쓰로틀밸브 급개방시 기류소음의 4극음원에 대한 정량적 해석

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Quantitative Analysis of Quadrupole Noise Sources upon Quick Opening The Throttle

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ABSTRACT

In recent years, modularization of engine parts has increased the application of plastic products in air intake systems. Plastic intake manifolds provide many advantages including reduced weight, contracted cost, and lower intake air temperatures. These manifolds, however, have some weakness when compared with customary aluminium intake manifolds, in that they have low sound transmission loss because of their lower material density. This low transmission loss of plastic intake manifolds causes several problems related to flow noise, especially when the throttle is opened quickly. The physical processes, responsible for this flow noise, include turbulent fluid motion and relative motion of the throttle to the airflow. The former is generated by high-speed airflow in the splits between the throttle valve and the inner-surface of the throttle body and surge-tank, which can be categorized into the quadrupole source. The latter induces the unsteady force on the flow, which can be classified into the dipole source. In this paper, the mechanism of noise generation from the turbulence is only investigated as a preliminary study. Stochastic noise source synthesis method is adopted for the analysis of turbulence-induced, i.e. quadrupole noise by throttle at quick opening state. The method consists of three procedures. The first step corresponds to the preliminary time-averaged Navier-Stokes computation with a $k-\varepsilon$ turbulence model providing mean flow field characteristics. The second step is the synthesis of time-dependent turbulent velocity field associated with quadrupole noise sources. The final step is devoted to the determination of acoustic source terms associated with turbulent velocity. For the first step, we used market-available analysis tools such as STAR-CD, the trade names of fluid analysis tools available on the market. The steady state flows at three open angle of throttle valve, i.e. 20, 35 and 60 degree, are numerically analyzed. Then, time-dependent turbulent velocity fields are produced by using the stochastic model and the flow analysis results. Using this turbulent velocity field, the turbulence-originated noise sources, i.e. the self-noise and shear-noise sources are synthesized. Based on these numerical results, it is found that the origin of the turbulent flow and noise might be attributed to the process of formulation and the interaction of two vortex lines formed in the downstream of the throttle valve. These vortex lines are produced by the non-uniform splits between the throttle valve and inner cylinder surface. Based on the analysis, we present the low-noise design of the inner geometry of throttle body.

I. INTRODUCTION

According to traditional mass law of transmission loss, the difference in noise transmissibility, ΔTL, can be theoretically determined by equation (1).

$$\Delta TL = 20\log\left(\frac{\rho_A}{\rho_P}\right) \tag{1}$$

Here, ρ_A and ρ_P denote the density of aluminium and plastic, respectively. As compared with aluminium intake manifolds, the transmitted noise level of plastic intake manifolds is higher by about 6 dB because of their lower material density. This difference causes several problems related to the flow noise, especially when the throttle is opened quickly in plastic manifold. Thus, the reduction of flow noise is indispensable in order to ensure high sound quality of the vehicle, which requires full comprehension of the mechanism of the noise generation during the quick opening of the throttle valve. In view of classical aeroacoustic theory, two types of noise sources are expected to be responsible for the flow noise generation from the quick-opened throttle valve. One is the turbulence velocity in the downstream side of the throttle valve. This can be classified into quadrupole source. The other is the unsteady pressure fluctuation on the surface of the throttle valve, which originated from the relative motion of the throttle valve to the airflow. This can be categorized into dipoles source. In this study,

the former is only concerned. The latter is now under investigation and will be soon issued in the future.
Based on Lighthill's theory, conventional aeroacoustic noise prediction methods rely on an analogy featuring a propagation equation associated with source terms. These formulations require time average or unsteady aerodynamic computation (k − , LES or DNS) and provide acoustic far-fields. They do not account for all acoustic/mean flow interactions. More complex wave operators were derived to describe these interactions allowing extensions to prediction of noise generated by complex free flows. However, application to confined configuration is not straightforward because it requires the determination of adapted Green's functions. Also, most of these methods depend on third order equations, which make numerical approaches difficult. Furthermore, propagation equations carry not only acoustic disturbances but also vorticity and entropy waves.
In this paper, the stochastic approach is utilized in order to analyze the turbulence noise from the throttle being quickly opened. The stochastic method does not feature some weakness of the aforementioned modelling. It is based on the computation of Euler equations describing the propagation and including acoustic source terms associated with turbulence. Propagation equations are linearized around a mean field obtained from a time average aerodynamic calculations. Noise sources are expressed in terms of a turbulent velocity field provided by a stochastic synthesis method.
An attempt to examine this similar phenomenon closely was made by Yoshihiro Naka et al [1]. But their work is based on numerical cut-and-discard approach, while our work is based on the well-developed aeroacoustic theory. Such an approach that is applied in this work is desirable for robust development of low noise design.
The first section is devoted to the summary on the stochastic model of turbulence and the synthesis of acoustic source terms. In the second part, the computation results of the steady flows at three different open angles (20, 35 and 60 degree) of the throttle are shown. The computations are made with STAR-CD, the trade names of fluid analysis tools available on the market. Finally, the results related to the noise source identification around the throttle valve are shown and the particular disturbance mechanism suspected of dominating the performance of turbulence noise in downstream of the throttle valve is discussed.

II. STOCHASTIC MODEL OF TURBULENCE

There are three steps in the computation. A stochastic turbulent velocity field in space is first created. Then, the turbulence time dependence is introduced. Finally, acoustic source terms are calculated. The spatial velocity field is synthesized with a method devised by Kraichnan [2] and improved by Karweit et al. [3,4]. In this method, one generates a random velocity field that is defined as a finite sum of discrete Fourier modes. This turbulent three-dimensional field is isotropic and homogeneous and considered to be frozen. The method provides a random velocity field having the suitable spatial

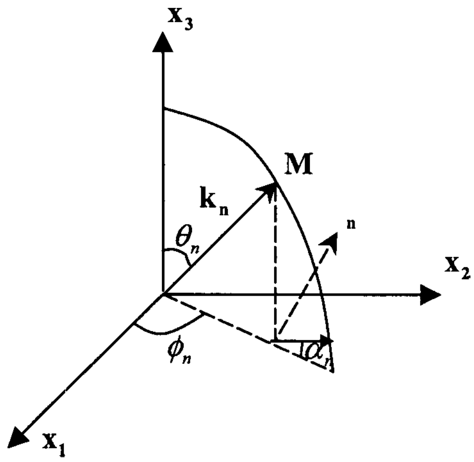

Figure 1. The wave vector geometry of a single Fourier velocity mode

characteristics. It has been utilized in the past to investigate the behavior of acoustic waves propagating through a turbulent medium. Walid et al. [5] have applied the method to the simulation of a turbulent velocity field having the turbulent kinetic K energy and the dissipation rate obtained from a standard K- code. In the following, the methods are summarized.

STOCHASTIC VELOCITY FIELD IN SPACE

A turbulent homogeneous isotropic field at given point x can be cast into three dimensional Fourier space as follows,

$$u_t(x) = \tilde{u}_t(k) e^{ik\cdot x} dk \cdot \quad (2)$$

Here k is the wave vector and j is the complex number ($j^2 = -1$). Transforming this Fourier integral into a finite sum of N modes produces

$$u_t(x) = 2 \sum_{n=1}^{N} \tilde{u}_n \cos(k_n \cdot x + \Psi_n)\sigma_n \quad (3)$$

where $\tilde{u}_m$, ψ_n, and σ_n are the amplitude, phase, and the direction of the n-th mode wave vector k_n. Furthermore, for an incompressible turbulent field, the relation $\partial u_{ti} / \partial y_i = 0$ requires that

$$k_n \cdot \sigma_n = 0, \qquad n = 1, \ldots, N \quad (4)$$

This means that in the spectral space, the unit vector σ_n is always perpendicular to the wave vector k_n and its position is determined by its polar angle α_n. The related vector geometry is illustrated in Fig. 1. The wave vector k_n may be characterized by its spherical coordinates (k_n, φ_n, θ_n) as shown in Fig. 1. The isotropic and homogeneous random field is obtained by electing probability density functions for the random variables φ_n, θ_n, σ_n, and α_n. It may be shown that $P(\varphi_n) = P(\alpha_n) = 1/2\pi$ and $P(\Psi_n) = 1/\pi$. On the other hand, the distribution of θ_n is given by a sign function: $P(\theta_n)=1/2 \sin\theta_n$.
For a complete determination of the field (3), one has to calculate the amplitude $\tilde{u}_m$ for each Fourier mode. The statistical mean (noted < >) of $1/2u_{ti}u_{ti}$ is the turbulent kinetic energy K, and according to Eq. (3), this quantity

takes the form

$$K = \sum_{n=1}^{N} \tilde{u}_m^2 \tag{5}$$

An homogeneous isotropic turbulence is characterized by a three-dimensional spectrum $E(k)$ [6] which is such that

$$K = \int_0^{\infty} E(k)dk \tag{6}$$

$$\varepsilon = \int_0^{\infty} k^2 E(k)dk \tag{7}$$

The amplitude $\tilde{u}_m$ of each mode is equal to $\sqrt{E(k_n)\Delta k_n}$, and one may use the modified Von Karman spectrum $E(k)$ to simulate the complete spectral range.

$$E(k) = A\frac{\overline{u^2}}{k_e}\frac{(k/k_e)^4}{[1+(k/k_e)^2]^{17/6}}e^{-2(k/k_v)^2} \tag{8}$$

The Von Karman Spectrum is known to represent the energy distribution of turbulence in wider length scale than other models. The two parameters A and k_e are determined by using Eqs. (6) and (7), whereas k_v is the Kolmogorov wave number defined by $(\varepsilon / \upsilon^3)^{1/4}$. The spectrum reaches its maximum at $k = k_e$.

To assign the spectral power to a finite number of N modes, it is desirable to use a logarithmic distribution of the N wave numbers. This provides a better discretization of the power in the lower wave number range corresponding to the larger, energy-containing eddies. The logarithmic step Δk_l of this distribution is given by

$$\Delta k_l = \frac{\log k_N - \log k_1}{N-1} \tag{9}$$

$$k_n = \exp[\log k_1 + (n-1)\Delta k_l] \tag{10}$$

The wave number $k_l = 2\pi/L$ corresponds to the largest eddy (L is the largest eddy scale), whereas $k_N = (\varepsilon / \upsilon^3)^{1/4} = k_v$ indicates the Kolmogorov wave number. In order to check the validity of the stochastic field, its statistical properties must be investigated.

TURBULENCE TIME DEPENDENCE

The turbulence unsteadiness depends upon two processes. One process is the convection of turbulence by the mean flow u_0. The velocity u_t is solution of the transport equation:

$$\frac{\partial u_t}{\partial t} + (u_0 \cdot \nabla)u_t = 0 \tag{11}$$

Therefore, the expression of u_t is given by:

$$u_t(x) = 2\sum_{n=1}^{N} \tilde{u}_m \cos(k_n \cdot (x - u_0 t) + \Psi_n)\ _n \tag{12}$$

The other is the time dependence of the field governed by the turbulence characteristic frequency. For each mode, we introduce a pulsation ω_n defined by $\omega_n = \varepsilon^{1/3} k_n^{2/3}$ as small structures contribute to high frequency radiation and conversely. Furthermore, when the wave number k is near k_e (in the region of maximal spectrum), pulsation ω_n tends to $\alpha 2\pi\varepsilon/k$ which is proportional to the characteristic turbulence pulsation [6]. The final form is:

$$u_t(x) = 2\sum_{n=1}^{N} \tilde{u}_m \cos(k_n \cdot (x - u_0 t) + \Psi_n + \omega_n t)\ _n \tag{13}$$

In Fig. 2 is given the calculated time history of the stochastic field at one specific location.

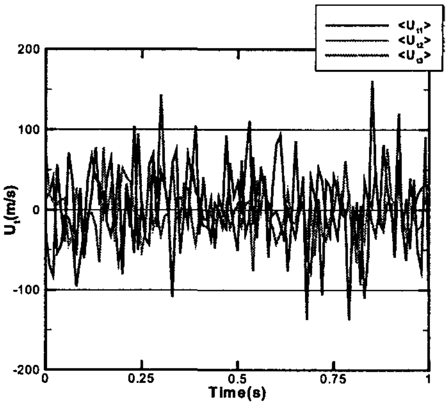

Figure 2. Time histories of the turbulence velocity at a specific

ACOUSTIC SOURCE TERM BUILDING

Let us now consider the generation of noise by a stationary turbulent flow-field. One may distinguish mean, turbulent, and acoustic components in each flow variable and express theses variables as follows:

$$\begin{aligned} p &= P + p_t + p_a \\ u_i &= U_i + u_{ti} + u_{ai} \\ \rho &= \bar{\rho} + \rho_t + \rho_a \end{aligned} \tag{14}$$

The acoustic fluctuations are generally small compared to the mean and turbulent variables, so that one may assume that the following relations are satisfied:

$$\begin{aligned} &p_a/p_t \ll 1, \quad u_{ai}/u_{ti} \ll 1, \quad \rho_a/\rho_t \ll 1 \\ &p_a/P \ll 1, \quad u_{ai}/U_i \ll 1, \quad \rho_a/\bar{\rho} \ll 1 \end{aligned} \tag{15}$$

If the mean and turbulent components of the flow are already known, the governing equation for acoustic variables can be formulated from the Euler equation as follows [5].

$$\begin{aligned} &\frac{\partial p_a}{\partial t} + U_i\frac{\partial p_a}{\partial y_i} + \gamma P\frac{\partial u_{ai}}{\partial y_i} + \gamma p_a\frac{\partial U_i}{\partial y_i} + u_{ai}\frac{\partial P}{\partial y_i} \\ &= -\frac{\partial p_t}{\partial t} - U_i\frac{\partial p_t}{\partial y_i} - u_{ti}\frac{\partial P}{\partial y_i} - u_{ti}\frac{\partial p_t}{\partial y_i} \end{aligned} \tag{16}$$

$$\begin{aligned} &\frac{\partial u_{ai}}{\partial t} + U_j\frac{\partial u_{ai}}{\partial y_j} + \frac{1}{\bar{\rho}}\frac{\partial p_a}{\partial y_i} + u_{aj}\frac{\partial U_i}{\partial y_j} - \frac{p_a}{\bar{\rho}^2\bar{c}^2}\frac{\partial P}{\partial y_i} \\ &= -U_j\frac{\partial u_{ti}}{\partial y_j} - u_{tj}\frac{\partial U_i}{\partial y_j} - u_{tj}\frac{\partial u_{ti}}{\partial y_i} - \frac{1}{\bar{\rho}}\frac{\partial p_t}{\partial y_i} - \frac{\partial u_{ti}}{\partial t} + \frac{\partial}{\partial y_j}\overline{u_{tj}u_{ti}} \end{aligned} \tag{17}$$

In Eq. (16), the term $\gamma p_a \partial U_i/\partial y_i$ is retained to obtain a set of expressions (16) and (17) featuring a left-hand side that is identical to the linearized Euler equations. To simplify the analysis, the terms describing effects of turbulence-acoustic interactions and of non-linear acoustics are neglected.

The right-hand side of system (16) and (17) exhibits the source terms responsible for the noise generation. The identification of the principal terms, which responsible for the noise emission, is not a simple matter. However, it is known that the main sources of sound generated by turbulence are the first terms of the right-hand side of Eq. (17) [7,8]. This reasoning based on previous knowledge is essentially confirmed by an order of magnitude analysis. In particular, the first two terms simulate the interaction between the mean and turbulent components of the flow. The third term represents turbulence-turbulence interactions. The noise associated with the first two terms is usually called *shear noise* whereas that due to the third term is denoted as *self noise*. These three terms are the cardinal sources of the sound generated aerodynamically and the other contributions may be neglected.

To estimate the source terms it is necessary to calculated the mean flow and simulate a space-time turbulent velocity field. The determination of this field is described in the next section.

III. ANALYSIS OF AIRFLOW UPON QUICK-OPENING OF THROTTLE

In this section are provided the numerical results and discussion on the airflow produced when the throttle is opened quickly. For this analysis, we used market-available analysis tool, STAR-CD.

MESHING FOR CALCULATION

To numerically analyze a three-dimensional flow, the flow fields must be exhibited by calculation meshes. Three types of flow field configuration at three open angles of 20, 35 and 60 degree are considered. Therefore, three calculation meshes are required in correspondence with throttle valve angles in order to numerically analyze airflow.

In Fig. 3 are shown the whole configuration of the mesh and the dimension of inner geometry of the throttle body used in analysis. The mesh for the conduit contains 100495 nodes and 93600 hexahedral elements. The 648 cells are used for the modelling of baffle type valve. Making use of symmetric geometry of the concerned problem, we analyzed only a half section of the throttle for the saving of calculation time.

SETTING OF FLOW AND SLOVER CONDITIONS

The fluid is assumed to be a compressible viscous flow with the properties of air. Table 1 shows detailed calculation conditions. To reflect the throttle conditions as much as possible, we use the measured value of pressure at points upstream and downstream from throttle as inflow and outflow boundary conditions. The pressure at inlet plane is kept almost constant at atmospheric pressure, while the pressure on the exit side increase steadily from low pressure to nearly atmospheric pressure during the quick opening behavior of the throttle.

Table 1. The detailed calculation condition

STAR CD (version 3.100A)	
Flow types	Compressible viscous flow
Turbulent model	k-ε high Re. Turbulent model
Solution Algorithm	SIMPLE
Discretization Scheme	MARS
Flow property	20°C Air

COMPUTATION RESULTS

We computed the airflow at the following three throttle open angles; 20, 35, and 60 degree.

In Fig. 4 are shown the numerical analysis result for airflow when the throttle is opened to 20 degree. This figure shows a longitudinal cross section passing through the duct axis, with airflow from left to right. The pressure contour diagram shows that, at relatively small open angle that mimics the initial stage of throttle valve opening, the pressure in the downstream region is low, indicating that the airflow does not reach the exit of the conduit. Turbulence kinetic energy K, calculated by the k-ε model, has a large value over a wide region downstream from the throttle valve and the maximum value locates on the lower part of the duct. The flow velocity vector diagram shows very fast airflow in the upper part of the throttle. This airflow is divided into an eddy current that whirls on a small scale and flows back toward the throttle valve, and a flow that whirls and flows into the lower part of the throttle. Observation of the airflow along a cross section perpendicular to the duct axis shows a flow in the central area of the duct that travels from the upper part to the lower part of the throttle. As a result, it can be found that the asymmetric vortex lines are formed in the downstream after the airflow passes through the throttle valve. This phenomenon is the origin of the energy that produces the intense turbulent flow and noise. This fact will be discussed in depth in the noise analysis chapter.

In Fig. 5 are shown the computational results for airflow when the throttle is open to 35 degree. In comparison with that of 20 degree, the pressure increases gradually in the area downstream from the throttle valve. There is a large turbulent flow area still remaining with a higher maximum turbulent kinetic energy than that of 20 degree.

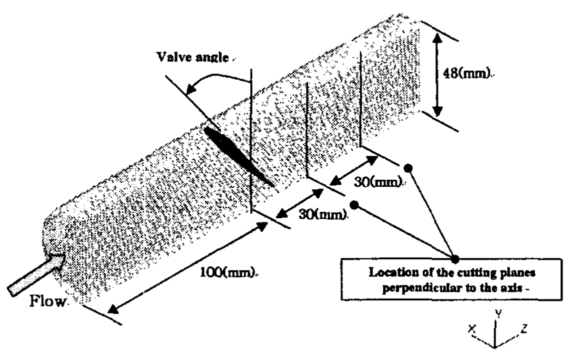

Figure 3. Mesh structure and dimensions of the throttle

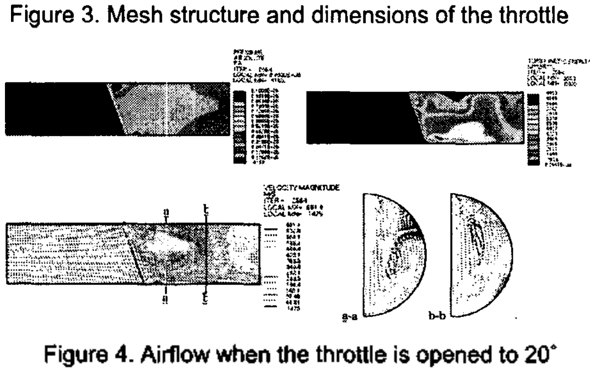

Figure 4. Airflow when the throttle is opened to 20°

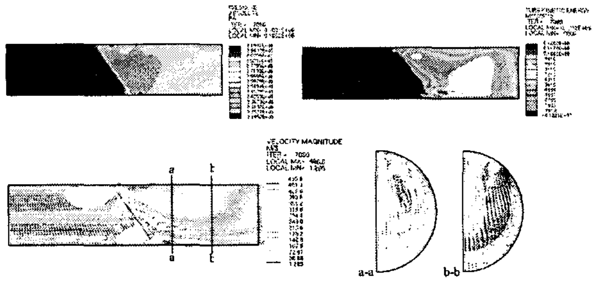

Figure 5. Airflow when the throttle is opened to 35°

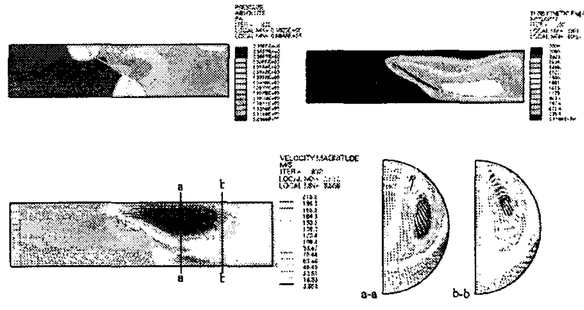

Figure 6. Airflow when the throttle is opened to 60°

The flow velocity vector diagram shows that a very fast airflow passes through the upper and lower parts of the throttle. The vector diagram of a cross section perpendicular to the duct axis shows also the eddy current, similarly observed in the previous case, in the pattern; the stream starts from the upper part of the throttle, and passes through the central area of the duct to flow into the lower part of the throttle and then leave the lower part of the throttle and flows into the upper part of the throttle, long the inner wall of the duct. At an area 30 to 60 mm downstream from the throttle, air flows from both the upper and lower parts of the throttle mix and merge. It can be found that the mergence of the two flows and the resultant eddy is most intensive in this case. Fig. 6 shows the numerical result of airflow analysis when the throttle is open to 60 degree. The pressure increases gradually as the fluid goes downstream from the throttle valve. However, the magnitude of the turbulence kinetic energy has decreased compared with previous two cases. The flow velocity vector diagram shows no fast airflows passing through the upper and lower parts of the throttle. Although the flow vector diagram of a cross section perpendicular to the duct axis shows that the eddy resulting from the whirling motion has still existed, the magnitude of the vortex are rapidly contracted.

IV. QUANTITATIVE ANALYSIS OF TUBULENCE NOISE

Noise source synthesis method, previously mentioned, is now applied to the quantitative analysis of turbulence noise from the quick-opening throttle in a confined configuration. Based on the numerical results of the airflow, the time-dependent turbulent velocity field is generated. Numerically, acoustic source terms are identified with regard to their turbulent kinetic energy K. In Fig. 7, are shown the numerical results of quantitative noise source identifications. These results are based on the flow analysis data of the throttle open angle of 35 degree, where noise is emitted more strongly than the other cases. The shear noise source I, II and self noise source are defined by the terms of Eq. (17); $U_j \cdot \partial u_{li} / \partial y_j$, $u_{lj} \cdot \partial U_i / \partial y_j$, and $u_{lj} \cdot \partial u_{li} / \partial y_j$, respectively. From the figures it can be found that the self noise source are stronger than the others and the maximum value for each source are located in the lower region of the conduit, where there is strong collision between two flows

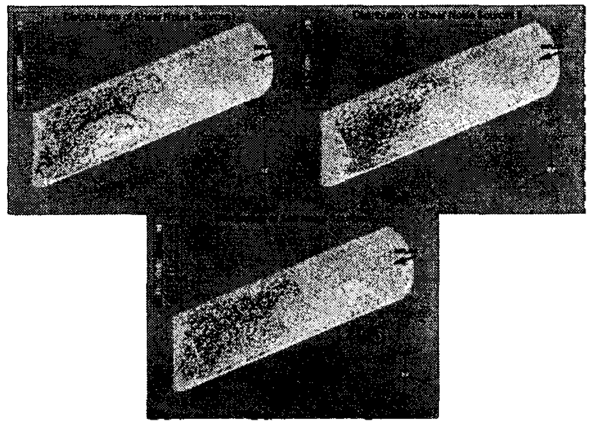

Figure 7. Quantitative noise source identifications

stemming from the upper split and lower split formed by the throttle and the conduit inner-surface. As previously mentioned, the energy of the noise source can be attributed to the two vortex lines with length scale of the diameter of the conduit. These vortex lines are produced by the non-uniform area of splits between the throttle valve and inner cylinder surface during the behavior of quick opening. From the theory of vortex sound [9], the formulation of vortices in the flow is the fundamental noise-producing mechanism. Thus, one of noise suppression method is to retain the uniform area of the splits during the opening event of the throttle.

V. CONCLUSION

Quantitative noise source identification is carried out for the noise from the throttle under quick opening. From this analysis, it can be found that the origin of the turbulence or noise source energy is the asymmetric vortex lines formed in the downstream of the throttle valve. The vortex lines are generated from the non-uniform space of the split between the throttle and the inner-surface of the conduit. From this founding, we infer that the uniform space split during the quick opening suppresses the formulation of vortex lines and also the noise. This idea can be applied to the low noise design, and practical optimisation on inner geometry of the throttle body will be achieved later.

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