Experimental Study of Flight Effect on Fan Noise*

(2nd Report , Fan Noise Source Variation due to Flight Effect)

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Clarification of fan noise source variation due to a flight effect is important for a turbofan noise reduction and a noise estimation. A fan noise spectral extent and a range of fan operation influenced by the flight effect were studied experimentally using a large turbofan engine and a geodesic 4m diameter semi-sphere inflow control device that can simulate the flight effect on fan noise in static engine tests. The fan noise reduction by the flight effect in a fan approach condition was higher than that in a fan take-off condition, because the fan rotor generates BPF tones by itself near the take-off condition. The highest reduced component in fan noise spectra was a fundamental fan blade passing frequency (BPF) tone, whose reduced level was 20 dB at maximum. Higher harmonic BPF tones and a buzz saw noise were also reduced by the flight effect, but a reduction of broadband noise was not evaluated in the whole range of fan operation.

Key Words : Aeroacoustics, Turbofan, Fan Noise, Inflow Control Device, Flight Effect, Inflow Turbulence

1. Introduction

Aircraft are required to meet the noise standard regulations ICAO-CAN 6 and FAR-PART 36 stage 3 with minimum decreases in performance and efficiency of both aircraft and aero-engine. Many engineers make their efforts to reduce aero-engine noise with the following two methods, because an aero-engine is a main noise source in aircraft [1][2]. One is a reduction in intensity of noise source, the other is sound absorption by acoustic linings equipped on insides of engine intake and exhaust ducts.

For accomplishment of the maximum aero-engine noise reduction in flyover, the two methods have to be effectively used at the base of accurate assessment of aero-engine noise in flyover. Aircraft flyover noise data pointed out that an aero-engine fan noise level in flyover was widely different from that in a ground static test, mainly on account of a new noise production through fan rotor-inflow turbulence interaction in the ground test [3][6][7][8].

Therefore, elucidation of fan noise difference between in flight and in

static test, namely a flight effect, was required and then a lot of studies for the flight effect on fan noise have been carried out in U.S.A. [1][3]. But, the flight effect on fan noise source variation is not yet made clear enough.

For research and development of aero-engine noise reduction techniques and noise estimation, a static engine test is cheaper than a flight test and also the experiment in static test is easy as compared with that in flight test. From a series of basic studies on inflow control devices (ICD), a geodesic 4m diameter semi-sphere inflow control device for large turbofan engines has been developed at NAL [4]. The ICD can suppress sufficiently inflow turbulence and distortion with no impediment to acoustic wave transmission. Therefore, it

Fig. 1 FJR 710 turbofan engine and ICD installed on out-door engine test stand

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can function effectively for simulating in-flight fan noise characteristics in the static test.

After verification of the capacity of the developed ICD, NAL carried out a static noise test of large turbofan engine with the ICD for the purpose of clarifying fan noise source variation due to flight effect and collecting turbofan engine noise data in a flight condition [6]. The engine noise study using a large turbofan engine and a large inflow control device as employed in our experimental study seems to be only a few such attempts in the world [5].

Our experiments were performed with a main emphasis on elucidation of the following two subjects (i) and (ii).

(i) Spectral extent of fan noise which is different between in static engine test and in flyover : an influence of the flight effect on noise level and radiation pattern of fan BPF tones, a buzz saw noise, and a broadband noise.

(ii) Fan operating range where the fan noise is affected by the flight effect.

From a series of our experiments, it was made clear that a fan noise reduction by the flight effect in a fan approach condition was higher than that in a fan take-off condition, because the fan rotor itself generates BPF tones nearly in the take-off condition. The highest reduced component in fan noise spectra was a fundamental fan blade passing frequency (BPF) tone, whose reduced level was 20 dB at maximum. Higher harmonic BPF tones and a buzz saw noise were also reduced by

Fig. 2 ICD structural element and flow conditioning materials

the flight effect, but a reduction in broadband noise was not evaluated in the whole range of fan operation.

2. Experimental installations and procedure

A turbofan engine FJR-710/600 equipped with a geodesic 4m diameter semi-sphere inflow control device (ICD) is illustrated in Fig.1. The inflow control device acts as a flyover fan noise simulator, not as flyover jet noise simulator.

Figure 2 illustrates a hexagonal structural element composing the ICD and flow conditioning materials used in the element. A perforated plate controls and reduces a steady component of inflow distortion and turbulence in accompany with two inflow conditioning materials such as a honeycomb core and a wire mesh. The wire mesh was placed downstream of the honeycomb core as a very efficient turbulence conditioning material ; this effect was found through basic experiments on turbulence reduction [4].

As the first step of our study, an ICD performance test was carried out in the two viewpoints of aerodynamics and acoustics. An acoustic test of the ICD revealed that an acoustic transmission loss of the ICD was less than 1 dB, and its impediment to acoustic waves radiated from the fan was little. Aerodynamic test results of the ICD indicated that the ICD could reduce a turbulence intensity by one-third to be 1 % intensity. The reduced turbulence level was the same as that on the fan face in a flight condition.

From the two tests, it was made clear that the ICD possessed an effective function of simulating the in-flight fan noise characteristics in a ground test. The fabrication and characteristics of the ICD are cited in Reference [4].

The flight effect on fan noise and the turbofan engine noise in flyover condition were studied with the ICD equipped on an intake nacelle of the turbofan engine. Fig. 3 is a view of outdoor engine noise test. The flight effect on

Fig. 3 Over view of out-door engine noise test

fan noise was evaluated from a difference in sound pressure level of the turbofan engine between the case of the ICD equipment and the case of no ICD equipment at the same fan operating conditions.

For examination of the fan operation range where fan noise is affected by the flight effect, six cases of fan rotational speeds were selected: these were 64%, 69%, 78%, (approach condition), 86%, 93%, and 100% (take-off condition) of a fan design rotational speed. In engine noise tests, acoustic lining equipped on the duct surface of a flight intake nacelle were covered with thick aluminium tapes in order to make clear the flight effect on fan noise source.

Sound pressure level radiated from the turbofan engine was measured with microphones equipped on 17 microphone stands which was aligned at 10° intervals on 45 m radius circle at the same height as the engine center line, as shown in Fig. 4. On each microphone stand, two microphones were set. One was a microphone placed at the same height as the engine center line, the other was a microphone placed at 25 mm above the ground level. Sound pressure signals from the 34 microphones were recorded during 100 seconds and were analyzed with digital spectral analyzers to obtain 128 times-averaged narrow band spectra and 32 times-averaged one-third octave band spectra. These were used in calculations of a sound power level (PWL) and a perceived noise level (PNL) of the turbofan engine.

The FJR 710-600 turbofan engine used in this experiment is a turbofan engine of 49 kN static thrust and 6.5 bypass ratio. In the turbofan engine, 33 fan rotor blades and 68 outlet guide vanes (O.G.V.) were selected; this blade number ratio can maintain a fundamental blade passing frequency (BPF) tone generated by fan rotor-O.G.V. interaction in the cut-off condition at the lower than 100% fan design speed, as indicated in Fig. 5. The BPF tones produced by a booster stage and a core-compressor may be affected by the flight effect. The

Fig. 4 Measuring method and location for turbofan engine noise

Fig. 5 Variation of BPF tone production with fan rotational speed

cut-on fan rotational speeds of BPF tones produced by several noise sources are illustrated in Fig. 5.

3. Experimental Results

3.1. Overall view of flight effect on fan noise

Figs. 6(a), (b) and (c) indicate one-third octave band spectra of sound pressure at measuring locations of 60° , 90° and 150° at a 78% fan design speed. A strong influence of flight effect on fan noise appeared at this fan speed.

In each figure, two acoustic data curves are illustrated. One is sound pressure spectra in the case of the ICD equipment on the intake nacelle (with-ICD), the other is sound pressure spectra in the case of no ICD equipment (without-ICD). Sound pressure level difference between the two curves at each one-third octave band centering frequency represents a sound pressure level reduced by the flight effect.

In the case of 60° measuring location, a strong influence of flight effect appeared on a fundamental fan blade passing frequency (BPF) tone, and the maximum reduction level was about 13 dB. The flight effect also affected higher harmonic BPF tones. The reduced sound pressure levels were 3 dB for 2nd harmonic and 4 dB for 3rd harmonic.

A broadband noise in the frequency domain below 1 kHz was not affected by the flight effect. This broadband noise was considered to mainly consist of an upper surface blowing noise, a fan exhaust jet, and a primary jet noise which

Fig. 6 Flight effect on fan noise spectra at 78 % fan speed

were not affected by the flight effect. The upper surface blowing noise is produced by interaction between the exhaust jet and the wing surface, which is a lower frequency noise centered at about 80 Hz.

At the 90° measuring location, a fundamental fan BPF tone was also strongly influenced by the flight effect, the same as in the case of 60° and its reduced level was about 10 dB. At this location, only a little flight effect was recognized on higher harmonic BPF tones. Examination of acoustic data at 60° and 90° measuring locations showed that the flight effect affected a radiation pat-

tern as well as a sound pressure level. A broadband noise level in a frequency domain below 1 kHz was affected only a little by flight effect, the same as in the case of 60° measuring location.

At 150° measuring location, a reduction of fundamental BPF tone was 5 dB and that of higher harmonic tones was nearly zero. Only a little reduction of broadband noise in a frequency domain below 1 kHz was recognized.

While, at 100% fan speed, flow Mach number relative to the fan rotor exceeds 1.0 and a buzz saw noise is generated whose main frequency domain is from 1 kHz to 4 kHz, as shown in Fig. 7. A broadband noise reduction due to the flight effect in a frequency domain below 600 Hz was not obtained, but in a frequency domain including the buzz saw noise, a sound pressure reduction level from 2 dB to 4 dB was recognized. A fundamental BPF tone reduction level was about 2dB and this level was remarkably lower than that in the case of 78% fan speed.

3.2 Flight effect on fundamental BPF tone

Figures 8 (a)-(c) represents fundamental BPF tone data of with-ICD and without-ICD at three fan rotational speeds of 78%, 86%, and 100%: these are results of examining the flight effect variation on sound pressure levels and a radiation pattern of the fundamental BPF tone with a fan rotational speed. These tone data were obtained from 20 Hz narrow frequency band analyses.

The influence of flight effect on fundamental BPF tone level and radiation pattern was strongly dependent on whether the fundamental BPF tone generated by a fan rotor itself was in cut-off or in cut-on. In the cases of 78% and 86% fan rotational speeds where the fundamental BPF tone was in cut-off, the tone level reduced by flight effect was 20 dB at maximum, and the direction of maximum reduction was in a range from 60° to 90°. This phenomenon indicated that a noise level in the lateral direction of turbofan engine was strongly influenced by the flight effect.

Fig. 7 Flight effect on fan noise spectra at 100 % fan speed

(a) In the case of 78 % fan speed

(b) In the case of 86 % fan speed

Meanwhile, in the case of 100% fan speed where the tone was in cut-on, the direction influenced by flight effect was an engine front, and the reduced level was 10 dB at maximum which was lower than that in the case of 86% fan speed.

The direction of the maximum tone reduction changes from the engine lateral direction to the frontal one, with the variation of fan speed from 78% to 100%. The cause of this phenomenon was considered as follows: the inlet distortion and the inflow turbulence breathed into the turbofan engine cause a circumferential distortion possessing a large lobe number at the fan face. The interaction between this distortion and the fan rotor produces spinning pressure waves possessing a comparatively large lobe number and thus these spinning pressure waves result in the maximum sound pressure in the turbofan engine lateral direction at fan speeds of 78% and 86%.

Meanwhile, as the fan speed increases to a 100% design speed, a cut-off ratio m_μ of the spinning pressure waves become a larger number. These waves radiate a high level tone in the frontal direction of engine. Therefore, the direction of maximum tone level changed from the turbofan engine lateral

(c) In the case of 100 % fan speed

Fig. 8 Flight effect on fundamental BPF tone radiation level and pattern

direction to the engine frontal direction.

The direction of the high tone level reduction due to the flight effect exactly corresponds to the direction possessing the maximum tone level generated by fan rotor-inflow distortion interaction, because the tone is reduced by the flight effect.

Figures 9(a) and (b) demonstrate the flight effect variation of fundamental BPF tone with a fan speed at two measuring locations of 60° and 90°. As a fan speed exceeded a 65% fan design speed, a sound pressure level reduced by the flight effect increased to the maximum 18 dB at 85% fan speed. However, at a fan speed beyond 90° where the fundamental BPF tone produced by fan rotor itself was in cut-on, a sound pressure level reduced by the flight effect decreased to 3 dB.

At a fan speed of 65%, a fundamental BPF tone level influenced by the flight effect was small. The reason was considered as follows: an inflow distortion is a small quantity and weak, because an engine mass flow is comparatively small, and thus a fan rotor-distortion interaction tone is weak.

As a fan speed increases from 64% to 90% design speed, an engine mass flow increases and the strength and quantity of inflow distortions increase. Besides this phenomenon, a cut-on acoustic waves produced by the fan rotor-inflow distortion interaction increases with a fan speed increase. These two phenomena resulted in an increase of radiated acoustic power. Therefore, with an increase in a fan 70% to 90%, the tone reduction level due to flight effect increased; the flight effect eliminates the inflow distortion-rotor interaction tone. Beyond a 90% fan speed, the flow Mach number relative to rotor exceeds 1.0 and the fundamental BPF tone is produced by fan rotor itself whose tone is not influenced by the flight effect.

From examination of tone levels variation with fan speed, the followings were presumed: beyond a 90% fan speed,

(a) At a measuring location 60°

(b) At a measuring location 90°

Fig. 9 Variation of flight effect on fundamental BPF tone with fan speed

the tone level produced by fan rotor itself is only a little lower than the tone level produced by fan rotor-inflow distortion interaction which is influenced by the flight effect. Therefore, the tone reduced by the flight effect was masked by the tone produced by fan rotor itself and thus the fundamental BPF tone level reduced by the flight effect appeared lower than that in lower fan speed cases.

Figures 10(a) and (b) indicate a flight effect on radiation pattern of 2nd harmonic at a 86% fan speed and a variation of flight effect with fan speed, respectively. In comparison with the case of fundamental BPF tone, the reduced 2nd harmonic level was lower, being 5dB at maximum. The flight effect decreased as the fan speed exceeded 90%, as in the fundamental BPF tone case. The direction of large reduction was from 30° to 90° near the engine side. The reasons for these phenomena were considered to be the same reasons for fundamental BPF tone case.

3.3. Flight effect on buzz saw noise

Flight effect on buzz saw noise is illustrated in Fig. 11. 2 kHz and 4 kHz spectral components representative of a

(a) Flight effect on 2nd harmonic BPF tone radiation pattern

(b) Variation of flight effect on 2nd harmonic BPF tone with fan speed

Fig. 10

buzz saw noise are selected in Fig. 11. The buzz saw noise reduction due to the flight effect revealed that the inflow distortion and turbulence influenced the production of buzz saw noise. The cause of buzz saw noise reduction was supposed as follows: the flow distortion and turbulence produce a little different flow pattern for each fan blade. The un-equality of location and intensity of shock waves of fan blades is reinforced so more that a buzz saw noise caused by the un-equality of shock waves could have a higher intensity sound. However, in the case of with-ICD, as the ICD attenuates the un-equality of shock waves by reduction of inflow distortion and turbulence, the buzz saw noise level drops.

3.4. Flight effect on broadband noise

An broadband noise can be produced by an inflow distortion or turbulence-fan rotor interaction and an inflow distortion-booster stage or compressor blades interaction. The flight effect on the broadband noise is given in Fig. 12, where one-third octave band data centering around frequency 1 kHz in 3 cases of fan speeds 64%, 78% and 86%, are displayed for two cases of with-ICD and without-ICD. The level difference of

Fig. 11 Flight effect on buzz saw noise

sound pressure between with-ICD and without-ICD cases corresponds to the influence of flight effect.

The flight effect appeared little in the whole radiative direction and either did not change with variation of fan speed, though only a little flight effect was recognized at fan speed 64%. From these experimental results, it was presumed that the broadband noise level produced by inflow turbulence-fan rotor interaction was lower than the broadband noise level produced by other noise sources and thus the flight effect on the broadband noise could not appear on the turbofan broadband noise data.

3.5 Flight effect on acoustic power level of turbofan engine

Flight effect on acoustic power

Fig. 12 Flight effect on broadband noise (In the case of 1 kHz centered frequency)

spectra of turbofan engine is shown in Figs. 13(a), (b) and (c) for three cases of fan speeds. Acoustic power spectra were calculated from far field acoustic data measured at 17 locations. In the cases of fan speeds 78% and 86%, a reduction of fundamental BPF tone power level by the flight effect was remarkably large and its level was 10 PWL(dB). This reduced level was close upon an acoustic power reduction level estimated by theoretical examination with turbulence intensity reduced by flight effect [4]. The reduced acoustic power levels due to flight effect were about 3dB in 2nd harmonic and 3dB in 3rd harmonic BPF. While, a broadband noise power level reduction by the flight effect was nearly zero in the whole range of fan speeds.

In the case of 100% fan speed, a reduction of acoustic power spectra in a frequency domain higher than 500 Hz was recognized, because a buzz saw noise was affected by the flight effect. A fundamental BPF tone reduction at a 100% fan speed was about 3dB and was smaller

Fig. 13 Estimation of flight effect on turbofan engine noise by PWL

(a) In the case of 78 % fan speed

(b) In the case of 100 % fan speed

Fig. 14 Estimation of flight effect on turbofan engine noise by PNL

than that at a 86% fan speed.

3.6 Flight effect on PNL(dB) estimation

Figures 14(a) and (b) indicate flight effect on a perceived noise level (PNL) estimation in the cases of 78% and 100% fan speeds, which is one of sound units for aircraft noise estimation. The flight effect on PNL estimation at 78% fan speed corresponding to an aircraft approach condition was 6 PNL(dB) larger than that at 100% fan speed corresponding to an aircraft take-off condition. The direction of large PNL reduction lay in a range from 60° to 90° at a 78% fan speed, while at a 100% fan speed, it did in a range from 0° to 40° .

4. Concluding remarks

For clarification of fan noise spectral extent which is different between in static engine tests and in flyover, and of fan operation range where fan noise is affected by forward flight effect, turbofan engine noise tests were carried out in the outdoor noise test field. In the experiments, were used a large turbofan engines and a geodestic 4m diameter semi-sphere inflow control device that can simulate the flight effect on fan noise in static engine test conditions.

The following have been revealed from the study.

(i) Fan noise is strongly influenced by the flight effect.

(ii) Fan operation range where fan noise is strongly affected by forward flight effect is from a 78% fan speed corresponding to an aircraft approach condition to a 90% fan design speed.

The remarkable influence of flight effect appeared on a fundamental blade passing frequency tone and the reduced sound pressure level was 20 dB at maximum in the direction of engine side. A reduced acoustic power level of fundamental BPF tone was 10 dB at a fan speed corresponding to aircraft approach. Higher harmonic tone was reduced by the maximum 3dB in PNL. A buzz saw noise was also affected by flight effect and the reduced level was in a range from 2dB to 5dB in SPL. Flight effect on a broadband noise was not evaluated in the whole fan operation ranges.

(iii) The fan noise reduction by the flight effect in a fan approach condition is higher than that in a fan take-off condition.

Beyond a 93% fan design speed, a fundamental BPF tone is generated by the fan rotor itself. This tone is not influenced by flight effect and this tone level approaches to a tone level produced by the inflow distortion-rotor interaction that can be reduced by flight effect. Therefore, at a fan speed higher than 93%, it was considered that the reduced fundamental BPF tone level due to flight effect was masked by the tone unaffected by flight effect and thus appeared lower than that at a fan speed lower than 93%.

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