Development of Hybrid Methods for the Prediction of Internal Flow-Induced Noise and Its Application to Throttle Valve Noise in an Automotive Engine

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Abstract

General algorithm is developed for the prediction of internal flow-induced noise. This algorithm is based on the integral formula derived by using the General Green Function, Lighthill's acoustic analogy and Curls extension of Lighthill's. Novel approach of this algorithm is that the integral formula is so arranged as to predict frequency-domain acoustic signal at any location in a duct by using unsteady flow data in space and time, which can be provided by the Computational Fluid Dynamics Techniques. This semi-analytic model is applied to the prediction of internal aerodynamic noise from a throttle valve in an automotive engine. The predicted noise levels from the throttle valve are compared with actual measurements. This illustrative computation shows that the current method permits generalized predictions of flow noise generated by bluff bodies and turbulence in flow ducts.

1. Introduction

Generation and propagation of flow-induced noise in internal flows have quite different aspects from those in external flows. From a physical standpoint of sound generation and propagation, acoustic waves radiated from noise sources in external flow are affected only by interference of noise sources themselves while those in internal flow are influenced by interference between wall and noise sources in addition to that of noise sources themselves. The interference of wall and noise sources leads to modal solutions to internal acoustic fields. Due to the complexity of aerodynamic noise in internal flow, scarcely any work at all has been reported on the generalized hybrid methods for the prediction of internal aerodynamic noise. There have been only purely numerical and purely theoretical approaches.

In this paper, semi-analytic model for the prediction of internal aerodynamic noise is developed. This hybrid method is based on the integral formula derived by using inhomogeneous wave equation, General Green's Function, Lighthill's acoustic analogy and Curl's extension of Lighthill's. The integral formula is so arranged as to predict the frequency-domain acoustic signal at any location in a duct by using the unsteady flow data in space and time, which can be provided by the computational fluid techniques.

This article contains four sections. In second section, fundamental formulations for the prediction of internal aerodynamic noise are derived. In third section, current method is applied to the flow noise from quick-opening throttle valve in an automotive engine. The numerical results and discussion of flow simulation and noise prediction results by using current hybrid method are described in detail. Final section is devoted to the concluding remarks.

2. Fundamental Formulations

2.1. Equation for the Sound Field

Coordinates moving with uniform mean flow are chosen with origin on one edge of the pipe, y_1 being coordinates in the axial direction, and y_2 and y_3 in the cross-sectional plane. The problem of sound generated by a flow in a duct can be treated by replacing the solid obstacle by a distribution of dipole sources and the turbulence by a distribution of quadrupole sources, respectively. Then, the equation governing the sound field in the duct is Lighthill's form and Curl's extension from Lighthill's as follows.

$$\left\{\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial \tau^2}\right\} p(y_k, t) = \left(\frac{\partial}{\partial y_i}\right)[f_i(y_k, t)] - \left(\frac{\partial}{\partial y_i}\right)\left[\frac{\partial T_{ij}}{\partial y_i}\right] \quad (1)$$

where p is the pressure, τ is time, c is the velocity of sound, f_i is force per unit volume and T_{ij} is Lighthill's turbulence stress tensor. T_{ij} denotes the expression $(p - c^2\rho)\delta_{ij} + \rho u_i u_j$, where δ_{ij} is the Kronecker delta and u_i is the particle velocity in the i-direction relative to the mean flow. Eq. (1) can be solved by means of a Green's function $G(\mathbf{x}, t \,|\, \mathbf{y}, \tau)$ defined as the solution of

$$\nabla^2 G - \frac{1}{c^2}\frac{\partial^2 G}{\partial \tau^2} = \delta(\mathbf{x} - \mathbf{y})\delta(t - \tau) \quad (2)$$

with $\frac{\partial G}{\partial n} = 0$ on the boundaries.

The Fourier transform of G with respect to time, written $g(\mathbf{x}, \mathbf{y}|\omega)$ satisfies the equation

$$\nabla^2 g - k^2 g = \delta(\mathbf{x} - \mathbf{y}) \quad (3)$$

and is related to G by the inverse transform

$$G(\mathbf{x},t|\mathbf{y},\tau)=\frac{1}{2\pi}\int_{-\infty}^{\infty}g(\mathbf{x},\mathbf{y}|\omega)\exp\{-i\omega(t-\tau)\}d\omega \qquad (4)$$

The Green's function is expressed as a sum of the normal modes of oscillation by considering the eigenfunction satisfying the following 2-D Helmholz equation

$$\left(\frac{\partial^2}{\partial y_2^2}+\frac{\partial^2}{\partial y_3^2}\right)\Psi_{mn}+\kappa_{mn}^2\Psi_{mn}=0 \qquad (5)$$

and the eigenfunction Ψ_{mn}, which are orthonormal.

$$\int_A \Psi_{mn}\Psi_{m'n'}dy_2dy_3=\begin{cases}0 & if\ m\neq m'\ or\ n\neq n'\\ \Gamma_{mn} & if\ m=m'\ and\ n=n\end{cases} \qquad (6)$$

Then the solution of Eq. (3) can be assumed to be the sum of the product of the eigenfunction and the function of the y_1. And by using Eq. (4), Green's Function in time-domain can be expressed as

$$G(\mathbf{x},t\mid\mathbf{y},\tau)=\frac{i}{4\pi}\sum_{m,n=0}^{\infty}\frac{\Psi_{m,n}(y_2,y_3)\Psi_{m,n}^*(x_2,x_3)}{\Gamma_{m,n}}\times\int_{-\infty}^{\infty}\frac{\exp\{ik_{mn}|x_1-y_1|\}}{k_{m,n}}\exp\{-i\omega(t-\tau)\}d\omega \qquad (7)$$

where $k_{mn}=\sqrt{k^2-\kappa_{mn}^2}$. By using the above equation, time-domain acoustic pressure from internal flow can be expressed as

$$p(\mathbf{x},t)=c^2\rho(\mathbf{x},t)=\int_v\int_t G(\mathbf{x},t\mid\mathbf{y},\tau)\left\{\frac{\partial f_i(\mathbf{y},\tau)}{\partial y_i}-\frac{\partial^2T_{ij}(\mathbf{y},\tau)}{\partial y_i\partial y_j}\right\}d\mathbf{y}d\tau$$

where the volume integral is over all space and the time integral ranges from -∞ to ∞. The Green's function chosen is an exact form, and with boundary conditions specified, ensures that the solution involves no surface integrals. Thus,

$$p(\mathbf{x},t)=c^2\rho(\mathbf{x},t)=\frac{i}{4\pi}\sum_{m,n=0}^{\infty}\frac{\Psi_{m,n}^*(x_2,x_3)}{\Gamma_{m,n}}\times\int_v d\mathbf{y}.\int_{-\infty}^{\infty}d\tau\int_{-\infty}^{\infty}d\omega\Psi_{m,n}(y_2,y_3)\times\frac{\exp\{ik_{mn}|x_1-y_1|-i\omega(t-\tau)\}}{k_{m,n}}\left\{\rho_0\frac{\partial f_i(\mathbf{y},\tau)}{\partial y_i}-\frac{\partial^2T_{ij}(\mathbf{y},\tau)}{\partial y_i\partial y_j}\right\} \qquad (8)$$

The term k_{mn}, defined by Eq. (7), denotes the wave number in the axial direction. For propagating wave motion this must be real, which it is above the cut off frequency which is denoted by $\omega_{mn}=ck_{mn}$. For frequency less than the cut-off frequency, k_{mn}^2 is negative and the pressure in that mode decays exponentially away from the source. Similar form of integral equation has been used in previous theoretical studies [1-3].

2.2. Rearrangement for Semi-analytic Algorithm

In this section, Eq. (8) is rearranged in order to develop the general hybrid algorithm, by which the internal aerodynamic noise signal can be predicted.

Rearrangement is carried out such that frequency-domain noise signal at certain position in a duct can be computed by using unsteady flow data in time and space, which are provided by using the Computational Fluid Dynamics techniques.

First, consider the inverse Fourier transform of Eq. (8) on the time t at position $\mathbf{x}$, and then ω component of pressure p at poison $\mathbf{x}$ can be described as follows.

$$p(\mathbf{x},\omega)=\frac{i}{2}\sum_{m,n=0}^{\infty}\frac{\Psi_{m,n}^*(x_2,x_3)}{\Gamma_{m,n}}\int_v d\mathbf{y}.\int_{-\infty}^{\infty}d\tau\Psi_{m,n}(y_2,y_3)\times\frac{\exp\{ik_{mn}|x_1-y_1|-i\omega(t-\tau)\}}{k_{m,n}}\left\{\rho_0\frac{\partial f_i(\mathbf{y},\tau)}{\partial y_i}-\frac{\partial^2T_{ij}(\mathbf{y},\tau)}{\partial y_i\partial y_j}\right\} \qquad (9)$$

In order to combine above equation with given flow data in space and time, Eq. (9) is rewritten as follows.

$$p(\mathbf{x},\omega)=\frac{i}{2}\sum_{m,n=0}^{\infty}\frac{\Psi_{m,n}^*(x_2,x_3)\exp\{ik_{mn}x_1\}}{\Gamma_{m,n}}\{\mathbf{D}_{mn}(\omega)+\mathbf{Q}_{mn}(\omega)\}$$

$$where,\ \mathbf{D}_{mn}(\omega)=\int_{-\infty}^{\infty}\int_v\Psi_{m,n}(y_2,y_3)\frac{\exp\{-ik_{mn}y_1+i\omega\tau)\}}{k_{m,n}}\times\left\{\rho_0\frac{\partial f_i(\mathbf{y},\tau)}{\partial y_i}\right\}dvd\tau$$

$$\mathbf{Q}_{mn}(\omega)=\int_{-\infty}^{\infty}\int_v\Psi_{m,n}(y_2,y_3)\frac{\exp\{-ik_{mn}y_1+i\omega\tau)\}}{k_{m,n}}\times\left\{\frac{\partial^2T_{ij}(\mathbf{y},\tau)}{\partial y_i\partial y_j}\right\}dvd\tau \qquad (10)$$

Here, $\mathbf{D}_{mn}$ denotes the ω component of noise from dipole sources and $\mathbf{Q}_{mn}$ does from quadrupole sources. By applying the divergence theorem to Eq. (10) with integral space enough to cover the whole field at the boundary of which the sources disappear, Eq. (10) can be rewritten as follows.

$$\mathbf{D}_{mn}(\omega)=-\frac{1}{k_{m,n}}\int_{-\infty}^{\infty}\int_v f_i(\mathbf{y},\tau)\times\frac{\partial}{\partial y_i}\{\Psi_{m,n}(y_2,y_3)\exp\{-ik_{mn}y_1+i\omega\tau)\}\}dvd\tau$$

$$\mathbf{Q}_{mn}(\omega)=-\frac{1}{k_{m,n}}\int_{-\infty}^{\infty}\int_v T_{ij\,i}(\mathbf{y},\tau)\times\frac{\partial}{\partial y_i\partial y_j}\{\Psi_{m,n}(y_2,y_3)\exp\{-ik_{mn}y_1+i\omega\tau)\}\}dvd\tau \qquad (11)$$

Unsteady data provided by flow simulations can be used to calculate the terms of f_i and T_{ij} of Eq. (11). By considering a cylindrical duct coordinate, Eq (11) can be expressed as

$$\mathbf{D}_{mn}(\omega)=-\frac{1}{k_{m,n}}\int_{-\infty}^{\infty}\int_v f_i(\mathbf{y},\tau)\times\frac{\partial}{\partial y_i}\left\{J_m(\kappa_{m,n}r)e^{-i(k_{mn}y_1+m\theta)}\right\}\exp\{i\omega\tau\}dvd\tau$$

$$\mathbf{Q}_{mn}(\omega)=-\frac{1}{k_{m,n}}\int_{-\infty}^{\infty}\int_v T_{ij\,i}(\mathbf{y},\tau)\times\frac{\partial}{\partial y_i\partial y_j}\left\{J_m(\kappa_{m,n}r)e^{-i(k_{mn}y_1+m\theta)}\right\}\exp\{i\omega\tau\}dvd\tau \qquad (12)$$

3. Analysis of Airflow upon Quick Opening of Throttle

Market-available analysis tool, STAR-CD is used for the flow analysis. The reasons for using the commercial software for the flow analysis instead of an in-house code are two-fold. The first is to show the capability of the developed algorithm to be combined with the commercial software, which is more convenient tool for engineers in the practical fields. The second is to avoid the severe code validation for the saving of time. The utilized algorithm in STAR-CD is as follows: QUICK scheme is used for spatial discretization, fully implicit scheme for time discretization, and the solution algorithm is based on the PISO algorithm. The flow field configuration changes as the throttle continues opening. The calculation area is divided into the duct section and the spherical section. The spherical section contains the baffle cells modeling the throttle valve and allows for the rotation of the baffle cell, i.e., the throttle valve. Figure 1 shows the calculation meshes where the entire spherical section is rotated about the throttle axis and the applied boundary conditions.

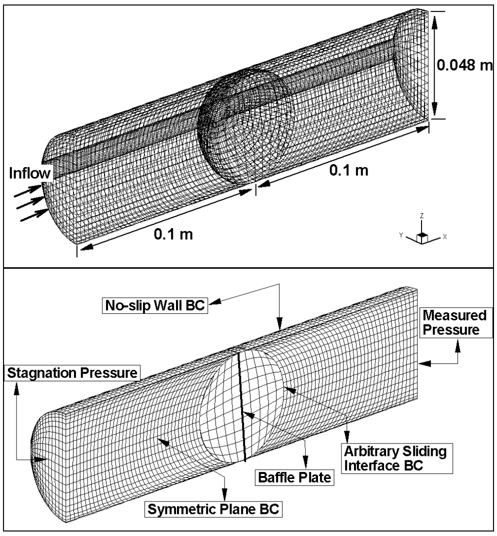

Figure 1: Calculation meshes and boundary conditions

The throttle opening time, from fully closed position to fully open position, is 0.227 second, which is set to meet the experimental condition. The fluid is assumed to be a compressible viscous flow with the properties of air. To reproduce the throttle conditions as much as possible, the measured value of pressure at points upstream and downstream from the throttle is used as inflow and outflow boundary conditions. The pressure at inlet plane is kept almost constantly at atmospheric pressure, while the pressure on the exit side increases steadily from low pressure to nearly atmospheric pressure during the quick opening behavior of the throttle.

Figure 2, 3 presents the F_1 variation due to pressure distribution on the surface of the throttle valve and the distribution of $\mathbf{T}_1$ due to turbulence kinetic energy over whole computation domain, along the direction of flow stream. Here, .the distribution of F_1 in time and space is utilized for the calculation of the dipole-originated, plane-mode noise signal using Eq. (12) and T_{11} is utilized to calculate the quadrupole-originated, plane-mode noise signal.

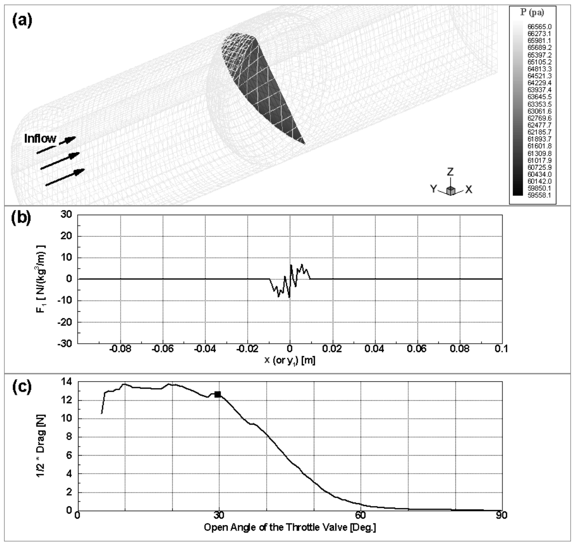

Figure 2: Variation of Force per unit density and area in the direction of duct axis and Drag during quick opening of throttle valve (Open Angle = 30 deg.)

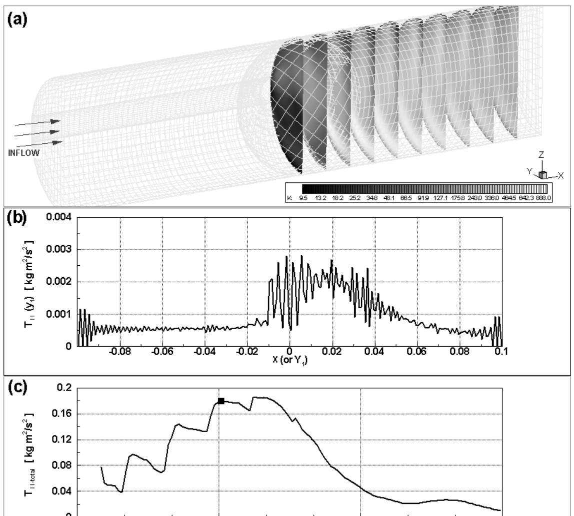

Figure 3: Variation of $v_z v_z$ in the direction of duct axis and integration value of $v_z v_z$ during quick opening of throttle valve (Open Angle = 30 deg.)

It is found that the components below 4150 Hz are cut-off frequencies and only (0,1) mode, i.e., plane wave is propagated. The time step in previous flow simulation is 0.0002 second and the Nyquist frequency is 2000 Hz.

Thus, in present noise prediction with previously calculated flow data, only plane mode is valid.

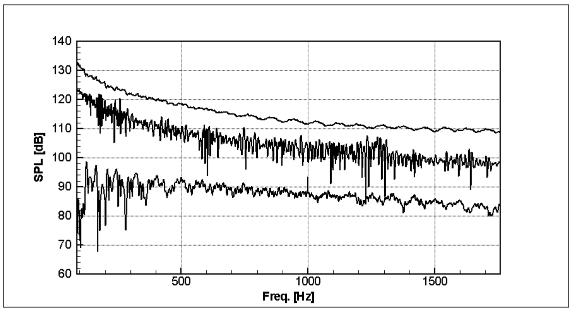

Figure 4: Comparison of sound pressure levels: (Upper) Predicted results by using the dipole source, (middle) Measured Data, and (Lower) Predicted results by using the quadrupole source

Figure 4 shows the calculated dipole- and quadrupole-originated noise levels, with measured data in the frequency band from 88 Hz to 1760 Hz. In this frequency range, only the plane mode is cut-on mode. It is found from this figure that the noise level from the dipole sources is bigger than that from the quadrupole sources, and thus noise generation mechanism from the quick opening throttle seems to be dipole-originated phenomena. It is also found that, although the discrepancy of prediction results from dipole sources and test values is approximately 8 [dB] at each frequency, the decreasing trend of the predicted noise level according to the frequencies agrees reasonably well with that of the testing results. For all frequency range, the predicted noise level is bigger than that of the measurement, i.e., the simulation results tend to be an over-prediction. This is because the cross-sectional area of the pipe suddenly changes as the airstreams flow from the duct containing the throttle valve to the manifold where the measurement is executed. From the theoretical analysis [4], the relation between the strength, I, of the incident harmonic pressure wave and the strength, T, of the transmitted wave is described as follows.

$$T = \frac{2A_1}{A_1 + A_2} I \tag{13}$$

where A_1 and A_2 are the areas of incident duct and transmitted duct, respectively. In this case, A_1 is the area of the conduit containing the throttle valve, $\pi \times 0.024^2$ [m^2] and A_2 is that of the manifold, 0.0796×0.0735 [m^2]. Insertion of these areas into Eq. (13) leads to the transmission loss –6.5 dB.

Figure 5 shows the sound pressure levels of the raw prediction, corrected prediction by using the transmission loss, and the measured data on one-third octave band frequencies. It can still be confirmed that the proposed methodology for predicting the internal aerodynamic noise is a reliable approach.

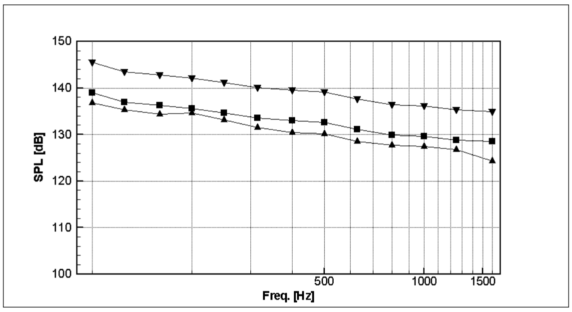

Figure 5: Comparison of sound pressure levels at one-third octave band frequencies. (Prediction result: ▼, Corrected prediction result by using the transmission loss: ■ , and measured data: ▲)

4. Conclusions

The hybrid method is developed for the prediction of internal flow-induced noise from obstacles, i.e. dipole sources and turbulent velocities, i.e. quadrupole sources. This method is based on the integral formula derived by using the General Green Function, Lighthill's acoustic analogy and Curl's extension of Lighthill's. Novel approach of this algorithm is that the integral formula is so arranged as to predict the frequency-domain acoustic signal at any locations in a duct by using the unsteady flow data in space and time, which can be provided by the Computational Fluid Dynamics techniques. This semi-analytic model is applied to the prediction of the internal aerodynamic noise from a quick-opening throttle valve in an automotive engine. The predicted noise level of the throttle valve shows similar decreasing trend according to the frequencies with the measurements. The prediction results corrected with the transmission loss shows good agreements with the measurement than the raw prediction data. This illustrative numerical application shows that the current method permits generalized predictions of flow noise generated by bluff bodies and turbulence in flow ducts.

5. References

[1] P. E. Doak, "Excitation, transmission and radiation of sound from source distributions in hard-walled ducts of finite length (I): The effects of duct cross-section geometry and source distribution space-time," *Journal of Sound and Vibration*, Vol. 31, pp.1-72, 1973.

[2] H.G. Davies and J.E. Ffowcs Williams, "Aerodynamic sound generation in a pipe," *Journal of Fluid Mechanics,* Vol. 32, pp.765-778, 1968.

[3] P.A. Nelson and C.L. Morfey, "Aerodynamic sound production in low speed flow ducts." *Journal of Sound and Vibration* , Vol. 79, pp.263-289, 1981.

[4] A.P. Dowling, J.E. Ffowcs Williams, *Sound and Sources of Sound,* Ellis Horwood Limited, 1983.