ACTIVE NOISE CONTROL

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Abstract

It has been proposed that prop fans could be used on a new generation of trans-atlantic aircraft but one major limiting factor is the very high internal noise levels that they are likely to produce. Novel methods of noise control will be needed to overcome this problem since adding extra stiffening or mass to the fuselage in a conventional manner will not be sufficient without a significant weight penalty. The control of this noise by active means has been suggested as it may be comparatively light and very effective at low frequency. Active noise control involves producing a cancelling sound field in antiphase as a duplicate to the existing noise so that the two add up to produce silence (at least in theory!). Within a confined space, like the aircraft cabin, it may seem appropriate to tackle the problem by attempting to reduce the internal acoustic modes, but since the cabin is relatively 'dead' the modes are heavily damped and overlap one another substantially. In this case it is more appropriate to consider the sound field as being radiated from the panels and propagating unimpeded. Consequently the most suitable position for the loudspeakers used to produce the antiphase field is in the propagation path just inside the fuselage skin. This paper will describe preliminary experiments conducted in a conventional propeller aircraft (BAe 748) which demonstrated the likely gains of using active noise control together with some of the factors that will limit its performance in practice. It concludes that active control systems will remove the internal noise limitations on the use of prop fans.

Noise transmission to the cabin

The internal cabin noise in an aircraft caused by the propellers, at the blade passing frequency and its harmonics, is generated and transmitted into the cabin in a variety of ways. The movement of the blades through the air causes intense local pressure fluctuations. These cause vibration of panels close to the blades and the panels excite the air inside the cabin, locally by responding directly to the external pressure and at a distance through the excitation of structural waves. The local pressure fluctuations around the propellers also generate an acoustic field which propagates away from the propellers and impinges upon the fuselage structure. This structural excitation also excites the internal cabin space.

The lift generated by the aerofoils of the propellers causes vortices to trail from the propeller tips. If the propeller is mounted in front of the wing, the vortices will act upon the wing and induce a structural response which in turn excites the cabin. The fluctuating lift and thrust forces which act equally upon the air and back upon the propeller cause vibrations of the propeller shaft which are transmitted to the cabin. If the propeller is mounted behind the wing, as a 'pusher', the wake of the wing generates a substantial non-uniformity in flow upstream of the propeller and this greatly increases the fluctuations in the lift and thrust forces on the propeller.

These sources and transmission mechanisms will exist for all different designs of aircraft but their relative importance in generating internal cabin pressure fluctuation will depend strongly on the geometry.

When the propellers are close to the fuselage skin the intense local aerodynamic pressure fluctuations, which rapidly decay with distance from the blades, will generate a large vibrational response in the fuselage skin. The acoustic far-field of the propellers which will impinge upon the rest of the fuselage will do so at grazing incidence. The effective impedance of the structure to waves away from normal incidence will increase with angle away from the normal and thus the transmission of sound through the structure will be substantially reduced for these large angles of incidence. This will only be valid for frequencies below the coincidence frequency, above coincidence bending waves travelling in the fuselage will have the same speed as the sound incident at some angles and the sound will be transmitted with little loss. For most conventional fuselage structures the coincidence frequency will be above a few kilohertz and thus this will not be relevant. Consequently, for low-frequency sound, the largest fuselage panel vibrations and thus the greatest transmission will be very close to the propeller plane.

When the propellers are positioned far from the fuselage skin the intense aerodynamic pressure fluctuations will not impinge upon the skin and the angles of incidence of the air-borne sound will be close to the normal. These two effects will combine to reduce the overall effect of the aerodynamic/acoustic sound path and will also spread the effect over the whole fuselage.

The level of the direct vibration excitation of the structure from the propeller shaft is unlikely to be affected by propeller position but will be changed by the design of the propeller and its position relative to the wing.

Active control

All of these transmission paths will excite the air inside the cabin and internal noise will result. Active noise control is a technique where the unwanted pressure fluctuations which constitute noise are cancelled by equal and opposite pressure fluctuations deliberately generated by loudspeakers or other acoustic sources. Since the aim is to reduce the internal noise the most direct approach would be to attempt to duplicate the internal cabin noise field with internally mounted loudspeakers.

The first question that arises is how many loudspeakers would be required to duplicate the field. Generally, this will depend upon how closely the field must be matched and thus on the degree of cancellation (i.e. reduction in sound level) required, but it will also be affected by the complexity of the sound field. One measure of the complexity which can be related to the number of loudspeakers required is the number of modes in the cabin excited by the propeller frequencies.

The modes with natural frequencies close to the propeller harmonics will be excited if their damping is sufficiently large that the modal width includes the propeller tones. Provided that the excitation of the fuselage is spread widely then all of these modes will be excited. The number of modes can be determined either accurately by measurement (using the technique described by Eatwell [1]) or approximately by a simple estimation, described below.

Modal Spacing

For a rectangular enclosure with rigid walls the expected number of modal peaks per Hertz is given by [2]

$$\frac{dN_f}{df} = \frac{1}{C}\left[\frac{4\pi V f^2}{C^2} + \frac{\pi S f}{2C} + \frac{L}{8}\right]$$

Where V is volume, S is the surface area, L is the edge length and C is the speed of sound. Whilst this will not be accurate for the shape of an aircraft if the rectangular shape that encloses the internal cabin is used the approximation will be fair.

Modal Width

The width of a mode can be determined from its damping and the rate of decay is related to the damping. Thus if some source mechanism could be used to excite just one mode then the source could be switched off and the decay of the sound field measured. In practice it is usually impossible to excite a single mode, but it is quite likely that the damping factors of modes close together in frequency will be similar. If a few modes in a narrow frequency band are excited then the damping, estimated from the combined decay rate, will be representative. The relationship between the reverberation time T, the time for the field to decay by 60 decibels, and the modal width is

$$\Delta f = 2.2/T$$

The total number of modes that are excited by a tone is the product of the modal width and the inverse of the modal spacing.

BAe 748

Measurements have been made on a propeller driven aircraft, a British Aerospace 748, to determine the number of modes that may be excited by the first three propeller tones. These show that, with the normal acoustic lining, the fundamental of 88 Hz will excite approximately 12 modes, and the first and second overtones will excite approximately 21 and 43 modes. Since the internal noise spectrum is dominated by these harmonics and the second overtone is likely to be the most disturbing, these measurements would suggest that some 50 loudspeakers positioned around the cabin would be sufficient to duplicate the field in antiphase. This number is rather large and it is likely that system involving that number of independently controlled loudspeakers would be expensive and difficult to maintain.

However, the propellers are positioned very close to the fuselage and measurements of the skin vibration show that the amplitude of vibration in the propeller plane is very significantly higher than away from it. In addition, measurements of the vibration of the engine nacelle at frequencies close to the propeller rate and of the resultant sound that this vibration causes in the cabin when compared with those at the propeller tones indicate that the transmission of sound into the cabin via the direct vibration path is not significant when compared with the air-borne path.

Thus the multi-mode sound field that will be set up in the cabin of the aircraft will be produced by vibration of panels of limited area. If loudspeakers are positioned close to these panels then it is likely that they will be able to excite the multitude of cabin modes in a similar way to the propeller source. The number of loudspeakers required will be determined by the extent of the vibrational area and the wavelength of the sound. The loudspeakers must be positioned closer than on a half-wave length grid, and the closer the spacing the more accurate will be the matching of the sound fields near the sources.

The number of loudspeakers required can be determined accurately by a measurement technique described by Ffowcs Williams and Ross [3] or approximately by measuring the extent of the vibrational area. If it is assumed that the radiation of sound from the panels is proportional to the amplitude of their movement then the radiating area will be that which vibrates most. This assumption is not entirely true because the radiation from a plate will depend upon the movement of the whole plate. Some types of motions will be much more efficient at radiating sound, for example waves travelling in the plate at supersonic speeds will launch sound in particular directions whereas subsonic waves with the same vibrational amplitude will only generate an evanescent field which decays rapidly with distance from the walls. However the vibrational pattern is likely to be composed of subsonic waves at the frequencies of interest and the radiation will be dominated by the scattering of waves from discontinuities in the fuselage structure. Since the discontinuities are fairly evenly distributed the approximate method of determining the area of cancellation will be fairly accurate.

Preliminary experiments

The building and testing of a working prototype active control system for a flying aircraft will require some extensive measurements and preliminary trials. The first stage of a series of experiments have already been conducted on a BAe 748.

These have identified the sound transmission paths and their relative levels of excitation. They have lead to the conclusions described above. Further proving trials have been conducted on the ground where the assumed source of noise, the aerodynamic pressure fluctuations, was simulated by a loudspeaker, and an active control system using only four loudspeakers was installed. The source was configured to produce excitation at the propeller fundamental frequency and in operation the control system reduced the level of the internal noise by 15 decibels in the propeller plane where the level was loudest and by slightly less further aft in the cabin where the level was initially lower.

Further measurements at the first three propeller tones showed that some 10 loudspeakers would be required to produce a reasonable level of attenuation in the cabin.

Practical limitations

The experiment was conducted using a single loudspeaker source, however, the aircraft has two propellers and these will inevitably be at close, but not identical, frequencies. The operation of the active sound cancellation system will be affected by the twin tones and measures will need to be taken to limit the deterioration in performance. These can normally be achieved with minor modifications to the active sound control system strategy [3].

The active control systems in the cabin will generate signals to cancel the internal field and these signals will be adjusted in response to the changing sounds produced by the propeller as its speed and pitch are changed. The response time of the adaptive controller will need to correspond to the likely rates of change of the sound field if there is not to be an increase in noise during the changes. Measurements of the dynamic noise environment described in Ffowcs Williams and Ross [3] can be made to ascertain the computation rate required by the adaptive controller but it must be noted that the rate generally increases with the cube of the number sources of cancelling sound.

The movement of passengers and crew inside the cabin should not affect the performance of the cancellation system. Provided that the loudspeakers of the control system are positioned to intercept the sound as it travels into the cabin, the launched cancelling sound and the primary sound fields will be affected equally by the movement. Consequently the cancelling sound that should be generated by the loudspeakers will be unchanged. However, if the performance of the control system is monitored in the cabin near any potential movement, then the system must be specifically tailored to suit.

Conclusions

Initial studies on a BAe 748 have shown that the internal cabin noise can be attenuated by 15 decibels in the loudest part of the cabin, i.e. around the propeller plane. Control systems of the complexity that will be required have been constructed and used routinely [4]. The technology is awaiting demonstration in flight on a BAe 748. The suitability of active sound control for other propeller and prop fan driven aircraft can be ascertained relatively easily using the procedures described here. Active control is likely to remove the internal noise limitation on the use of prop fans.

References

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