agreement between the measured and modelled tonal propeller noise is quite good, particularly in absolute level, though perhaps with the fundamental Blade Pass Frequency (BPF) in the measurement being slightly higher in frequency than is predicted.

5.3 Noise subcomponent analysis

To understand the influence of the individual modelled noise source components it is useful to compare them separately with the measured values. An example of this is shown in Figure 7 for the departure (left) and approach (right), both of which show the contribution of three noise source components with frequency (1/3rd octave bands). Also included are both the measured and modelled (total of all components) spectra. Additional measurements, as with Figure 4, are shown in light blue for reference. Note: the level shown here is the total energy in the noise event (within a specific 1/3rd octave band) normalised to a reference duration time of one second; the levels are hence the un-weighted SPL contributions to the SEL. This forms an intuitive step between the 1/3rd octave band data and the overall predicted noise level, though in the analysis below both SPL variation with time (for fixed frequency bands) and frequency (for fixed times) have been studied.

As can be seen in Figure 7, the general trend in the total predicted SPL with frequency on departure and approach is similar (relative to measurements); their overall levels are consistent with the measurements though with an under prediction at low to mid frequencies. The same trend is observed when considering the additional measurements. The three components contributions shown – the propellers, the wings and the Low Pressure Compressors (LPCs) – have been included as they are representative of three of the major types of noise source modelled: tonal noise, low to mid frequency broadband airframe noise and higher frequency propulsive noise sources. Note: no High Pressure Compressor (HPC) is currently implemented in the code as the HPC for the DHC-8 is a centrifugal compressor – unlike the axial LPC – and no reliable model and/or extrapolation from existing models for axial compressors proved to be applicable. Based on analysis of both the time (envelope shape) and frequency (spectrum shape) response of the existing predicted components the following summary can be made:

- On departure, in the 1/3rd octave bands where the tonal noise produced by the fundamental BPF of the propeller dominates (approximately 100-125Hz), the agreement is very good and a discrepancy of less than 1dB between measured and modelled values is seen. The location of the second harmonic (located at twice the frequency of the BPF) is slightly out, and suggests that the BPF is possibly slightly higher in frequency than is predicted (higher propeller rotational speed).
- On approach, the propeller noise is over predicted by approximately 5dB. As this is at relatively low frequency and only over a single 1/3rd octave band, this only has a small effect on the predicted overall noise levels.

- In the remaining low to mid frequency range (50Hz-2.0kHz) there is general shortfall in broadband noise of up to approximately 12dB, both on departure and approach. The most likely candidates for the general under prediction in SPL are the low to mid frequency broadband noise sources: the high lift devices (specifically the wings, horizontal stabilisers and (on approach) the flaps)

- On approach, an additional candidate for the shortfall in low to mid frequency SPL is the landing gear.

- At high frequency (above approximately 2.0kHz) the agreement is quite good, particularly on departure, and the high frequency roll-off in the SPL seen in the measurement is generally well matched. Agreement on approach is not quite as good, due predominantly to an additional peak in the measured SPL at approximately 5.0kHz. This is perhaps due to the omission of the centrifugal HPC and hence may be improved if a suitable model were found for implementation.

It should be noted that the components mentioned above are the most likely candidates for which an alteration in contribution would make up for the shortfall/excess in the total prediction, and it is possible that other combinations of components could be altered to produce a better agreement. Nevertheless, for the two examples shown the closest agreement was achieved by: increasing the contribution from the wings, horizontal stabilisers and (on approach) the flaps and landing gear noise by 7dB. This resulted in an improved maximum deviation in 1/3rd octave band SPL between measured and predicted spectra (excluding the sub 80Hz region) of less than 7dB on approach and 10dB on departure, an improvement from 22dB. The average deviation was 3.1dB and 2.2dB on departure and approach respectively. These alterations also gave SEL and EPNL values within 1.4dB/EPNdB of those obtained from measurement.

6. DISCUSSION

The above comparison with measurements should be viewed in the knowledge that there are a high number of uncertainties involved. In addition to the ambiguity in some aircraft parameter inputs (which rely on a variety of data sources, e.g. manufacturer’s documents, technical papers, digital photographs etc...), factors such as the lack of precise meteorological conditions; measurement errors; background noise; and the unknown exact location and operations of the aircraft add to the large uncertainties and complexities involved. Despite this, the model shows modest agreement with these measurements, with the overall noise levels on departure in particular being in close agreement with measured values. In the individual 1/3rd octave bands, however, larger discrepancies are seen.

Altering the contribution from the most likely candidate subcomponents results in much closer agreement, and compensates for the under prediction at low to mid frequency. Whilst the alterations applied here are simply an empirical fix – and further investigation would be required to ascertain what combinations and under which conditions (if any) these suggested alterations hold true – they do, however, provide an indication of the areas in which further improvements to the model may be sought. Note: the alterations are not for use in the model, and are intended solely to inform the areas in which improvement would be most profitable. These improvements may for example be obtained through more accurate input parameter knowledge (e.g. component dimensions, propulsion system speeds and frequencies of operation etc...) and/or subcomponent models based more on physical principles – the latter potentially requiring step changes in knowledge. These changes are desirable since improved agreement with frequency, whilst not a requirement for many end users in aircraft noise management, should at least result in a more robust model.

Whilst the above comparisons are for two measurements only (one on both approach and departure), the remaining measured fly-overs display a similar trend (see for example Figure 4 and Figure 7): an under prediction at low to mid frequencies that would most likely be compensated for by an increase in airframe and landing gear noise.

7. CONCLUSIONS

This paper has sought to provide validation through measurement of a holistic commercial turboprop aircraft noise model. Sample noise measurements have been taken at two separate locations under both the takeoff and landing flight paths of Manchester Airport, UK. The measurements were
carried out on the 16th of November 2012, using a SLM to obtain both overall and 1/3rd octave band SPL, capturing fly-over noise from Bombardier Dash 8 (DHC-8) aircraft. These in most cases were identified by their registration. Predictions have been obtained using the noise prediction code FLIGHT Version 5.9.4. Operational data from previous flights (taken from the FDRs) were used as inputs to the model; currently no FDR data for the specific flights measured here is available. The predictions have been compared with SPL measurements, both in terms of overall noise level values (EPNL, SEL, $L_{\text{max}}$, and $L_{\text{Amax}}$) and their variation with time (sampled once per second) and frequency (in 1/3rd octave bands). During the measurements the general weather conditions were dry and settled with low wind, though with variable cloud cover.

The overall noise level predictions compare modestly with measurements; a maximum deviation between the predicted and measured EPNL of 1.2EPNdB and 4.3EPNdB was seen on departure and approach respectively. For the SEL this discrepancy was 2.2dB and 4.2dB. Similar differences were seen in the maximum SPL metrics, $L_{\text{max}}$ and $L_{\text{Amax}}$. Note: particularly on departure, multiple DHC-8 noise events were captured which would give different values to the above. The choice of measurement is inherently partially subjective, and to some extent arbitrary.

The (1/3rd octave band) frequency content of the predictions – relative to measurements – shows similarity at both of the measurement positions. In general there is an under prediction in SPL in the low to mid frequency range (below approximately 2.0kHz). The exception to this is the tonal propeller noise, which displays a fundamental BPF at approximately 100Hz, and is well predicted by the model, particularly on takeoff. In contrast to the overall noise levels, the predicted 1/3rd octave band SPL values can be out by as much as 22dB. The closer agreement in the overall levels is due to the improved agreement at higher frequencies and, on departure, in the tonal propeller noise.

By studying the individual noise source components that make up the model’s predictions, both in terms of their time and frequency response, the components have been assessed to determine the most likely candidates for accounting for the discrepancies. In the low to mid frequency region it is the high lift airframe components – the wings, stabilisers and flaps – which best compensate for the shortfall in the predicted noise levels. An increase in SPL produced by each of these components of 7dB, along with an additional 7dB increase in landing gear noise on approach, provides the closest agreement with measurements.

Applying the above alterations provides improvement in the overall predicted noise level values as well as giving more accurate agreement with frequency. This, in turn, could help provide a more robust model. These alterations are currently empirical, not intended for use in the model and only tested on the case considered here. They do, however, provide an indication of the areas in which further improvements may be sought. This may require step changes in knowledge in the relevant areas.

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