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Numerical assessment of impulsive sound propagation on a ground surface in time-domain

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ABSTRACT

To predict the impulsive/broadband sound field, it is important of considering of ground reflection. Considering the ground reflection in time domain, the time domain impedance modeling which describes the characteristics of ground surface is required. However, the traditional impedance modeling cannot describe the response in the low frequency-band ground reflection. To approach the discrepancy, the proper ground impedance modeling is suggested. Using the computational aeroacoustics (CAA) techniques, it is calculated whole acoustic field considering ground reflection numerically in time domain. The results of numerical calculation of acoustic field agree well with each frequency domain numerical solution. The comparison of experimental data and the numerical approach data is fully supported each other, which comparison of experiment and the traditional approach has the difference in low frequency band. To expand the more practical cases, numerical calculation is executed about the factors which influence the ground reflection.

KEYWORDS: Computational Aeroacoustics, Impedance, Time-domain Numerical Method

INTRODUCTION

Today, noise as an environmental issue has an important impact on the human life. Noise problems are arising with complex relationships which are someone and someone, someone and an organization, or an organization and another organization. Consequently, the social expense of noise has been increased. To deal with this problem, several noise assessment methods are used.

First, International Standard Organization (ISO) suggests the noise assessment method based on frequency-domain estimation [1]. Once, the source is defined by the source measurement at frequency spectra and its magnitude. It calculates sound pressure level (SPL) of specific area using the simple equation regarding the geometric spreading. It is very simple and efficient; however, it doesn't focus on the physical phenomena of complex condition. As a result, it is called empirical formula.

Second, time-domain method is based on mathematical modeling. It calculates the whole computation domain. In comparison with ISO method, it is a little complex concerning the harmonic noise sources. But, if impulsive/broadband source is applied, there is no difference between frequency domain method and time domain method. This is why frequency-domain method computation time is dependent on the numbers of frequency band. Also, time-domain method can consider the ground effect analytically.

The assessment methodology is introduced which based on the time-domain computational aeroacoustic technique which assesses the propagation and reflection of impedance surface. And, modified broadband ground impedance condition is proposed for correction of low-frequency band. Finally, impedance influence factors are evaluated by this numerical assessment method.

METHODOLOGY

1. Governing Equation.

In the far-field, acoustic wave motions which are propagation and reflection satisfy the linearity condition. Linearized Euler Equation (LEE) is used.

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{F}}{\partial y}=\mathbf{Q} \tag{1}$$

Where,

$$\mathbf{U}=\begin{bmatrix}\rho\\u\\v\\p\end{bmatrix}\quad \mathbf{E}=\begin{bmatrix}u\\p\\0\\u\end{bmatrix}\quad \mathbf{F}=\begin{bmatrix}v\\0\\p\\v\end{bmatrix}\quad \mathbf{Q}=\begin{bmatrix}S_1\\S_2\\S_3\\S_4\end{bmatrix}$$

With no mean flow presence, ρ is the density perturbation, u is the velocity perturbation of x-direction, v is the velocity perturbation of y-direction, and p is the pressure perturbation, and the quantities of primitives are non-dimensionalized by length scale Δx, velocity scale of speed of sound c, time scale $\Delta x/c$, density ρ_∞, and pressure $\rho_\infty c^2$. And the righthandside term, $\mathbf{Q}$, means the unsteady acoustic source.

2. Radiation Boundary Condition.

In the computation domain, only the acoustic wave passes by. Using the asymptotic solution of acoustic wave, radiation boundary condition is determined [2].

$$\left(\frac{1}{V(\theta)}\frac{\partial}{\partial t}+\frac{\partial}{\partial r}+\frac{1}{2r}\right)\begin{bmatrix}\rho\\u\\v\\p\end{bmatrix}=0 \tag{2}$$

Where, $V(\theta)=a_0\left[M\cos\theta+\left(1-M^2\sin^2\theta\right)^{1/2}\right]$, $r=\sqrt{x^2+y^2}$

3. Impedance Boundary Condition.

A. Semi-empirical Model of Ground Impedance.

The characteristic impedance of ground has been measured by Delany and Bazely in many fibrous materials [3]. According to the measurement, impedance characteristic depends on the angular frequency ω and on the flow resistivity σ of the material. With measurement of the acoustical impedance and the acoustical properties, a good fit of impedance data is proposed.

$$\frac{Z}{\rho_0 c}=1+0.0571\left(\frac{\rho_0 f}{\sigma}\right)^{-0.754}+i0.087\left(\frac{\rho_0 f}{\sigma}\right)^{-0.732} \tag{3}$$

It has practical advantages to the impedance estimation of various materials with given flow resistivity. However, this model fixes not only the frequency dependency but also the relative magnitude of acoustic impedance. With low frequency band and high resistivity condition, it is occurred the over estimation in impedance reactance under $200\,Hz$. K. Attenborough suggests the modified approximation which added another parameter to the impedance model [4].

$$\frac{Z}{\rho_0 c}=0.218\left(\frac{\rho_0 f}{\sigma}\right)^{-0.5}+i\left[0.218\left(\frac{\rho_0 f}{\sigma}\right)^{-0.5}+9.74\left(\frac{\alpha_e}{\rho_0 f}\right)\right] \tag{4}$$

Where, α_e is the added parameter, effective rate of decrease in porosity with depth.

B. Extension to Finite Ground Impedance Model.

Let us consider the acoustic field with pure tone, ω. If the acoustic field and velocity field are time dependent, both can be written as follows

$$\begin{aligned}p(\vec{x},t)&=\mathrm{Re}\left[\hat{p}(\vec{x})e^{-i\omega t}\right]\\ v(\vec{x},t)&=\mathrm{Re}\left[\hat{v}(\vec{x})e^{-i\omega t}\right]\end{aligned} \tag{5}$$

Impedance can be written with normalized form in frequency-domain.

$$\frac{Z}{\rho_0 c}=R-iX \tag{6}$$

As impedance boundary condition is basically established in frequency-domain, it cannot be used in time-domain. Because time-domain impedance boundary has the well-posedness problems, boundary condition should satisfy the stability requirements due to initial and boundary data. In stability analysis with impedance coefficients, boundary conditions of each case are given [5].

$$\begin{aligned} X < 0, &\quad \frac{\partial p}{\partial t} = R\frac{\partial v_n}{\partial t} - X\omega v_n \\ X \geq 0, &\quad p = Rv_n + \frac{X}{\omega}\frac{\partial v_n}{\partial t} \end{aligned} \tag{7}$$

C. Extension to Ground Broadband Impedance Model.

In the Computational Aeroacoustics (CAA) methodology, broadband impedance boundary condition is proposed by Tam *et al*[5]. From the impedance measurement data, typical 3-Parameter model is established.

$$\frac{Z}{\rho_0 c} = R - i\left[X_{-1}/\omega + X_1\omega\right] \tag{8}$$

However, as we mentioned before, acoustic characteristic of the ground surface is mainly from the flow resistivity. Real measurement data of the ground impedance resistance is different form the 3 parameter model. It might cause more consideration about the impedance resistance.

Now, let us consider the several expansions of impedance resistance. Using the polynomial bases, impedance resistance is expanded generally. Also, it needs minimum expansion for numerical stability of boundary condition. There are 3-types of resistance expansions.

Type 1 : $R(\omega) = R_0 + R_1/\omega^2$
Type 2 : $R(\omega) = R_0 + R_1/\omega^2 + R_2/\omega^4$
Type 3 : $R(\omega) = R_{-1}\omega^2 + R_0 + R_1/\omega^2$

From the acoustical impedance data of ground with 506,000 MKS $(Pa \cdot m^{-1}s)$ flow resistivity, 3-type expansions are evaluated [6]. Type 1 expansion is agreeable to the impedance data. Other types have no difference with Type 1 (Type 2) or negative value on high-frequency band (Type 3). Hence, the modified impedance model is determined.

$$\frac{Z}{\rho_0 c} = R_0 + R_1/\omega^2 - i\left[X_{-1}/\omega + X_1\omega\right] \tag{9}$$

The broadband impedance boundary condition in time-domain is given.

$$\frac{\partial^2 p}{\partial t^2} = R_0\frac{\partial^2 v_n}{\partial t^2} - R_1 v_n - X_{-1}\frac{\partial v_n}{\partial t} + X_1\frac{\partial^3 v_n}{\partial t^3} \tag{10}$$

RESULT AND DISCUSSION

1.Application of Numerical Method

To the source term with 3-kind of frequency components which are consisted 1200 Hz , 1600 Hz , and 2000 Hz , numerical method is evaluated numerically.

$$S_1 = S_4 = \varepsilon \exp\left[-\ln 2 \left(\frac{(x-x_0)^2 + (y-y_0)^2}{r^2} \right) \right] \times \sum_{i=1}^{3} \cos(\omega_i t) \tag{11}$$

Two approach methods are used. First, finite impedance data is extracted from the broadband ground impedance modeling of 506,000 MKS. It is calculated in each frequency. Second, broadband impedance boundary condition is applied directly. Finally, sum of finite impedance solution is evaluated with broadband impedance solution.

In *fig.1*, it is shown that sum of finite impedance solution is identical with broadband impedance solution in each direction. It presents that the modified broadband impedance condition is more efficient in computing time than the finite impedance condition.

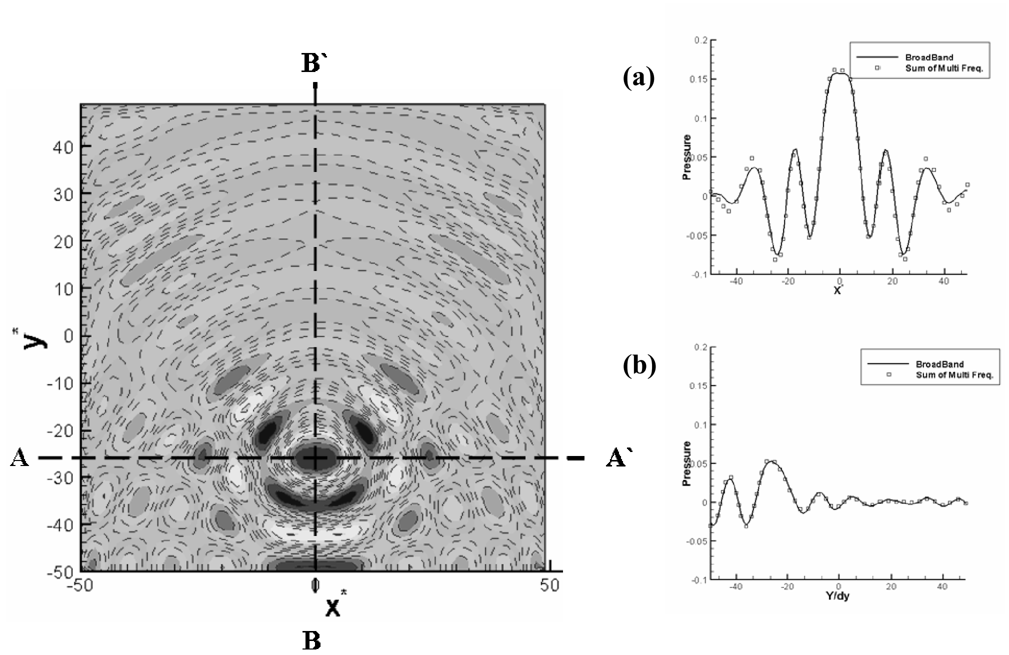

Fig 1. Pressure distribution. (a) horizontal axis, A-A` (b) vertical axis B-B`, solid line(━) is the broadband impedance solution and symbolic point(□) is the finite impedance solution

2. Numerical Validation.

Using the gaussian impulse, numerical method is validated with experiment data. The source point is located near-vertically to the observer point. And, the observer point is located on the 1.22m relative to the ground surface [6]. Excess attenuation is used for the characteristic of reflected surface. Excess attenuation means the comparison between free acoustic field and reflected acoustic field.

$$EA = 20\log\left(\frac{P_{reflected}}{P_{free}}\right) \tag{12}$$

In *fig. 2,* numerical calculation agrees well with experiment data. It presents that it is useful in the practical analysis on impulsive/broadband sound propagation.

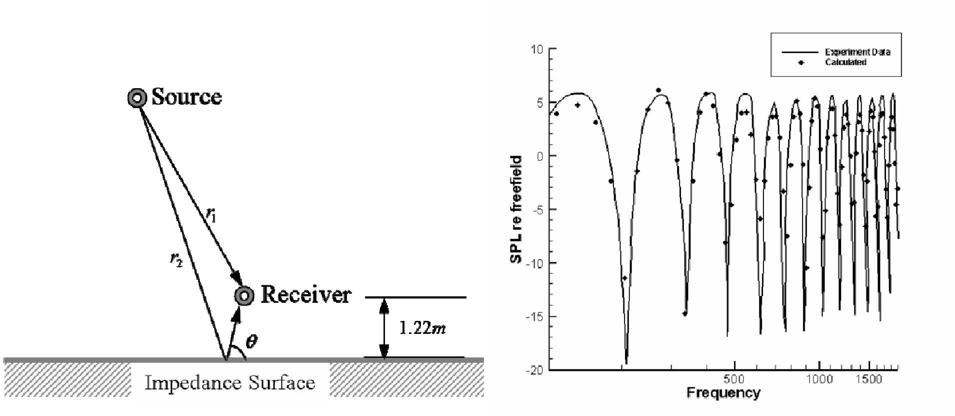

Fig 2. Numerical experiment and result, solid line(▬) is the experiment data Embleton *et al.* symbolic point(◆) is the numerical calculation with Fourier transformed.

3. Influence factor analysis.

As mentioned, impedance model parameters are related with frequency dependency, flow-resistivity, and relative source position. Excess attenuation is changed by the impedance parameters. The numerical schematic is shown in *fig. 3*

A. Flow Resistivity

Flow resistivity means that quantity is related between material and mean flow of air unit area [7]. It is defined by,

$$\sigma = \frac{p_2 - p_1}{Ve} \tag{13}$$

Where, V is the mean flow, e is the thickness of the material of unit area, $p_2 - p_1$ is the pressure difference of the both sides of material.

The higher flow resistivity increased, the bigger transmission loss is. As a result, impedance is increased on the high flow resistivity.

In *fig. 4-(a)*, with flow resistivity increased, the difference of EA converges to the zero. It means that impedance surface is acting like the near-hard wall surface above a certain flow resistivity.

B. Frequency Dependency.

When the observer point is located in a certain height, EA is affected by the frequency characteristic. Since, relation between the height and the wavelength causes the magnitude variation which is the amplification or the attenuation.

In *fig. 4-(b)*, it is shown that EA varies in frequency spectra at each observer point.

C. Oblique Incidence.

When observation point is location to the various positions, reflection characteristic of ground surface is changed. If the observer point is located near the ground surface, the phase shift is negligible. But, in the case of high incident angle and high flow resistivity, the phase shift which alters the EA pattern is increased.

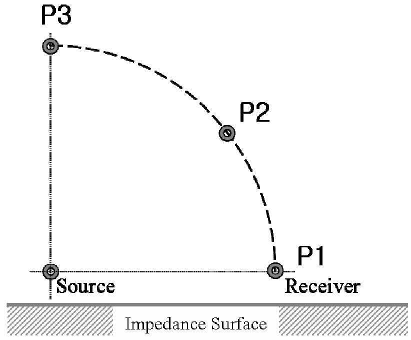

Fig 3. Schematic View of Numerical Experiment

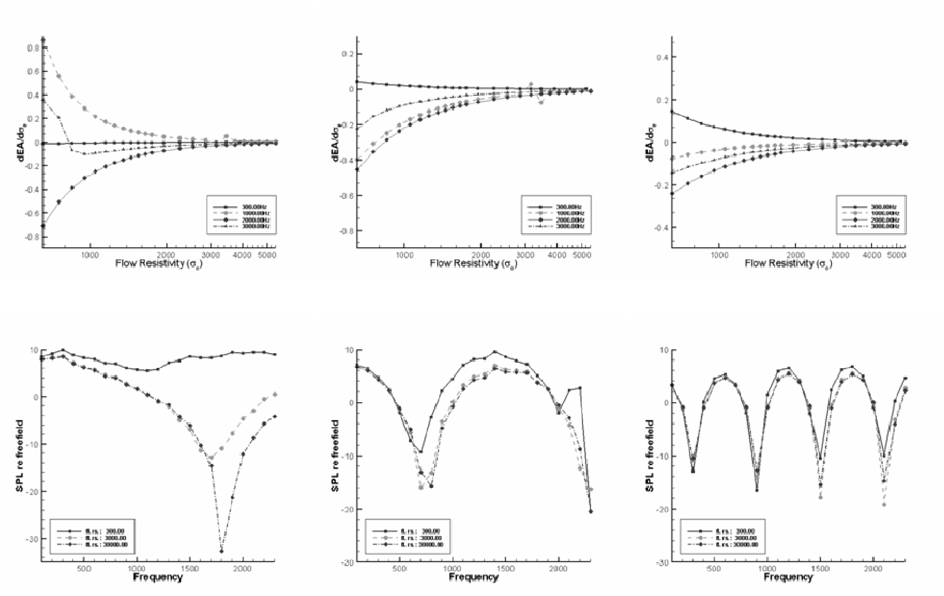

Fig 4. Influence factor investigation (a) Flow resistivity where frequencies(■,●,◆,▲) are 300Hz, 3KHz, 30KHz, and 300KHz, respectively (b) Frequency dependency where flow resistivity (■,●,◆) are 300MKS, 3,000MKS, and 30,000MKS respectively.

CONCLUDING REMARKS

The time-domain methodology has been suggested for the impulsive/broadband sound propagation in this paper. It is consisted of the finite impedance model and the broadband impedance model with ground condition. Comparing with the traditional frequency-domain methodology, the time-domain methodology is not dependent on the numbers of frequency spectra of sources. This makes the time-domain methodology have relatively less computing time on the impulsive sources.

For the accuracy at the observation point in far-field, the computational aeroacoutic technique is adopted. It is easily applicable to the noise assessment due to the impulsive/broadband noise sources with various ground surfaces. Furthermore, it has more probability of assessment of complex geometry.

ACKNOWLEDMENT

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