AIRCRAFT FUSELAGE NOISE TRANSMISSION MEASUREMENTS USING A RECIPROCITY Technique

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The cabin noise environment in typical turbo-prop aircraft is high. To evaluate potential noise reduction approaches, a method of predicting the internal noise is desired that avoids costly flight tests. Instead of carrying out a ground simulation of the propeller sound pressure field, a much simpler reciprocal technique can be used if a computed pressure field is available. A capacitive scanner is used to measure the fuselage vibration response on a deHavilland Dash-8 fuselage, due to the internal noise source. The approach is validated by comparing this reciprocal noise transmission measurement with the direct measurement. The fuselage noise transmission information is then combined with computer predictions of the propeller sound pressure field data to predict the internal noise at two points.

1. INTRODUCTION

The high noise environment within the cabin of commercial turbo-prop aircraft has long been recognized as a significant problem. Numerous researchers, and many aircraft manufacturing companies, have investigated noise reduction approaches (see, for example, references [1–4].) The methods considered include structural modifications, passive damping and active vibration or noise control. Prior to implementation, these and other approaches must be evaluated. It is therefore necessary to characterize the aircraft cabin noise properties.

Sources of externally generated cabin noise include boundary layer flow noise, acoustic excitation of the fuselage from the propeller, and structure-borne noise due to both engine vibration and flow distortion over the wing [5]. The relative contributions of these different noise sources vary between aircraft. For typical turbo-prop aircraft, the level of harmonic propeller noise is 20–30 dB(A) higher than the broadband flow noise. For the deHavilland Dash-8 aircraft shown in Figure 1, the proximity of the propeller disc to the fuselage results in the acoustic excitation of the fuselage being the dominant source of noise, and the contribution from structure-borne noise transmission through the wing-box is relatively minor.

There are several options for determining the cabin noise caused by the propellers. Flight tests are ultimately required, but in the early stages of a potential noise reduction technique,

† Both Basso and Slingerland have since retired from the NRC.
they are undesirable because they are expensive. A ground simulation of the propeller noise field incident on the fuselage surface is possible [6]; however, this technique requires a complex two-dimensional array of many loudspeakers with mutual phases and gains correctly adjusted to reproduce the correct sound pressure distribution. This approach is limited in applicability, because the simulation will always be imperfect, and may also be quite expensive. Computer modelling and simulation of the propeller noise field, structural dynamics and acoustic field can also be used to predict the interior noise. However, while computer codes exist to do this, the models must still be validated by experiment at some point in the design process.

An alternative approach to experimentally determining the cabin noise is to use a reciprocal technique. This approach is much simpler to implement than the direct simulation of the propeller noise field. For a linear, passive system, the response at one point due to a source at a second point is the same as the response at the second point due to a source at the first [7, 8]. Hence, rather than measuring the noise transmission from an external pressure source to a point in the interior of the aircraft, one can measure the surface vibration of the fuselage due to a point noise source inside the aircraft. This information can be combined with computer generated propeller sound pressure fields to predict cabin noise levels. One of the advantages of such a technique is that once the noise transmission data have been obtained, the internal noise can be predicted for any propeller pressure field distribution, corresponding to different engine r.p.m. or flight conditions.

A reciprocal approach for examining structure-borne sound transmission into aircraft has been suggested by Ver [9, 10], who gives an experimental validation comparing the direct and reciprocal transfer functions between a point force and internal sound pressure. Mason and Fahy [11–13] developed a reciprocal approach for measuring transmission from external sound pressure to internal noise. The approach subdivides the surface area into small scan elements, and uses a capacitive measurement of the surface vibration on each element. The technique was validated on a box, with excellent agreement obtained between direct and reciprocal measurements. The reciprocal technique was then used for noise evaluation on scale models of aircraft-like structures [12]. Further comparisons of direct and reciprocal data can be found in reference [14].

This paper extends the work of previous authors by developing, validating and demonstrating a reciprocal approach for measuring sound transmission through the fuselage on a full-scale aircraft. As in Mason and Fahy’s work, the approach taken here involves a monopole sound source located inside the fuselage, and a non-contacting capacitive probe to measure the external surface volume velocity on the fuselage. The arrangement is shown schematically in Figure 2. In order to verify reciprocity, the direct transfer function is also measured, using a horn designed to insonify a single element of the fuselage surface. Excellent agreement has been obtained between direct and reciprocal measurements.

![Figure 1. The deHavilland Dash-8, showing the propeller disc clearance.](image-url)
The capacitance probe is used to scan the aircraft fuselage, and then the computer generated propeller sound pressure field information is combined with the scanned data to predict interior noise at two locations. The final prediction of internal noise agrees well with measured flight test data. Finally, the total number of scan elements used in the noise prediction is gradually reduced so that the minimum number required to obtain a useful prediction can be determined.

2. THEORY

Reciprocity was first shown to hold for vibrating systems by Lord Rayleigh [7] in 1873, and it holds for any linear, passive system [8], including vibro-acoustic systems. The aircraft fuselage will have some non-linear damping mechanisms, but the effect of these on the reciprocity relationship is small.

The fundamental principle of reciprocity is that the transfer function from a source at one point to a response at a second is the same as the transfer function with source and response interchanged. This property holds for linear passive systems provided that the input and output variables at each of the two points are chosen such that their product represents the power flow into the system due to that input [8]. Thus one pair might be a force and collinear velocity on a structure, or acoustic sound pressure and volume velocity. Reciprocity can be shown by writing the two outputs as a linear combination of the inputs, and noting that the total power input to a passive system must be positive for any arbitrary combination of inputs. The reciprocity property is used extensively, because it is frequently simpler to measure the reciprocal transfer function than the direct transfer function of interest.

To conduct interior noise measurements due to the propeller sound pressure field, the external surface of the aircraft fuselage is first subdivided into a number of scan areas, as illustrated in Figure 3. The size of the scan area required is based on the minimum vibration wavelength to be considered, and on the fuselage structural dynamic properties. The subset of scan elements on which the external propeller sound pressure field is highest is considered, as indicated on the figure. The noise transmission of the fuselage from each of these scan elements to each internal point desired is measured. The total internal noise is obtained by combining this information with the computer predicted propeller pressure field on each scan element, and summing over the propeller’s acoustic “footprint”.

The direct noise transmission transfer function on the aircraft fuselage is that from an external pressure field $p_e$ applied to a single scan element to the pressure $p_i$ at an internal point (shown in Figure 2(b)). The transfer function $p_i/p_e$ is the response that is required to predict internal noise. The reciprocal measurement is from an internal acoustic volume
velocity source of strength \( Q_i \) to the vibrational volume velocity \( Q_e \) on the surface (shown in Figure 2(a)). For a single element, then reciprocity gives that these two transfer functions are equal,

\[
\frac{Q_e}{Q_i} = \frac{p_i}{p_e},
\]

(1)

where both quantities are functions of frequency. Note that reciprocity holds because the power input to the vibro-acoustic system due to the source \( p_e \) is given by the product of the variables \( Q_e p_e \), and the power due to the source \( Q_i \) is given by the product \( Q_i p_i \). The transfer function \( Q_e/Q_i \) is used instead of the direct measurement, as it is simpler to measure. The primary reason for this is that it is easier to measure the response of a single surface element than it is to apply acoustic loads to only that element.

Given the external sound pressure distribution, then the internal sound field can be computed as the sum over the \( N \) scan elements of the footprint,

\[
p_i = \sum_{n=1}^{N} \left( \frac{Q_e}{Q_i} \right)_n (p_e)_n.
\]

(2)

This form of the reciprocity relationship is clearly presented in references [10, 13].

Once the transfer functions \( Q_e/Q_i \) have been measured, then \( p_i \) can be predicted for any external field \( p_e \) for any flight regime. The measurements can be made on operational aircraft without modification, and because the sensor is non-contacting, it does not itself change the
response that would be observed. However, the source $Q_i$ must be located at each internal point for which $p_i$ is desired, and the fuselage response scanned. The number of scan elements required to obtain an accurate prediction may be large. However, if only the approximate difference in noise level between two cases is needed, then an adequate prediction of $p_i$ could be obtained by measuring $Q_e$ over a much smaller number of elements on which the external sound pressure $p_e$ is largest.

The reciprocal method can also be used to evaluate structure-borne noise transfer functions. The internal sound pressure response due to an externally applied point force is $p_i/f_e$. By reciprocity, this transfer function satisfies

$$p_i/f_e = v_e/Q_i,$$  

where $v_e/Q_i$ is the response from the internal volume velocity source to a point velocity measurement taken using an accelerometer located at the point of force application [9]. This result could be used to evaluate the contribution to the interior noise due to engine imbalance and wing vibration loads being transmitted into the internal acoustic field through the wing-box.

3. EXPERIMENT EQUIPMENT

The full-scale demonstration of the reciprocal approach for noise transmission measurements involves a monopole noise source located inside the aircraft, and a capacitive scanner to measure the external fuselage vibration. This measures the transfer function $Q_e/Q_i$ in equation (1) or (2). The approach was validated by comparing this transfer function for one element to the directly measured transfer function, $p_i/p_e$, in equation (1). The direct measurement required a horn designed to insonify a single element of the aircraft fuselage. The arrangement of the sensors and sources in the two approaches is shown in Figure 2. The equipment is described in detail below.
3.1. AERIAL FUSELAGE

The experimental aircraft is a deHavilland Dash-8 Series 100 fuselage without wings and empennage, shown in Figure 4. The interior is “green”; there is no trim or seats, although the internal insulation is present. As a result, there is less acoustic and structure damping than would be present in an actual aircraft. The aircraft was supported during the tests by an overhead crane attached to the fore and aft edges of the wing box on either side of the fuselage. The aircraft was prevented from swinging by either a foam-lined cradle, or by the foam-lined support stands visible in Figure 4. This support system provides a reproducible method of supporting the aircraft that is representative of the true flight conditions.

The external surface of the fuselage between the fore and aft ends of the passenger compartment was marked off into scan elements 21.5 inches in the axial direction and 5 inches in the circumferential direction. This element size was selected so that the element boundaries are defined by the fuselage frames and stringers. The frames and stringers dominate the structural dynamics of the modes that couple with the internal and external acoustic field and, therefore, details of the skin vibration in between frames are irrelevant. The scan elements are labelled, for reference, A–Q in the axial direction, and 01–64 circumferentially, counter-clockwise when viewed from the front.

3.2. MONOPOLE SOUND SOURCE

The internal sound source is a dodecahedron, with 12, 6 inch, 100 W r.m.s. bass drivers, each centred on a pentagon of sides 6 inches. The sound source is shown inside the aircraft fuselage in Figure 5. Based on the enclosed volume of the dodecahedron, the equivalent spherical radius of the source is 7.5 inches, which is small compared to the wavelengths of interest. Calibration tests indicated that this configuration operates as a uniform monopole source over a frequency range from 50 to 500 Hz, except at distances on the order of the equivalent radius or smaller.

The sound source was calibrated in an anechoic chamber using a reciprocal approach. An auxiliary loudspeaker was placed in the chamber, and the transfer function from the drive current $I_d$ applied to the dodecahedron sound source, to the voltage response $E_v$ of the auxiliary speaker was measured. Next, the dodecahedron was replaced by a microphone,

Figure 5. The internal dodecahedron noise source used for reciprocal measurements.
and the sound pressure $P_d$ at that location due to the drive current $I_a$ applied to the auxiliary loudspeaker was measured. Using reciprocity gives that $E_a/Q_d = P_d/I_a$, since both $E_aI_a$ and $Q_dP_d$ represent power flow into the acoustic system. The calibration curve for the dodecahedron sound source is therefore given by

$$Q_d/I_d = (E_a/I_d)(I_a/P_d).$$

### 3.3. Capacitance Probe

Vibrational volume velocity of the external surface is measured with a hand-held capacitance probe with a concave surface to match the curvature of the fuselage, and with dimensions equal to that of a single scan element. The probe measures the area-averaged surface velocity of the fuselage. This is desirable, since only those features of the vibration that transmit sound effectively below 300 Hz are of interest; finer details of the vibration field are unimportant.

The change in capacitance caused by motion of the fuselage is measured by the circuit shown in Figure 6. The 1000 V polarizing voltage between the probe and aircraft is used to improve sensitivity. This does not pose a hazard to the operator, due to the high impedance of the circuit. Zener diodes are used to protect the electronics. The capacitance plate is also shielded to reduce noise, and the aircraft is grounded.

The probe is shown in Figure 7. A schematic diagram is included as Figure 8 for clarity. The probe has four feet with built-in Linear Variable-Displacement Transducers (LVDT’s) and springs to give a measure of the pressure being applied. This information is displayed on a set of Light-Emitting Diodes (LED’s) so that the operator can maintain a constant holding pressure, and therefore constant offset. An error of $\pm 1$ LED bar corresponds to an error in offset of $\pm 0.002$ inches, yielding a 1.5% change in sensitivity, or an error of $\pm 0.13$ dB. Variations of several bars on the LED display are therefore tolerable. Also, since only frequencies above 50 Hz are important, low frequency errors due to variations in the holding pressure are irrelevant. The Dash-8 fuselage is not a perfect cylinder, and the radius of curvature changes at approximately the floor level. The position of each foot can be adjusted so that the correct offset of the scanner can be maintained while taking data in this region.

The probe was calibrated using a stiff lightweight plate with the same curvature as the aircraft fuselage. The plate’s first bending mode was at a frequency higher than those of interest. The calibration plate was mounted on a shaker, and the output of the probe was compared with the output of 14 accelerometers mounted on the plate. At an offset of 0.25 inches, the probe output is approximately $10^4 V/(m^2/s)$, with an increase in sensitivity as the offset is decreased. Due to surface irregularities on the fuselage, offsets less than
0.25 inches cannot be used at all locations, and this value was therefore used during the scan. Also, some of the elements had patches or protrusions which decrease the effective offset and increase the probe sensitivity. Fringe effects were not measured or accounted for, however, the fringing is on the order of the offset, and is therefore small compared to the dimensions of the plate [15, p. 201].

Figure 7. The non-contacting capacitance probe for surface velocity measurements, set up for hand-held operation.

Figure 8. A schematic of the capacitance probe, including the capacitance plate, frame, LVDT sensor and electrical shield. The fuselage is shown flat for clarity.
3.4. EXTERNAL SOUND SOURCE

To validate the reciprocal approach, the fuselage noise transmission properties on one element were measured directly, using a reversed horn designed to insonify a single element of the aircraft fuselage. The sound output of a loudspeaker is directed through the horn to the scan element, shown schematically in Figure 9. The inside walls of the horn are lined with foam, to eliminate acoustic resonances and improve both the spatial and frequency uniformity of the sound pressure at the mouth of the horn. A probe with a microphone was inserted on one side of the horn near the aircraft surface, and measurements were taken at two points to obtain the average value of the sound pressure field impinging on the aircraft.

Particular care in the design of the horn must be paid to the quality of the seal between the horn and the aircraft. The seal used included both an aluminum shroud that did not quite touch the structure, and a flexible rubber hose. The rubber contacts the structure, but does not alter the dynamics substantially due to its high compliance. Even with a good seal, other elements receive substantial noise, due to both leakage from the seal, and radiation from the sides of the horn. This extraneous excitation of the structure degrades the quality of measurements made with the horn. The results of a scan of the noise on nearby elements indicated that the total force applied to the structure over all of the other elements is roughly one third of that applied to the desired element. Thus, it is likely that the extraneous excitation from the horn is the primary source of discrepancy between the direct and reciprocal measurements.

4. RECIPROCITY VERIFICATION

Several experiments were performed on the Dash-8 fuselage to verify that the system obeyed reciprocity, and that the equipment used provided the desired behaviour and did not itself alter the transfer functions being measured. A typical comparison of the direct and reciprocal transfer functions in equation (3) is given in Figure 10. These data were obtained using a shaker and load cell to force the external surface at a single point, and an accelerometer to measure the surface motion. The reciprocal transfer function used the dodecahedron internal noise source. The point reciprocity test verifies that the vibro-acoustic system is indeed reciprocal, and also verifies the operation of the internal noise source.

Results, comparing the transfer function between sound pressure excited by the horn and internal sound pressure, and between internal volume velocity generated by the dodecahedron source and the external surface vibration measured by the capacitance probe, are shown in Figures 11 and 12. The magnitude and phase are shown for two interior
Figure 10. The magnitude of the direct (solid) and reciprocal (dashed) measurements of the response from a point force to internal noise.

locations; one 28.6 inches (73 cm) from the excitation point and the second 170 inches (432 cm). Excellent agreement is obtained in both cases. The near location is within one wavelength for most of the frequency range shown, while the far location is more than one wavelength away from the excitation. Note that while it is only the magnitude of the final

Figure 11. Element reciprocity verification, near location. Direct transfer function (solid) and reciprocal (dashed): (a) magnitude and (b) phase are shown.
prediction \( p_i \), that is important, the phases of the transfer functions that are used to make this estimate are critical to correctly perform the sum in equation (2). Furthermore, the good phase agreement provides additional verification of the accuracy of reciprocity.

An independent check of the capacitance probe was obtained by comparing its output to that of accelerometers mounted on the fuselage. The largest source of discrepancy between the direct and reciprocal curves is likely to be the inability of the horn to insonify a single element without some leakage affecting other elements of the structure. Thus, it is the reciprocal transfer function that is believed to provide a more accurate characterization of the noise transmission.

5. SCAN RESULTS

5.1. PROCEDURE

Two dodecahedron noise sources were located in the fuselage interior; one near the peak of the port propeller sound pressure field, and a second on the starboard side of the aircraft, approximately one propeller diameter aft. Both interior points were at the head height of a seated passenger. The capacitance probe was then used to measure the transfer function from the internal volume velocity generated by each dodecahedron to the fuselage volume velocity on 480 of the external scan elements. Only those elements on which the applied propeller pressure field was within approximately 15 dB of the peak sound pressure were
scanned. This footprint information is shown superimposed on a “map” of the scan elements, in Figure 13. Analysis of the data indicates that fewer elements are needed; this will be discussed in the next section. A few elements could not be scanned due to surface protrusions greater than 0.25 inches in height. Also relevant to the ability to scan an element are the surface irregularities in adjacent elements on which the scanner feet lie. This problem could be alleviated if the offset was determined and maintained based on the actual offset of the plate, rather than on the offset of the feet.

The noise could be predicted at twice as many internal locations if either the aircraft or the pressure distribution were sufficiently symmetric. Since this aircraft does not have counter-rotating props, the pressure fields on the two sides of the aircraft differ. Furthermore, measurements indicate that due to the asymmetries associated with the doors and their additional frames and stringers, symmetry cannot be used on this aircraft.

A dwell time of roughly 12 seconds was used for each noise source on each element, with broadband noise being used for excitation. This provided reasonable coherence data in most locations at most frequencies, while limiting the total time involved in the scan, and reducing operator strain.

The aircraft cross-section in Figure 2 is not drawn to scale; it is important to note that the radius of curvature of the aircraft is not constant. The area below the floor has a larger radius (62 inches, compared to 53 inches), but this is not as important as the high curvature section (20 inch radius) near the floor on either side in between the upper and lower parts of the fuselage. The offset of the scanner had to be individually adjusted for three rows of elements in this area.

The scan of the fuselage vibration for two internal points allows the computation of the cabin noise at those points due to the propeller sound pressure field. An alternative noise transmission path is the structurally transmitted noise from engine mount vibration, through the wing box, and into the aircraft cabin. This transmission path could also be measured with a reciprocal method, although not on this particular fuselage. The transfer function between applied forces at the engine mount locations to the internal noise is equal to the reciprocal transfer function between the internal volume velocity and the velocity measured by accelerometers at the engine mount points.

Figure 13. A contour plot of the magnitude of the propeller sound pressure field applied to the aircraft fuselage at cruise engine r.p.m., at the blade passage frequency, port side. The area under the wing-box shroud is left blank. Elements shown dotted were not scanned.
5.2. INTERNAL NOISE PREDICTIONS

The information collected for each scan element can be combined with the computer generated propeller pressure field information to predict the internal noise at the dodecahedron noise source locations. The propeller pressure information used was obtained from the propeller manufacturer, and is based on a free field model evaluated at the surface of the aircraft fuselage. As a result, the predicted external sound pressures will be too low, since the model does not take into account either the reflected field, or any other installation effects.

The resulting predicted internal noise levels obtained herein will be low because of this, and also for several other reasons. First, only the fundamental and first harmonic of the blade passage frequency are included, while the next few harmonics are also important. Second, propeller sound pressure information is only available over a part of the fuselage, and the remainder of the area is ignored. Furthermore, while the scan accounts for the dominant noise transmission path, it neglects noise transmission through wing-box vibration. Finally, the boundary layer noise has been neglected. The reciprocity approach is capable of accounting for all of these aspects, provided that the relevant data are available. For this aircraft, only the truncation of the higher harmonics, and the inaccuracies in the specified external pressure distribution are significant sources of error.

The magnitude of the propeller sound pressure field at the blade passage frequency, on the port side of the aircraft fuselage, is shown as a contour plot in Figure 13. These data correspond to a standard cruise engine r.p.m. However, once the scanned data are available, any number of pressure cases can be considered. The response to other engine speeds, and at multiples of the blade passage frequency, were also computed. Several comments about the pressure field information can be made. Because of the direction of rotation of the propellers, the centre of the distribution is higher on the aircraft on the port side (where the tips are downsweeping) than on the starboard side. The peak sound pressure is also higher on the port side. The sound pressure drops off from the peak far more rapidly at higher harmonics, and hence it is the distribution at the blade passage frequency that controls which elements need to be scanned.

The interior noise at the locations of the dodecahedron sound sources can be computed for any given pressure case, based on equation (2). Elements for which no data were available due to the wing shroud were ignored; it is assumed that there is little transmission through the extra skin layer. Elements for which no data were available due to a problem in scanning the element were reconstructed based on the average over existing neighbouring elements.

The internal noise that would have resulted from each sound pressure distribution, had the disturbance frequency differed by a few percent, was computed. The scanned reciprocal transfer functions were used at different frequencies in addition to that desired; however, the effects of the frequency variation on the loading distribution were not accounted for. The reasons for including additional scanned data are twofold. First, errors in the data at a single frequency would produce poor predictions at that frequency. This is particularly important near 60 Hz, where electrical noise effects the results. Second, the variation in internal noise over nearby frequencies is indicative of the variation that could be expected between aircraft or between different operating conditions. Modal frequencies are likely to vary by several percent, and therefore, the variation in the response of a single aircraft over a frequency range of a few percent width is representative of the variation in response that may be observed between aircraft. Hence, the average response over neighbouring frequencies is a better prediction of the internal noise than the prediction at only the desired frequency.
The internal noise predicted for the higher of the two engine r.p.m. cases considered is shown in Figure 14. The magnitude of the A-weighted response is normalized by the average response at the first location at this r.p.m. A range of ±5 Hz is shown for both the blade passage, and twice the blade passage frequency. There is substantial variation over frequency between the prediction and the average values, shown in Table 1. The average was computed with a triangular weighting on the nearby frequency points. The average levels are consistent with those measured for these harmonics on actual aircraft in flight. The specific entries in this table are not as important as the observed trends. On average, the noise at the near location was 4·2 dB(A) higher than that at the far location. The response at the blade passage frequency was 2·7 dB(A) higher than that at the next harmonic; and the response at higher engine r.p.m. was on average 0·9 dB(A) higher than at the lower speed.

Of particular interest to the potential user of the scanning technique developed and demonstrated here, is the number of elements that must be scanned to predict the internal noise with adequate accuracy. The effort involved in future scans could be greatly reduced if the number of elements required were reduced. The noise prediction in Figure 14 used sound transmission and external noise pressure information for all 450 of the available elements. The same prediction was also made using only those elements on which the pressure field was highest. The results obtained from these tests are plotted in Figure 15 for

<table>
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<tr>
<th></th>
<th>BPF</th>
<th>2 x BPF</th>
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<tbody>
<tr>
<td></td>
<td>Near</td>
<td>Far</td>
</tr>
<tr>
<td>Lower r.p.m.</td>
<td>2·1</td>
<td>−4·9</td>
</tr>
<tr>
<td>Higher r.p.m.</td>
<td>0·0</td>
<td>2·1</td>
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one of the propeller sound pressure distribution cases. Again, the magnitude is normalized by the average response at location 1 at the higher r.p.m. Curves are shown for the cases in which those elements that received less than 15 dB, less than 10 dB, and less than 7.5 dB below the peak sound pressure were dropped. The number of elements used, and the change in the average noise predicted for these cases are shown in Table 2. In general, omitting elements with sound pressure more than 15 dB below the peak level does not substantially alter the prediction. Some degradation in prediction occurs at the 10 dB level, and with a further reduction in elements, the prediction quality suffers further. The information in Table 2 implies that fewer elements than the total used herein could be scanned, while still providing an adequate prediction. Furthermore, even with the least number of elements considered, the trends in the data are still noticeable. Thus, for purely comparison purposes to establish how much reduction has been obtained by a particular noise reduction scheme, a small number of elements may be adequate.

**Table 2**

*Predicted noise using fewer elements. The number of elements kept in the prediction is shown. Also shown is the resulting change in predicted internal noise at two points at the blade passage frequency and twice the BPF.*

<table>
<thead>
<tr>
<th>dB level kept</th>
<th>Number of elements</th>
<th>Predicted noise (dB)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>BPF 2×BPF</td>
<td>BPF near</td>
</tr>
<tr>
<td>All</td>
<td>450 450</td>
<td>0.0</td>
</tr>
<tr>
<td>−15</td>
<td>377 306</td>
<td>+1.0</td>
</tr>
<tr>
<td>−10</td>
<td>292 186</td>
<td>+0.7</td>
</tr>
<tr>
<td>−7.5</td>
<td>202 123</td>
<td>−0.5</td>
</tr>
<tr>
<td>−5</td>
<td>95 53</td>
<td>−1.9</td>
</tr>
</tbody>
</table>
The other key component in reducing the time needed to complete a scan of the aircraft is the dwell time on each element. The data taken here used a total dwell time (for both reciprocal source locations used) of roughly 25 seconds for each element scanned. This time could be reduced, but with little gain. The time taken per element is dominated by the time it takes to move the scanner into position, and obtain the correct offset distance. This could be reduced with either an automated approach, or with a lighter scanner design to reduce operator strain. The dwell time for measurements would be more important if more internal reciprocity noise source locations were used.

6. CONCLUSIONS

A reciprocal technique was used to evaluate the noise transmission characteristics of an aircraft fuselage, which can be used for validating computer models, or for evaluating noise reduction methods. The aircraft fuselage was divided into a number of scan elements, and the transfer function between interior noise and the response on each element was combined with a specified computed external propeller sound pressure field to predict the interior noise at specified locations. The reciprocal approach uses a monopole noise source inside the aircraft, and a capacitance probe to measure the fuselage surface response. The approach was validated by comparing the direct transfer function (internal sound pressure over applied external sound pressure) for one element with the reciprocal measurement (fuselage surface volume velocity over internal source volume velocity). Excellent agreement between these reciprocal transfer functions was obtained.

The total time needed to perform the scan could be reduced by reducing the number of fuselage elements scanned. Analysis of the data indicated that a reasonable prediction of internal noise is obtained if only those external elements on which the propeller sound pressure field is within 10 dB of the peak are measured. Further improvements could be made with a lighter scanner to reduce operator strain, or an automated system for moving the scanner. The probe offset distance could also be automatically measured, and actively controlled by some displacement actuators within the scanner. This would reduce the requirements on the operator, and improve accuracy. The data from these experiments also indicate that the probe used herein provided unnecessary circumferential resolution, however, a larger probe would have been unwieldy. Only two internal noise source locations were used to predict the noise due to the propeller at two interior locations. Additional noise sources, or an automated approach to moving those used, would be useful in obtaining noise predictions throughout the cabin. The key advantage of the reciprocal approach is that once the transmission information is obtained for a given internal location, the noise at this location can be predicted for any external sound pressure distribution.

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