Numerical Simulation of Engine Noise Shielding around Blended Wing Body Aircraft*

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A numerical simulation of sound propagation around a blended wing body (BWB) aircraft with an open rotor engine is performed to understand the shielding effect of the engine noise. A boundary element method (BEM) code based on the Helmholtz equation is developed for this purpose. The effect of uniform flow and the surface impedance of the aircraft is analyzed in detail. The mean flow showed little effect on the amount of shielding since the approach speed is a relatively low Mach number. On the other hand, when a soft-surface condition is applied to the upper side of the aircraft, a larger amount of shielding is observed throughout the analyzed field when compared to a rigid surface case. Additionally, an effective area for applying the soft-surface condition is clarified in order to reduce the usage of such material.

Key Words: Blended Wing Body Aircraft, Acoustic Shielding, Boundary Element Method

Nomenclature

- $a$: sphere radius
- $b$: wing span length
- $c$: wing chord length
- $c_0$: speed of sound
- $d$: spanwise width of the soft surface
- $E$: field outside the body
- $G$: Green’s function
- $k$: wave number
- $M$: Mach number
- $n$: unit surface normal
- $p$: acoustic pressure
- $p_{ref}$: reference pressure
- $S$: body surface
- SPL: sound pressure level
- SPL$_1$: SPL when aircraft is present
- SPL$_2$: SPL without aircraft
- $U_{0i}$: velocity of uniform flow
- $V$: field inside the body
- $v_i$: particle velocity
- $X$: location of source point
- $y$: location of observation point
- $Z$: surface impedance
- $\phi$: total velocity potential
- $\phi_i$: incident velocity potential
- $\rho_0$: fluid density
- $\omega$: angular frequency
- $\nabla^2$: Laplacian operator

1. Introduction

Since commercial air transportation is increasing rapidly, the development of low-noise aircraft is required to protect the environment around airports. All of the aircraft flying today are designed based on a tube and wing configuration, and noise reduction on the ground is achieved by reducing the acoustic power at the noise source. One typical example is jet noise reduction using high by-pass ratio engines. However, in order to meet future noise reduction targets, such as NASA N+3,1 a radical configuration outside the limit of the tube and wing configuration should also be considered. It is believed that such a configuration will open up a new design space for further noise reduction.

In most conventional transport aircraft, engines are mounted under the wing. Thus, the engine can be seen directly from an observer on the ground in most instances. The noise emitted from the engine propagates directly to the observer. On top of that, the reflected noise from the wing increases the noise. Therefore, several concepts which place the airframe between the engine and the observer on the ground have been proposed. One of the candidates is a blended-wing body (BWB) configuration2–4 which is characterized by a highly integrated configuration of a large wing planform with the engine mounted over the wing. For example, an estimation of acoustic sound shielding of SAX03 was conducted by Agarwal and Dowling5 using the boundary element method (BEM).6,7 A point sound source that represents turbo-fan noise was located above the wing as an engine noise source and the difference between the total and incident sound level was calculated in the shielded region below the aircraft. They observed at least 5 dB of reduction in the shielded region. In those studies, the amount of acoustic shielding was estimated numerically without the effect of uniform flow.

On the other hand, an open-rotor engine (unducted fan) was revisited recently due to its high fuel efficiency and low-emission characteristics. This engine is characterized by a very large rotating fan without a nacelle, which achieves a higher by-pass ratio than conventional turbo-fan engines. However, the large rotating blades are not covered by the nacelle, thus the noise level is estimated to become larger than...
the turbo-fan engines. New noise reduction technology must be investigated in order to utilize an open-rotor engine as a candidate of future aircraft propulsion systems.

Based on previous research, the shielding effect of a BWB aircraft with an open-rotor engine is investigated, including the effect of the mean flow using BEM. BEM was selected because the tonal noise from the blade is on the order of several hundred Hertz, and it was also widely used in previous research. The idea is to utilize the large wing area of the BWB to shield and absorb the noise from the open-rotor engine to reduce the noise on the ground. Further noise reduction capability is investigated by applying an acoustic liner on the upper surface. The location where the acoustic liner is effective will be identified in order to reduce liner usage.

This paper is organized as follows. In the next section, the governing equation of BEM is revisited and the validation of the code developed is described in Section 3. In Section 4, a simulation of the sound propagation from a monopole sound source mimicking an open-rotor engine noise above a BWB aircraft is conducted using the BEM code. Section 5 summarizes the paper.

2. Boundary Element Method

2.1. Conventional boundary integral equation

The governing equation for a propagating acoustic wave through a three-dimensional homogeneous medium with a point source is described by the wave equation,

\[
\nabla^2 \phi - \frac{1}{c_0^2} \frac{\partial^2 \phi}{\partial t^2} + \frac{Q_\text{fl}}{c_0^2} (x, \vec{x}_0) = 0, \quad \forall x \in E
\]

(1)

where \( \phi \) is the velocity potential \( (v = \nabla \phi) \). The Helmholtz differential equation, which is the governing equation for an acoustic field, is derived by substituting \( \phi = \phi \exp(-i\omega t) \) into Eq. (1) and by replacing \( \phi \rightarrow \phi \).

\[
\nabla^2 \phi + k^2 \phi + \frac{Q_\text{fl}}{c_0^2} (x, \vec{x}_0) = 0, \quad \forall x \in E
\]

(2)

In BEM, it is important to derive Green’s theorem, which is the fundamental solution of the governing equation. In an acoustic field, the equation that expresses the effect to observation point \( y \) from source point \( x \) is written as,

\[
G(x, y, \omega) + k^2 G(x, y, \omega) + \delta(x, y) = 0,
\]

(3)

where \( \delta \) is the Dirac delta function. The fundamental solution for Eq. (3) in a three-dimensional acoustic field is,

\[
G(x, y, \omega) = \frac{1}{4\pi r} e^{-ikr}
\]

(4)

where \( r \) is the distance between \( x \) and \( y \). The inward normal derivatives of Eq. (4) on point \( y \) is,

\[
F(x, y, \omega) = \frac{\partial G(x, y, \omega)}{\partial n(y)}
\]

\[
= \frac{1}{4\pi r^2} (ikr - 1)r_j n_j(y) e^{-ikr}.
\]

(5)

These two equations will be used in the boundary integral equation to be shown later. To derive the boundary integral equation, Green’s theorem is used.

\[
\int_E \left[ \nabla^2 v - v \nabla^2 u \right] dE = \int_{S \cup S_R} \left[ \frac{\partial v}{\partial n} - v \frac{\partial u}{\partial n} \right] dS.
\]

(6)

The conventional boundary integral equation (CBIE) is derived as,

\[
c(x) \phi(x) = \int_S \left[ G(x, y, \omega) q(y) - F(x, y, \omega) \phi(y) \right] dS(y) + \phi(y) \quad \forall x \in S
\]

(7)

where \( q = \partial \phi / \partial n \). For an exterior domain problem,

\[
c(x) = 1 - \int_{S_R} \frac{\partial G}{\partial n} dS,
\]

(8)

2.2. Surface boundary conditions

For Eq. (2), there are three types of boundary conditions.

\[
\phi = \overline{\phi}, \quad \forall x \in S
\]

(9)

\[
q = \frac{\partial \phi}{\partial n} = i \nu_0 \omega \overline{\nu_n}, \quad \forall x \in S
\]

(10)

\[
\phi = \overline{Z} \nu_n, \quad \forall x \in S.
\]

(11)

Each boundary condition is defined on the body surface, and the top line indicates the value that will be defined on the boundaries. Equation (10) is used to define the pressure along the surface while Eq. (11) is used to define the velocity. The direction of the unit normal vector \( \overline{n} \) is pointing into the body. The surface impedance \( Z \) in Eq. (12) is the ratio of velocity potential to velocity. As the absolute value of \( Z \) increases, the boundary condition becomes close to that of perfect reflection (rigid surface) and vice versa.

2.3. Mean flow effect

Consider a steady uniform flow with a velocity of \( U_0 \) in an axial direction (x direction) around an object with a closed surface. The fluid flow can be considered to be incompressible if the Mach number is low (\( M^2 \ll 1 \)). Under such conditions, where terms of the order \( M^2 \) can be neglected, the convected wave equation can be written as,

\[
\nabla^2 \phi - \frac{1}{c_0^2} \left( \frac{\partial}{\partial t} + U_0 \frac{\partial}{\partial x} \right)^2 \phi = 0.
\]

(12)

The source term is omitted in the above equation for simplicity. The relational expression between velocity potential and excess pressure becomes,

\[
p = -\rho_0 \left( \frac{\partial}{\partial t} + U_0 \frac{\partial}{\partial x} \right) \phi.
\]

(13)

The same equation is valid, as in Eq. (2) for particle velocity. By substituting the following Prandtl and Glauert transformation,\( ^9,10 \)
for the convected wave equation, Eq. (13) transforms into,

\[ \nabla^2 \phi - \frac{1}{c_0^2} \frac{\partial^2 \phi}{\partial T^2} = 0. \tag{16} \]

The form of this equation is identical to Eq. (1), thus the same procedure can be applied to calculate the field pressure. The only difference is that Eq. (14) is necessary when calculating acoustic pressure from the velocity potential.

2.4. Burton-Miller method

The fundamental formulation of acoustic BEM is Eq. (8). However, the integral equation of the Helmholtz problem for external acoustic field is known to have a non-unique solution at certain frequencies, referred to as eigenfrequencies. This non-uniqueness is not a physical problem, but a mathematical issue due to an internal Dirichlet problem. Such frequency is usually not known before the simulation, thus it is important to prevent this phenomenon. Therefore, the Burton-Miller method\(^6\) is applied. This method linearly combines the CBIE (Eq. (8)) with its normal derivative equation,

\[ c(x)q(x) = \int_S [K(x, y, \omega)q(y) - H(x, y, \omega)\phi(y)]dS(y) \]

\[ + q'(x) \quad \forall x \in S, \tag{17} \]

where,

\[ K(x, y, \omega) = \frac{\partial G(x, y, \omega)}{\partial n(x)}, \quad H(x, y, \omega) = \frac{\partial F(x, y, \omega)}{\partial n(x)}. \tag{18} \]

Equation (17) is named the hypersingular boundary integral equation (HBIE). The linear combination of Eq. (8) and Eq. (17),

\[ \text{CBIE} + \beta \text{HBIE} = 0, \tag{19} \]

is known to yield unique solutions at all frequencies if \( \beta \) is a complex number. The value is set to \( \beta = i/k \) in the following calculations.

3. Code Verification

3.1. Sphere with a monopole sound source

In this section, the BEM code using the Burton-Miller method is verified by solving acoustic scattering around a rigid sphere due to a point sound source. The sphere radius is set to \( a = 1 \) and the monopole sound source is located at distance \( L = 2 \) from the center of the sphere (Fig. 1). The sphere is discretized by 960 triangular elements. The acoustic pressure is calculated at location \( R = 100a \) from the sphere center and is compared with the analytical solution.\(^{11}\) The result for Helmholtz numbers \( ka = 0.5, 5.0 \) and 10.0 are given in Fig. 2(a), (b) and (c), respectively. The solutions from the BEM calculation show a positive agreement with the analytical solution for all frequencies. For Fig. 2(b) and (c), a peak can be seen at 180 degrees. This is due to the location...
of the sound source. The acoustic waves add constructively to build a relatively high pressure on the opposite side of the sphere. This effect is not clear in Fig. 2(a). At $ka = 0.5$, the wavelength corresponds to $\lambda = 12.6$, which is much longer than the sphere diameter. Thus, at such a low frequency, the effect of acoustic interference becomes very small.

4. Acoustic Shielding of a BWB Aircraft

4.1. Problem setting

The geometry of the BWB is modeled by the author based on X-48B pictures in the public domain. The root chord length of the aircraft is $c (=3.6 \text{ m})$, and the sound source is located at $(2/3c,0,0.1c)$, as shown in Fig. 3 (the nose of the BWB is the origin). The noise source of the open-rotor engine is modeled by a single monopole source following the work by Stephens and Envia. The simulations are performed at three different Helmholtz numbers, which are non-dimensional parameters to describe the frequency of the sound source. The Helmholtz numbers $kc = 3, 6$ and 12 correspond to 50, 100 and 200 Hz, respectively. The source strength is set to 80 dB at the semispan distance of $b/2 = 0.86c$. The definition of the sound pressure level (SPL) is as follows,

$$\text{SPL} = 10 \log (p^2/p_{\text{ref}}^2),$$

where $p_{\text{ref}} = 2 \times 10^{-5} \text{ Pa}$.

4.2. The effect of uniform flow

First of all, Fig. 4 shows the SPL pattern on the observer plane for three different frequencies at $M = 0$. The observer plane is parallel to the horizontal plane and is located 0.86c (equal to the semispan $b/2$) below the aircraft. The whole surface of the aircraft is assumed to be rigid, which assumes a perfect reflection. For $kc = 3$, the wavelength is comparable to the chord length of the BWB. Therefore, the BWB is acoustically compact and a concentric SPL pattern is obtained on the observer plane, which is similar to the pattern without the BWB. As the frequency increases, the shielding effect appears, and the contour patterns are no longer concentric.

Next, the effect of an uniform flow is investigated. The shielding effect is evaluated by $\Delta \text{SPL}$,

$$\Delta \text{SPL} = \text{SPL}_1 - \text{SPL}_2,$$

where $\text{SPL}_1$ and $\text{SPL}_2$ are the SPL with and without the BWB, respectively. Thus, the negative value indicates the amount of shielding caused by the presence of the BWB. Figure 5 shows the $\Delta \text{SPL}$ distribution on the same plane for $kc = 12$, with and without the mean flow. Figure 5(a) has no uniform flow, while Fig. 5(b) and (c) have uniform flows of $M = 0.2$ and 0.4 in the $x$-direction, respectively. At first glance, the differences between these three figures are small. Figure 6 compares the distribution of $\Delta \text{SPL}$ along line A, shown in Fig. 5. The locations of local maxima and minima and those levels are slightly different due to the effect of the mean flow. For a more quantitative comparison, the shielding effect is evaluated by the following value

$$\Delta \text{SPL} = 10 \log \left( \frac{1}{\Delta L} \int 10^{\text{SPL}_2/10} \, dL \right)$$

$$- 10 \log \left( \frac{1}{\Delta L} \int 10^{\text{SPL}_1/10} \, dL \right),$$

which is an integration along line A ($L$ is the coordinate along the line). The line is set on the field from point $(-20c,$.
This corresponds to the acoustic energy received by the observer on the ground when the aircraft is flying over.

The mean flow Mach number ranges from 0 to 0.4, and three different frequencies ($kc = 3, 6, 12$) are calculated. The results are summarized in Fig. 7. The shielding effect is 0 to 3 dB depending on the frequency, and the values are independent of the mean flow Mach number.

To summarize, the variation of SPL reduction, with respect to the mean flow Mach number, is small when the mean flow Mach number is less than 0.4. The shielding effect depends more on the frequency of the source. Since the mean flow effect is small, the freestream Mach number is set to zero, hereafter.

### 4.3. The effect of surface impedance

The surface impedance on the upper surface of the aircraft is changed to reduce the SPL on the ground. Figure 8 shows the $\Delta$SPL distribution on the plane for $kc = 12$ when the absorption rate is set to 1. The absorption rates of 0 and 1 correspond to rigid and soft surfaces, respectively. Significant noise reduction is observed on the plane when compared to Fig. 5(a).

In order to clarify the sensitivity of the absorption rate to noise shielding, the absorption rate on the upper side of the BWB is varied from 0 to 1 and the results are summarized in Fig. 9. The vertical axis is the $\Delta$SPL defined by Eq. (22). The figure indicates that the relation between the absorption rate and the SPL reduction is not linear. Significant noise reduction can be achieved when the absorption rate nears 1.
Next, the new parameter \(d\), which controls the spanwise width of the soft surface (absorption rate of 1) as described in Fig. 10, is introduced. It is important to investigate the specific area where sound absorption is effective. Figure 11 shows the SPL defined by Eq. (22) vs. \(d/b\). The values \(d/b = 0\) and 1 correspond to the rigid and soft wall cases, respectively. The area responsible for SPL reduction is limited to the wing root regions (\(d < 0.3b\)). The variation in SPL reduction between \(d = 0.3b\) and \(b\) is less than 1 dB. This clarifies that it is important to shield noise close to the noise source.

To summarize, it is important to choose a high-absorption material (absorption rate close to 1), and place it close to the engine to effectively reduce the noise. For the frequency range we have investigated, an additional noise reduction of 1 to 3 dB on top of the shielding effect can be achieved. The same reduction can be achieved simply by placing the liner close to the noise source. Application of the acoustic liner on the upper surface of a BWB aircraft is an effective method for reducing the noise transmitted toward the ground.

5. Conclusion

Sound propagation simulations from a monopole sound source mimicking an open-rotor engine noise above a BWB aircraft were conducted using the BEM code. The idea was to utilize the large wing area of the BWB to shield and absorb the noise from the open-rotor engine in order to reduce the noise on the ground. First, verification of the developed BEM code was conducted by calculating the scattering pressure from a sphere with a monopole sound source. The result showed good agreement with the analytical solution.

Next, the shielding effect of the BWB configuration was evaluated including the mean flow. The shielding effect is 0 to 3 dB, which increases at higher frequencies. The results clarified that the acoustic shielding effect is not sensitive to the presence of the mean flow. Afterward, the effect of surface impedance on acoustic shielding was investigated for further noise reduction. It was proven that by choosing a high-absorption material (absorption rate close to 1) as the acoustic liner, an additional noise reduction of 1 to 3 dB on top of the shielding effect can be achieved. The same reduction can be achieved simply by placing the liner close to the noise source. Application of the acoustic liner on the upper surface of a BWB aircraft is an effective method for reducing the noise transmitted toward the ground.

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