NOISE REDUCTION BY THRUST VECTORING FOR SUPERSONIC BUSINESS JET

Shigeru HORINOUCHI
Japan Aerospace Exploration Agency

Keywords: SST, SSBJ, Noise reduction, Thrust Vectoring, Conceptual Design

Abstract

This paper describes the possibility of thrust vectoring for supersonic business jet (SSBJ) to reduce jet noise by making use of its directional distribution characteristics. The Noise calculations for an arrow wing SSBJ and a variable sweep wing SSBJ showed significant noise reduction under take-off climb, sideline and approach conditions. The effect of the thrust vectoring was up to 9dB reduction in take-off climb noise and up to 20dB reduction in cumulative noise. The variable sweep wing configuration with thrust vectoring showed the best result of 27dB reduction in cumulative noise.

1. Introduction

The noise reduction for civil supersonic aircraft is a very important design issue. Numerous efforts have been made to decrease engine exhaust noise, but it still looks difficult for supersonic civil airplane to satisfy the current airport noise regulation. This paper investigates the possibility of the thrust vectoring to decrease airplane noise during take-off and landing phase. Usually, airplane jet noise has strong directional distribution characteristics that forms a highly directional lobe directed at approximately 20 deg. to 40 deg. angle from the centerline of the jet exhaust direction. When the jet thrust vector is deflected downward, the jet exhaust direction moves upward and the noise lobe is pointed upward. Consequently, the directional distribution of noise toward ground decreases (Fig.1). However, the thrust vectoring will apparently degrades the airplane climb capability, and the airplane altitude over the ICAO noise reference point is decreased, and the noise level increases on the ground. The total result of those two effects is calculated for future SSBJ type airplanes [6], and shows that the thrust vectoring is effective in the airplane noise reduction. It is also expected to be applicable for subsonic airplanes to reduce jet noise even though jet noise is not so dominant compared to supersonic airplanes.

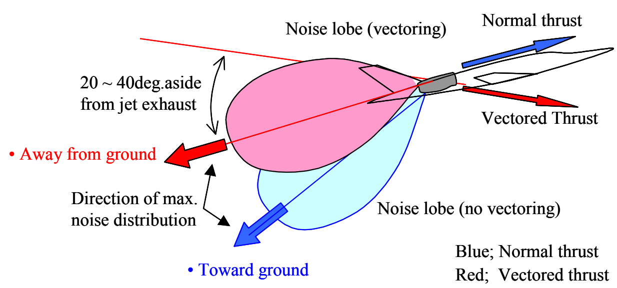

Fig. 1 Concept of the thrust vectoring

2. Methodologies

The estimated noise level at the IACO noise reference points (Fig.2) for take off climb, sideline and landing approach conditions were calculated with some simplification.

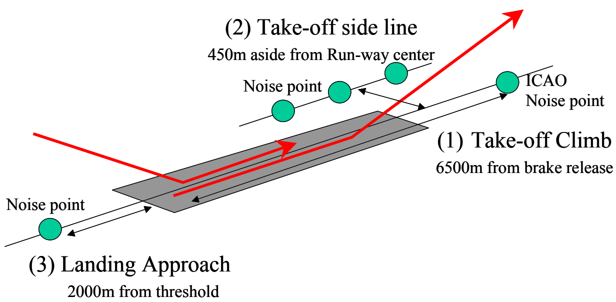

Fig. 2 ICAO noise reference points

2.1 Noise Calculation Method

The noise level was calculated based on the noise lobe, angle of noise distribution (Az), thrust level, distance and time delay. The analyses of this paper were based on the nominal distribution assumed as the typical distribution characteristics from examples shown in Fig.3.

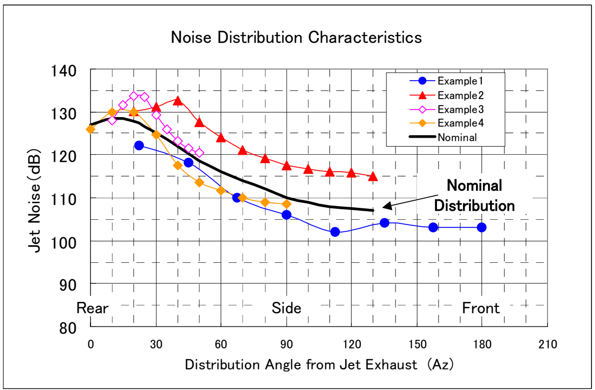

Fig. 3 Noise distribution characteristics

There is a distinctive directional distribution of jet exhaust noise, however, typical pattern is difficult to be specified because of the difference in the noise measurement units or conditions; therefore, an average distribution was assumed from some experimental data normalized to 25m distance and 1ton thrust level as a nominal noise distribution in overall dB(A) for the calculation of this paper. The followings are the correction methods of each parameter.

Noise Correction Method

- Noise level= Nominal Noise
  + Thrust correction
  + Distance correction
- Nominal Noise; Fig.3 and distribution angle
- Thrust correction;
  ΔdB=K1×10·log (thrust ratio)
  K1=1.0 for scaled engine
  K1=1.8 for partial thrust [1]
- Distance correction;
  ΔdB=1.1× 20·log (Distance ratio)
  1.1: assumed for atmospheric attenuation
- Time delay;
  Time = Elapsed time + Propagation time Δt
  Δt=(distance/speed of sound)

2.2 Take-off Climb Noise

Fig.4 shows the airplane flight path and relative position over the ICAO take-off noise point.

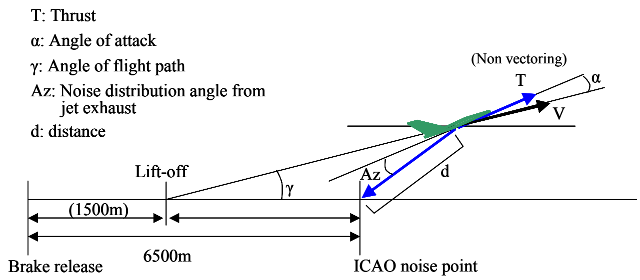

Fig. 4 Take-off flight path and noise point

Assumed calculation conditions;

- Take-off ground run distance: 1500m
- Vectoring angle: to be set at lift-off
- Vref: 1.2Vs+10kt

The noise level at the ICAO noise point was calculated as the time elapsed from airplane lift-off. Although the airplane configuration change other than the landing gear retraction is not permitted during take off 2nd segment climb phase until the landing gears are fully retracted and airplane reaches 400 feet altitude under FAA regulation, the assumption shown above is on safety side at the prediction of the effect of the thrust vectoring because the airplane height over ICAO point decreases by thrust vectoring at lift off than vectoring after 2nd segment.
The take-off climb paths were calculated for the SSBJ type airplanes with fixed arrow wing and variable sweep wing. Fig.5 shows the equilibrium of forces and noise distribution angle for the calculation.

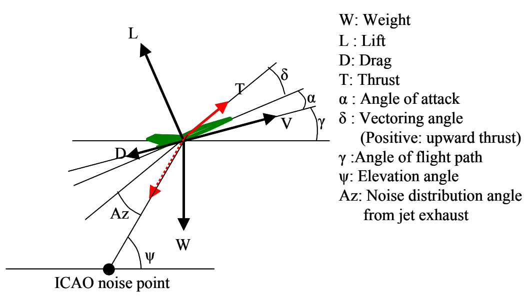

Fig. 5 Equilibrium of forces

$$W\cos\gamma = L + T\sin(\alpha + \delta) \qquad (1)$$
$$T\cos(\alpha + \delta) - D = W\sin\gamma \qquad (2)$$
$$AZ = \psi - \gamma - \alpha - \delta \qquad (3)$$

Fig.6 shows the effects of the thrust vectoring on climb path angle derived from the equations shown above and the airplane angle of attack was kept constant against vectoring angle.

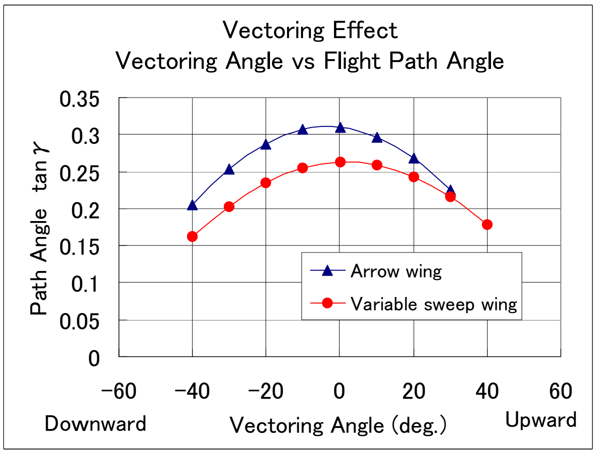

Fig. 6 Climb path and vectoring angle

The maximum path angle corresponds approximately to the vectoring angle that make the thrust line is aligned to the direction of speed vector.

2.3 Take off Sideline Noise

The ICAO measurement point is on the line 450m aside from runway center, and the downrange position is the point where the noise reaches the maximum. To simplify the calculation, the sideline noise was calculated at the point 500m downrange from airplane lift off point where the sideline noise generally reaches the maximum level in this analysis. The airplane altitude where the noise reaches the maximum level is between 300 and 400m. The noise correction methods used are the same as the ones used in sec.2.2.

2.4 Landing Approach Noise

Figure 7 shows the flight path and the relative position of the airplane to the ICAO noise point in the landing approach phase.

Assumed calculation conditions;

- Touchdown point: 300m from threshold
- Vectoring angle: fixed until touchdown
- Vref: 1.3Vs+10kt

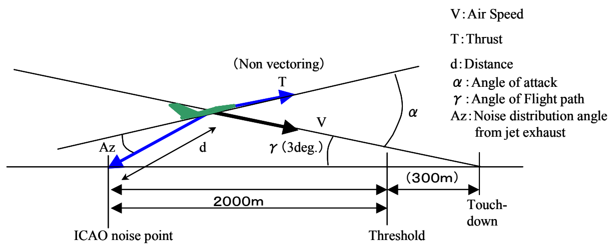

Fig. 7 Approach flight path and noise point

The approach noise was calculated at 2000m from the threshold for the airplane approaching on the 3deg. glide slope and touching down 300m beyond threshold. When the thrust vectoring was applied during approach phase, the thrust component along flight path decreases and vertical component increases downward; therefore the required thrust should be increased to maintain the glide slope angle. Fig.8 shows the required thrust level to maintain 3 deg. glide slope against the thrust vectoring angle.

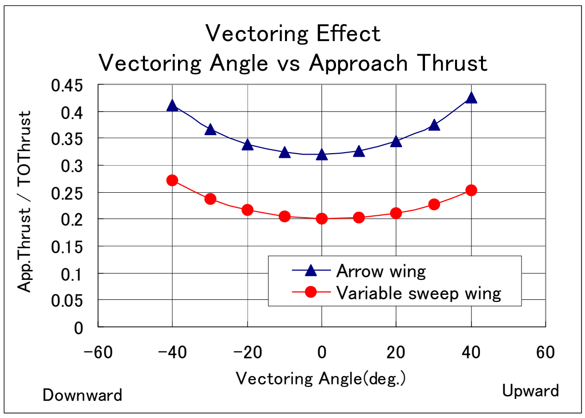

Fig. 8 Thrust level to keep 3deg glide slope

For subsonic airplane with relatively low thrust level and the large engine bypass ratio, jet noise is not so predominant. But in case of supersonic airplane which has a very low L/D in the approach configuration due to it's slender airplane geometry, the thrust level required to maintain 3 deg. glide slope angle is unusually high. In addition to this, the altitude over the ICAO measurement point is very low compared to the takeoff climb case. Therefore, a reduction in jet noise during landing approach is important for supersonic airplanes. In this case also, the thrust vectoring effectively decreased the jet noise on account of the directional distribution effect, even though the thrust level required to maintain the glide path angle increased. The noise correction for partial thrust was calculated by multiplying 1.8 to 10·log (thrust ratio) due to jet velocity change [1].

2.5 Airplane Configuration

The reference airplane configuration was based on the SSBJ type airplane shown in Table 1 and Figure 9. The SSBJs with arrow wing and variable sweep wing were configured for the same mission requirement composed of 2+8 passenger, cruise speed of Mach 1.8, and 3500nm range, etc. [5], [6].

Table 1 SSBJ specification

		Arrow Wing	Variable Sweep Wing
TO Weight	ton	44	39
Wing Area	m^2	130	90
Engine Thrust	ton	10	7
Number of E/G	–	2	2
Range	nm	3500	3500
Cruise Mach	—	1.8	1.8
W/S	kg/m^2	340	430
T/W	—	0.45	0.36
TOFL	ft	6000	7000
LFL	ft	7000	5700
Cr. L/D	—	7	7
Takeoff L/D	–	6	9
Approach L/D	–	5	8

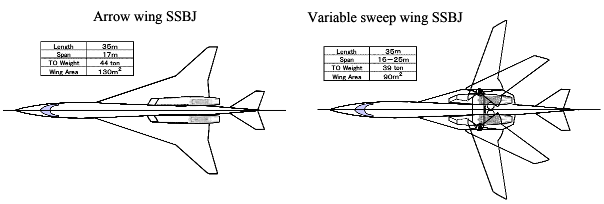

Fig. 9 SSBJ plan form

3. Results

3.1 SSBJ with Arrow wing configuration

3.1.1 Take off climb noise

Figure 10 shows the result of thrust vectoring of -30deg. downward thrust case. X-axis shows the elapsed time from airplane lift off, and Y-axis shows the noise level calculated at the ICAO measurement point. The peak noise decrease of -7.4dB was obtained in this case.

Figure 11 shows the noise distribution angle (Az) change according to the airplane position downrange from the lift off point. When the noise reached the maximum level, the distribution angle for the non-vectoring case was about 20 degrees, and it was about 40 degrees in case of -30deg. vectoring. The noise distribution characteristics shown in Figure 3 can be effectively utilized for noise reduction. When the noise reaches the maximum level, the airplane already passes over the ICAO reference point, and the elevation angle looking up the airplane from the point becomes about 60 to 70 degrees behind.

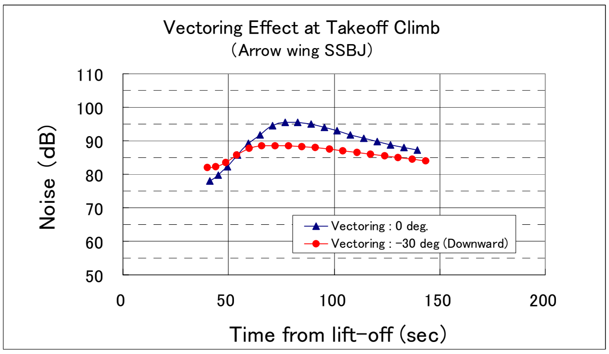

Fig. 10 Noise time history at ICAO take off point

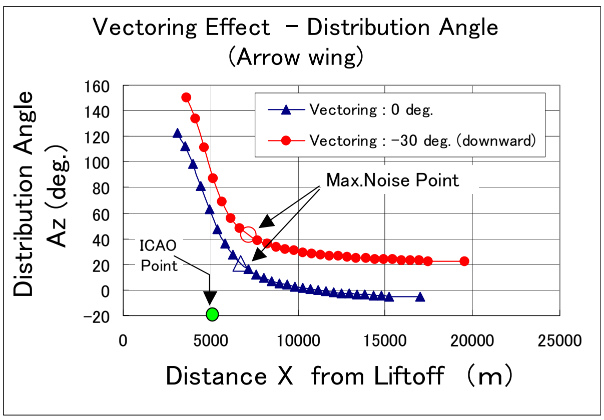

Fig. 11 Noise distribution angle time history

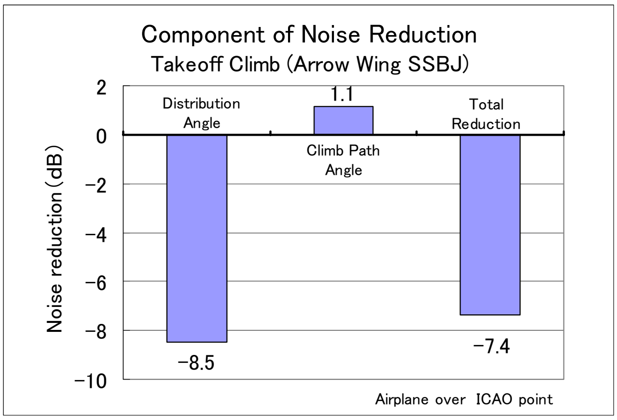

Fig. 12 Component of take off noise reduction

Figure 12 shows the breakdown of the noise decrease. The noise decreased by -8.5dB due to distribution angle and increased by +1.1dB due to degraded climb performance. In total, the noise decrease of -7.4dB was obtained.

3.1.2 Take off sideline noise

The effect of the thrust vectoring on sideline noise was not so effective as the takeoff climb noise as it is easily imagined. But the effect still exists in this case.

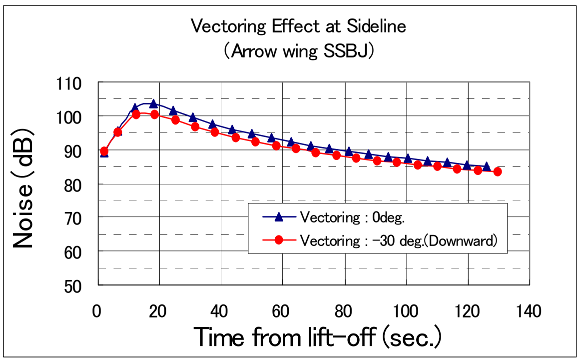

Fig. 13 Noise time history at ICAO sideline point

Figure 13 shows the effect of the -30deg. thrust vectoring. The peak noise decrease of -3.1dB was obtained in this case.

3.1.3 Landing approach noise

Figure 14 shows the result of thrust vectoring of -30deg. downward case. X-axis shows the time to airplane touch down and Y-axis shows noise at ICAO measurement point. The peak noise decrease of -4.9dB was obtained in this case. The airplane altitude over the ICAO approach point was only 120m compared to over 1000m of takeoff climb case, therefore, the noise level was still high even though the engine power was reduced to about 30% of takeoff thrust.

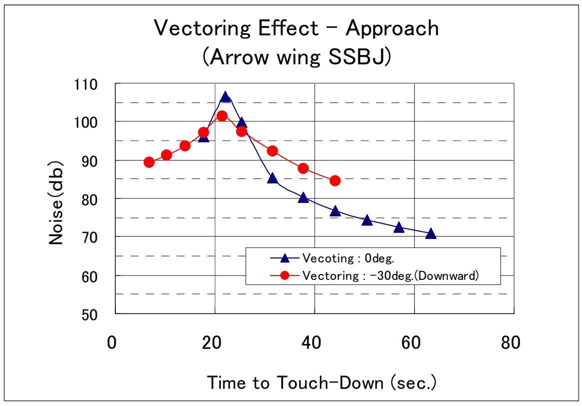

Fig. 14 Noise time history at ICAO approach point

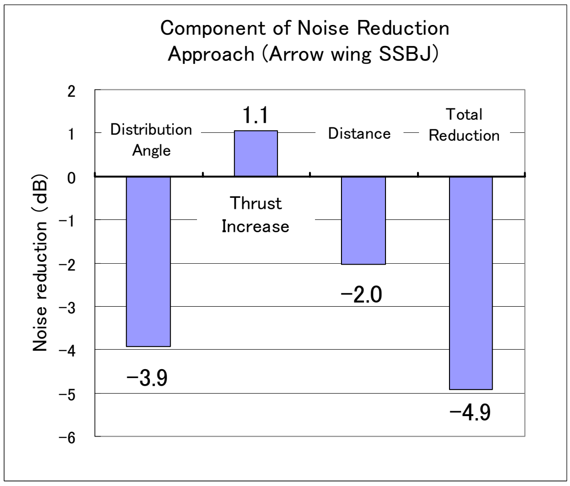

Fig. 15 Component of approach noise reduction

Figure 15 shows the breakdown of the noise decrease. The noise decreased by -3.9dB due to distribution angle, increased by +1.1dB due to thrust increase, decreased by -2.0dB due to distance increase from ICAO point, and in total, the noise decrease of -4.9dB was obtained.

3.2 SSBJ with variable sweep wing configuration

3.2.1 Take off climb noise

The SSBI with variable sweep wing configuration will have a good lift to drag ratio and maximum lift capability at low speed, therefore, the airplane size is smaller and lighter than the arrow wing configuration. The airplane itself is quieter, and also has smaller angle of attack due to the large aspect ratio of the main wing at its low speed position that will enhance the vectoring effect. Figure 16 shows the comparison of the arrow wing without vectoring, variable sweep wing without vectoring and variable sweep wing with -30deg. vectoring. The peak noise decreased by -2.0dB due to the variable sweep wing effect, decreased by -8.7dB due to the thrust vectoring, and in total, the noise decrease of -10.7dB was obtained.

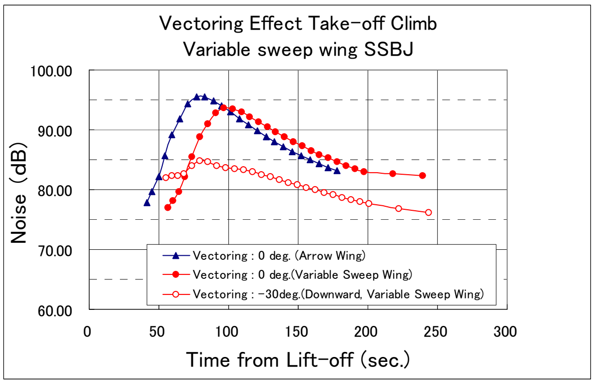

Fig. 16 Take off noise reduction by Variable sweep wing

3.2.2 Take off sideline noise

Figure 17 shows the comparison of the same cases for sideline noise.

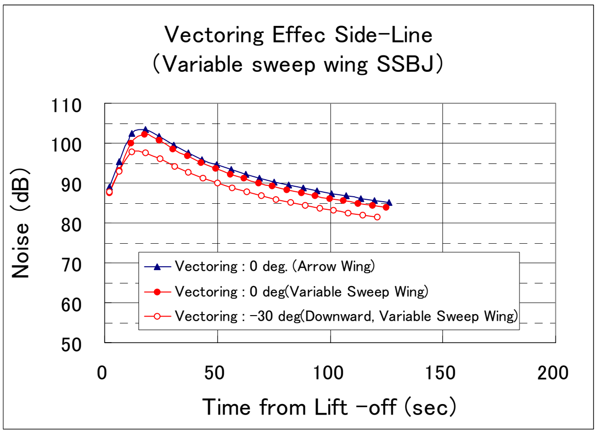

Fig. 17 Sideline noise reduction by Variable sweep wing

The peak noise decreased by -1.4dB due to variable sweep wing, decreased by -4.4dB due to thrust vectoring, and in total, the noise decrease of -5.8dB was obtained.

3.2.3 Landing approach noise

Figure 18 shows the comparison of the same cases for approach noise. The peak noise decreased by -3.3dB due to variable sweep wing, decreased by -7.1dB due to thrust vectoring, and in total, the noise decrease of -10.4dB was obtained.

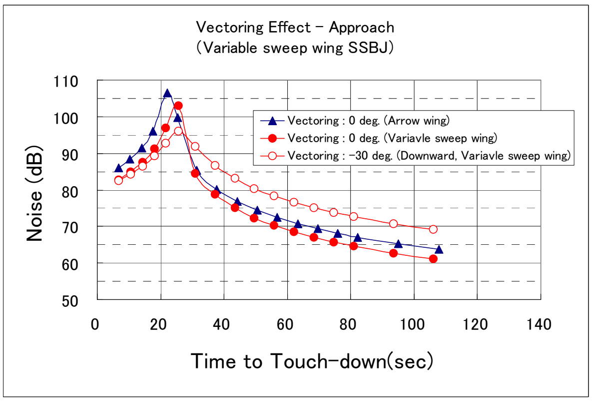

Fig. 18 Approach noise reduction by Variable sweep wing

3.3 Summary of effect of thrust vectoring

Table 2 shows the summary of the thrust vectoring effects for the ICAO noise conditions for the arrow wing and variable sweep wing SSBJs in the case of -30deg. downward thrust vectoring condition. The total noise reductions for three conditions were -15 to -20dB for those airplanes, and the variable sweep SSBJ with -30deg. vectoring was quieter by -27dB than the arrow wing SSBJ without vectoring.

Table 2 Summary of vectoring effect

ICAO Noise Condition	Vectoring Effect (-30deg. Dwnward)		Variable Sweep Effect
	Arrow Wing	Variable Sweep Wing	
TO Climb	-7.1	-8.7	-2.0
Sideline	-3.1	-4.4	-1.4
Approach	-4.9	-7.1	-3.3
Total	-15.1	-20.2	-6.7
Total Effect for Variable sweep wing : -26.9 dB			

4. Discussion

- *Regulation*

Figure 19 shows the noise margin of ΔEPNdB against ICAO chapter 3 total noise of three conditions for the current subsonic business jet airplanes. The noise regulation for supersonic civil airplanes has not yet been decided, but it is said that supersonic airplanes would be required to satisfy the Chapter 4, and preferably the same level of margin of current subsonic airplane as well.

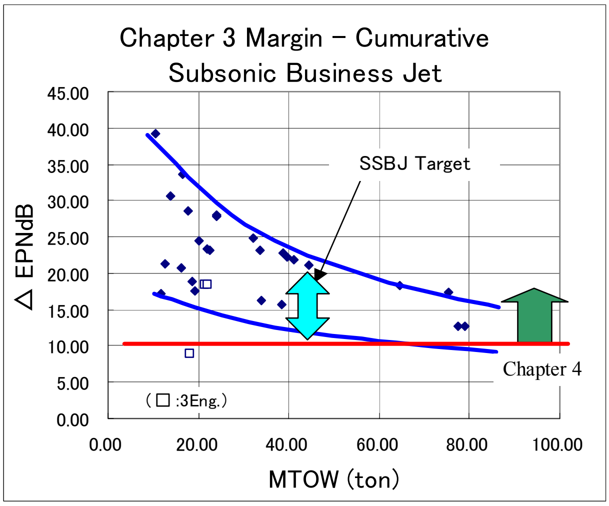

Fig. 19 Noise margin to ICAO chapter 3 for current subsonic business jet

The SSBJ shown in Table 1 is configured for the mission requirement of 3500nm range and low bypass ratio engines with mixer-ejector nozzle and extended noise-absorbing duct. The estimated noise level of the airplane marginally satisfies Chapter 3 [5], and it is expected that when the effectiveness of the thrust vectoring is realized, those airplanes will satisfy Chapter 4 regulation hopefully.

- *Noise distribution characteristics*

The noise directional distribution was assumed in this paper to be the one shown in Figure 3. The distribution characteristics affect the effectiveness of the thrust vectoring, therefore it is important to investigate the characteristics of the future candidate engines for supersonic civil airplane.

- *EPNdB*

The ICAO regulation is specified in EPNdB of noise level taking into account duration time and tone correction. In this paper the noise value was calculated simply as overall dB (A), or SPL for an initial analysis of the effectiveness of the thrust vectoring. When the thrust vectoring is applied, the effectiveness before and after that of the peak noise reduction tend not so effective than at the peak value (Fig.10), therefore, it is necessary to discount the effects a little when evaluated in EPNdB.

- *Nozzle Concept*

When applying vectoring nozzle to actual airplane and engine, it is necessary to have three basic modes of cruise, reverse and vectoring as shown in Fig.20. To change the nozzle geometry, actuator/guide-rail system would be applicable. Other possibilities are to tilt the nacelle itself according to flight conditions, or to install vectoring flap just behind the nozzle exit.

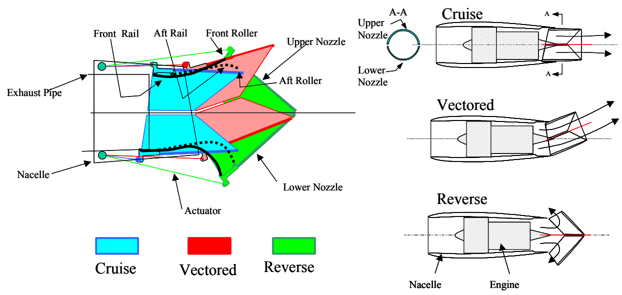

Fig. 20 Vectoring nozzle concept

- *Others*

There are many other noise sources beside the jet exhaust noise such as shock-associate noise, airframe noise, fan noise, etc. but airframe parts such as wing and fuselage could shield the noise from the intake. The shock noise from the exhaust nozzle may possible to be shielded with the rear fuselage and vertical fin. The configuration study in JAXA about SSBJ and small SST (Fig. 21) will include and continue to analyze such effects.

5. Conclusions

This paper has described the effectiveness of thrust vectoring for noise reduction during take off and landing by calculations.

The effect is derived from the directional distribution characteristics of jet exhaust noise, and the thrust vectoring deflects the peak noise distribution away from the ground. Although the thrust vectoring degrades the airplane climb capability or approach glide performance, total result of those two effects will effectively decrease the airplane noise consequently.

The cumulative noise reductions for three conditions are -15 to -20dB for the SSBJ type airplanes, and the variable sweep wing SSBJ with -30deg. vectoring is quieter by -27dB than the arrow wing SSBJ without vectoring.

The maximum vectoring angle will be about 30 degrees downward when considering the one engine inoperative case and keeping altitude without changing thrust vectoring angle on the other engine similar to the thrust cut-back operation.

The effectiveness shown here would be that the future SSBJ and small SST could hopefully satisfy ICAO Chapter 4 regulation. Also, the concept of this effect will be applicable to subsonic airplanes.

The analysis in this paper is simple and preliminary, but shows a significant possibility in noise reduction of supersonic airplane; therefore, the further studies as shown below are necessary and will be continued.

- Evaluation in EPNdB
- Proof test with real engine or simulated jet
- Analysis about secondary noise due to vectoring devices
- Effect of aerodynamic noise
- Influence of Doppler effect
- Application to subsonic airplane

6. Acknowledgements

The analysis in this paper was conducted by some engine noise data and noise analysis method supported by researchers in Supersonic Transport Team, Civil Transport Team, and Clean Engine Team of Aviation Program Group of JAXA. All those support are highly appreciated.

Fig. 21 Conceptual study about SSBJ and SST in JAXA.

References

[1] Kroo I. *Aircraft Design: Synthesis and Analysis*. Desktop Aeronautics Inc, Sep. 2006.

[2] Craig L. Technology Development and Implementation for Stage 4. *Airport Noise Symposium 2001*, Feb. 2001.

[3] Hubbard H H. *Aeroacoustics of Flight Vehicles Theory and Practice Volume 1: Noise Sources*. Acoustical Society of America 1995.

[4] Boettcher J. Annex 16, Volume 1 and equivalent procedures. *Noise Certification Workshop,* Nov. 2006. Bangkok.

[5] *Investigation report of supersonic civil airplane performance according to engine specification and airframe configuration.* NEDO (New Energy and Industrial Technology Development Organization), Report 2004. Japan.

[6] Horinouchi S. Conceptual design of a low sonic boom SSBJ. *43rd AIAA Aerospace Sciences Meeting and Exhibit,* AIAA 2005-1018, Reno.

Copyright Statement