

Development of Exhaust Orifice Noise Optimization Technology Using Light-CAE

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ABSTRACT

A prediction optimization technology for exhaust orifice noise and exhaust gas flow rate has been developed as an easy-to-use development support tool for designers.

The accuracy of predicted exhaust orifice noise was increased by using the Lighthill analogy and by correcting for airflow noise using empirical values. Combining this optimization technology with a Light-CAE system enables the relationship between the design parameters and the target values of orifice noise and exhaust gas flow rate to be represented by an approximation function. It also allows designers to carry out analyses in real time. As Light-CAE systems can be easily used in the initial design phase, this technology is positioned as a product development support tool.

1. Introduction

Computer Aided Engineering (CAE) is more and more widely used in various stages of product development. In the development of exhaust systems, specifically, detailed CAE analysis prior to testing a prototype can enable quantitative prediction of a variety of performance parameters, including vibration, strength, silencer attenuation and exhaust gas flow rate. An increasing number of designers now seek a CAE development support tool that enables such performance predictions to be made quickly, easily and with comparative accuracy at the primary design phase. Recent dramatic advances in hardware and software have made the realization of such a tool a possibility.

The authors therefore developed a light CAE system enabling analyses to be conducted easily, even by designers without specialist CAE knowledge. The new system enables designers to conduct real-time analyses, using an optimization technology to represent the relation between target values for exhaust orifice noise and exhaust gas flow rate and design parameters (variables) as approximation functions. This paper discusses the details of this development project.

2. The Need for Light CAE

“Light,” CAE⁽¹⁾ is the opposite of “powered” CAE. Powered CAE is widely used as an alternative to testing. It is used to provide highly accurate quantitative simulations of physical phenomena covering a broad range of testing procedures, and can be used for tests ranging from analyses of body skeletal structure to detailed structural analyses of brackets. However, powered CAE requires extensive computer resources, and normally also necessitates the expenditure of a considerable amount of time on the generation of meshes for detailed three-dimensional models.

There is no clear definition of the boundaries between light CAE and powered CAE, and they are relative to each other. Figure 1 shows a comparison between the two forms of CAE analysis, with the CPU performance required to enable predictions to be made in a day of run-time (number of floating-point operations per second: FLOPS) on the horizontal axis and the degree of freedom in the model at which the required accuracy can be obtained (number of coordinate axes per grid point: DOF) on the vertical axis.

This graph clearly indicates that considerably fewer performance prediction tools are used in light CAE than in powered CAE.

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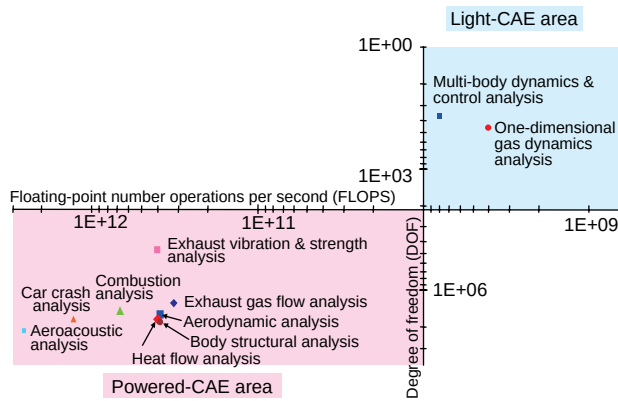


Fig. 1 Map of Light-CAE & powered-CAE analysis tools

The initial stage of development consists almost entirely of primary design, also termed conceptual design. At this stage, component parameters such as shape, dimensions and materials have not yet been defined in technical drawings. Detailed design procedures are carried out downstream from the initial design procedures, after these parameters have been defined. Designers use CAE in the primary design process to enable them to decide specifications for components; the time required for CAE analyses may represent up to 30% of the man-months expended in primary design. This expenditure of time is due to the fact that specifications must be analyzed in detail at this stage to prevent the necessity of changing them repeatedly during the later development process.

This situation called for the development of a light CAE system that was easy for designers to use. A development support tool that would reduce the time required from model production to analysis while enabling sufficient examination of component specifications using the relation between design parameters and target values in real-time.

3. Light CAE System

Figure 2 shows an outline of the light CAE system.

The system is broadly divided into three parts: Exhaust gas dynamic calculation, optimization and real-time analysis. The optimization module is the core of the system; it automatically seeks optimal solutions to enable it to determine optimum functions for the relation between design parameters and exhaust orifice noise and exhaust gas flow rate target values. The one-dimensional gas dynamic calculation module (light CAE) automatically performs repeated calculations, and the optimum function is automatically determined using a predetermined optimization algorithm. The optimum functions are fed into a Visual Basic for Application (VBA) program in the real-time interface that uses Microsoft Excel's macro command function. This allows exhaust orifice noise and exhaust gas flow rate corresponding to multiple design parameters input by designers to be plotted on graphs in real-time.

3.1. One-dimensional Gas Dynamic Calculation

Exhaust gas dynamic calculations based on gas dynamics theory⁽²⁾ are used to simultaneously calculate and analyze exhaust orifice noise and exhaust gas flow rate. This method allows changes in the pressure, velocity and temperature of the moving gas upstream of the exhaust pipe to be calculated for a series of time

steps. These variables are used as input conditions for time history calculations using the Navier-Stokes equation and governing equations for conservation of mass and energy. A time history calculation of the pressure, flow rate and temperature of the gas in the exhaust pipe is generated.

The authors used the one-dimensional gas dynamics CAE WAVE produced by Ricardo as a light CAE tool for these calculations. WAVE provides a model of exhaust noise source upstream from the exhaust pipe, generating the dynamic motion of the gas from engine specifications (bore/stroke, compression ratio, valve dynamic lift, etc.), and allows upstream noise to be calculated with downstream orifice noise and exhaust gas flow rate. However, exhaust orifice noise is made up of pulsation noise and flow noise, and its sources are the compression wave at the end of the exhaust pipe and changes in the pressure of the vortex rings in the exhaust jet⁽³⁾. Flow noise predictions cannot be made using one-dimensional gas dynamics CAE. The effectiveness of corrective calculations using Lighthill analogy equations (to be discussed below) in increasing the accuracy of predictions of orifice noise made by means of CAE using one-dimensional gas dynamics software was therefore attempted⁽⁴⁾.

3.1.1. Calculation of pulsation noise

For pulsation noise calculations, the sound power generated by pressure at the end of the exhaust pipe is attenuated in proportion to the square of the distance from the end of the pipe. The sound pressure up to a specified measurement point (a microphone) is given by Eq. (1)⁽⁵⁾.

$$P(t) = \frac{\rho}{4\pi R} \frac{dS(t - R/c)}{dt} \quad (1)$$

P : Sound pressure of pulsation noise (Pa)

S : Volumetric flow rate (m^3/s)

R : Distance from sound source to microphone (m)

c : Speed of sound (m/s)

t : Time (s)

ρ : Air density (kg/m^3)

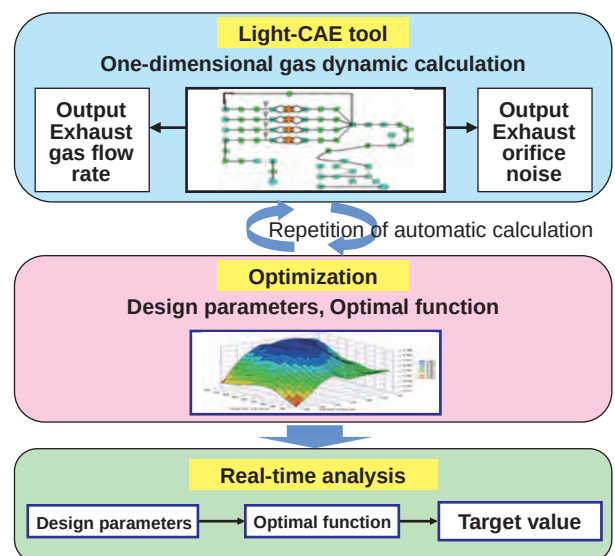


Fig. 2 Flow diagram of Light-CAE system

Figure 3 shows a comparison between measurement results for exhaust orifice noise at a microphone and calculations using Eq. (1). At high engine speeds (3000 rpm and above), the calculation results fall below the measurement results.

This is considered to be because the calculation results represent only the pulsation noise component, without factoring in the flow noise component.

3.1.2. Calculation of flow noise

In the case of exhaust orifice noise, Lighthill analogy equations⁽⁶⁾ enable the sound intensity of flow noise, Ei , to be expressed by Eq. (2).

$$Ei = \frac{\rho}{r^2 c^3} L^2 U^6 \quad (2)$$

Ei : Sound intensity of flow noise (W/m²)

ρ : Density (kg/m³)

r : Distance from sound source (m)

c : Speed of sound (m/s)

L : Typical length of sound source (m)

U : Flow velocity (m/s)

Here, L refers to the typical length of the source of flow noise, i.e. the distance from the generation of the main vortex rings to the point at which they become attenuated.

The relation between sound intensity, Ei , and the sound pressure level of flow noise, Ep , is given by Eq. (3).

$$Ep = \sqrt{Ei \times \rho \times c} \quad (3)$$

Ep : Sound pressure level of flow noise (Pa)

Based on the results of tests using a high-speed pulsation flow generator⁽⁷⁾, Lighthill analogy equations (2) and (3) were used to determine the relationship between flow velocity (U) and the length of a sound source generating a specific sound pressure of flow noise at the microphone (Ep) (Fig. 4).

Figure 4 shows that U becomes greater as L decreases. This is caused by the increase in the high frequency component as the spaces between the multiple vortex rings, that are the source of flow noise, became narrow. In addition, the results indicate that L is largely unaffected by the pulsation cycle, and is almost entirely dependent on the flow velocity.

In other words, it is possible to predict the sound pressure of flow noise when U and L are known.

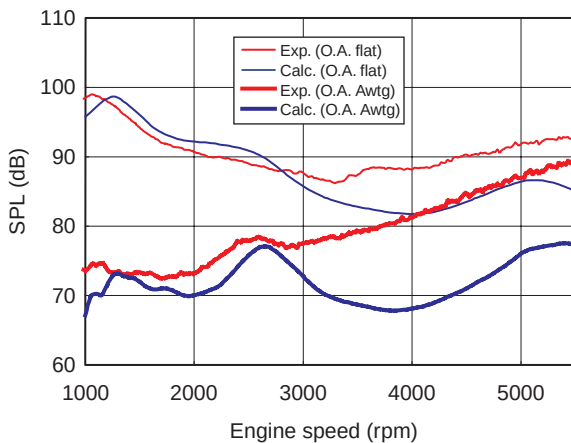


Fig. 3 Comparison of orifice noise level in combustion

3.1.3. Calculation of exhaust orifice noise

Figure 5 shows a comparison of calculation and measurement results for the sound pressure level (pulsation noise + flow noise) close to the exhaust orifice (microphone position: 50 cm/45 deg behind the exhaust orifice) of a 4-cylinder, 1.3L internal combustion engine under fast acceleration. Results are plotted against engine speed on the horizontal axis. Calculation results were obtained by inputting L and U into Eqs. (2) and (3).

Figure 5 indicates that the accuracy of predictions of exhaust orifice noise is increased by calculating both pulsation noise and flow noise.

3.1.4. Calculation of exhaust gas flow rate

The flow rate (Q) in the exhaust system can be quantitatively determined by positioning a flow tester that uses a blower fan to generate a laminar flow upstream. The flow tester is used to find the flow rate when the difference between the pressure upstream and the pressure of the flow downstream escaping to the atmosphere is equivalent to a fixed water head pressure (600 mmAq). The exhaust system model used in gas dynamic calculations (excluding the exhaust noise source model) and the light CAE tool were used to calculate the results of such a test. Figure 6 shows a comparison between calculation results and the experimental results.

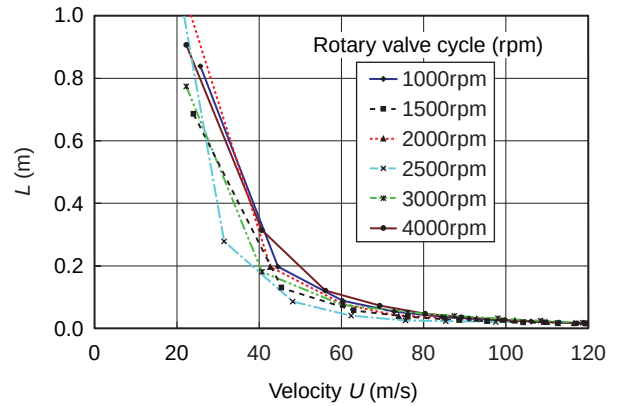


Fig. 4 Relationship between L (noise source length) and flow velocity

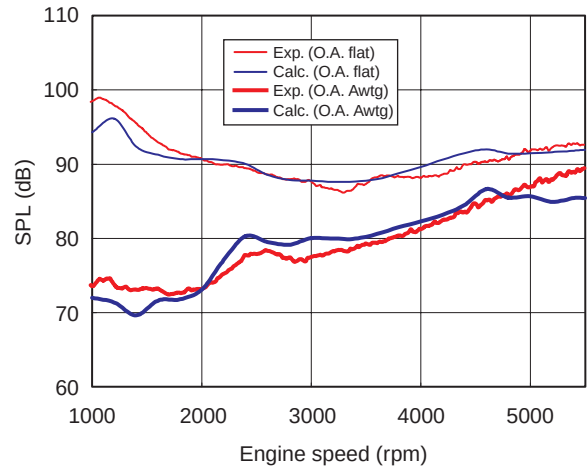


Fig. 5 Comparison of orifice noise level in combustion engine

3.2. Optimization Technology

Optimization in this system refers to the expression of the relation between the design parameters, i.e. the required shapes and dimensions when the designers formulate the design drawings (length and diameter of pipe, length and diameter of silencer, etc) and the target values for exhaust orifice noise and exhaust flow rate as optimum functions. Response surface models (RSM)⁽⁸⁾ are used to determine these optimum functions.

3.2.1. Response surface models

Response surface models are statistical approximation models based on regressive analysis and used in engineering applications. The nth optimum function is estimated using the least squares method to minimize the error in target values against design parameters.

To enable response surface models to be used, the system uses iSIGHT, produced by Engineous, to control the light CAE and automatically search for optimum functions.

Figure 7 shows the approximation function for the relationship between exhaust orifice noise and the design parameter pipe length as determined using an RSM. Figure 8 shows the approximation function for the relationship between exhaust gas flow rate and the design parameter pipe diameter as determined using an RSM. The points marked with squares in both figures show results obtained using light CAE in isolation.

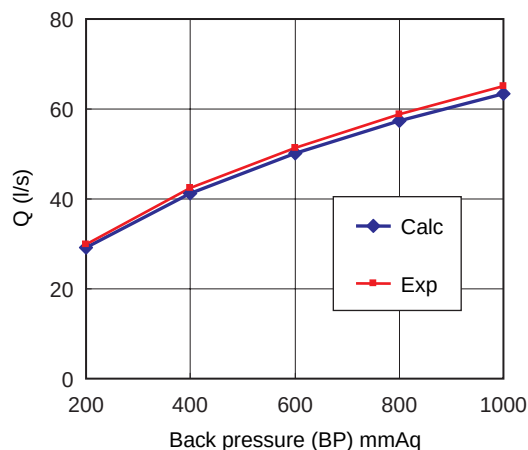


Fig. 6 Calculated and experimental accuracy of flow tester

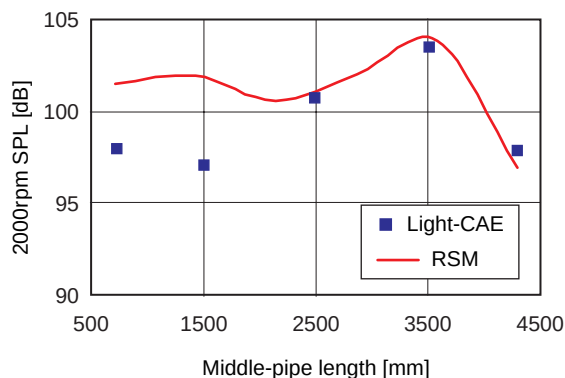


Fig. 7 Relationship between RSM approximation error and Light-CAE (Orifice noise)

3.2.2. Method of enhancement of approximation accuracy

Figures 7 and 8 show approximation error on a regression curve against results determined using CAE in isolation. Exhaust orifice noise shows strong nonlinearity against many design parameters, and significant approximation errors are often observed between regression curves and light CAE in the case of this parameter.

The following countermeasures are available in this case:

- (1) Increase the order of polynomial equations for the regression curve
- (2) Increase the number of searches for learning data
- (3) Restrict the range of design parameters

The response used in the present research is discussed below.

Design parameters in the form of two different exhaust pipe lengths were established as horizontal and vertical axes, and searching points representing searches for learning data by light CAE in these design parameter spaces were plotted between them (Fig. 9).

As this graph shows, using light CAE to search for learning data across the entire design parameter space means increasing the number of calculations required for optimization, and is therefore impracticable. The algorithm shown in Fig. 10 was used to resolve these issues.

This algorithm does away with the requirement to search for study points across the entire design parameter space. Instead, it increases the number of searches for learning data across the space

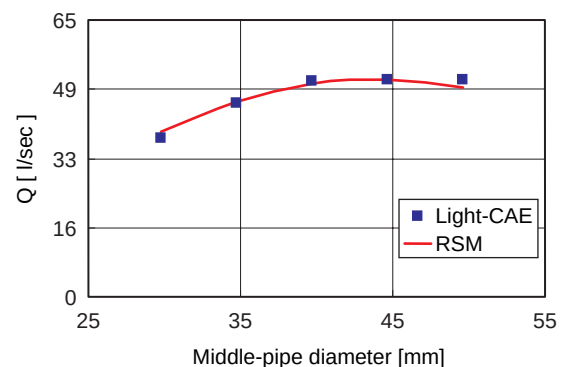


Fig. 8 Relationship between RSM approximation error and Light-CAE (Exhaust gas flow rate)

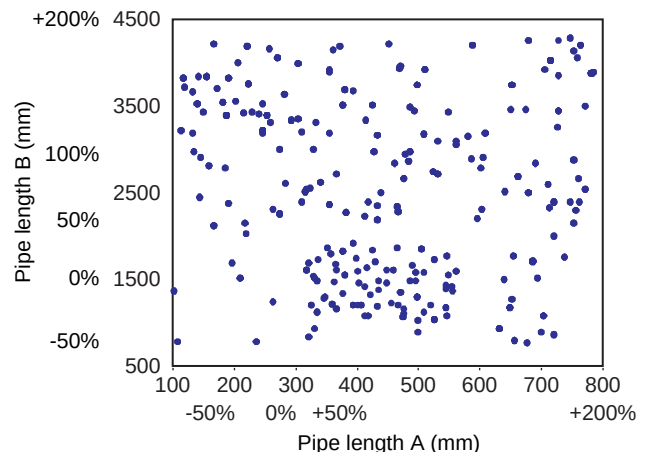


Fig. 9 Search map of optimal study data (Before enhancement)

of important design parameters to a range $\pm 50\%$ from an indicated median point (Fig. 11).

Figure 12 shows a comparison between approximation functions for the relationship between the design parameter pipe length and exhaust orifice noise, as determined by an RSM following enhancement of approximation accuracy, and the relationship determined by light CAE in isolation.

This graph shows a reduction in the degree of error between approximation functions obtained using an RSM and results obtained using light CAE than that shown in Fig. 7.

3.2.3. Method of real-time analysis

The optimum functions expressing the relationship between design parameters and target values for exhaust orifice noise and exhaust gas flow rate obtained using RSM are high degree polynomials made up of enormous amounts of coefficient data.

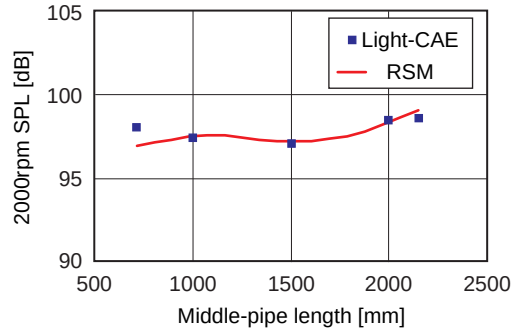


Fig. 12 Relationship between RSM approximation error and Light-CAE (Orifice noise)

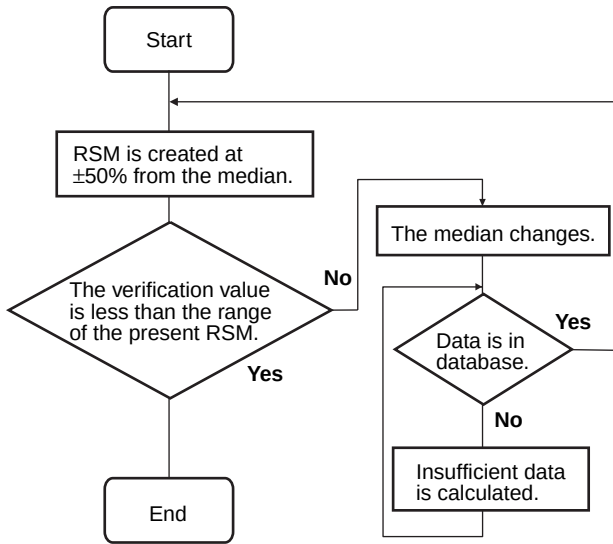


Fig. 10 Enhancement algorithm in RSM approximation accuracy

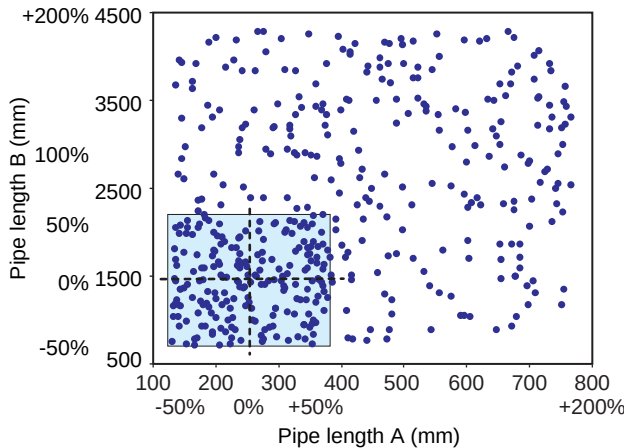


Fig. 11 Search map of optimal study data (After enhancement)

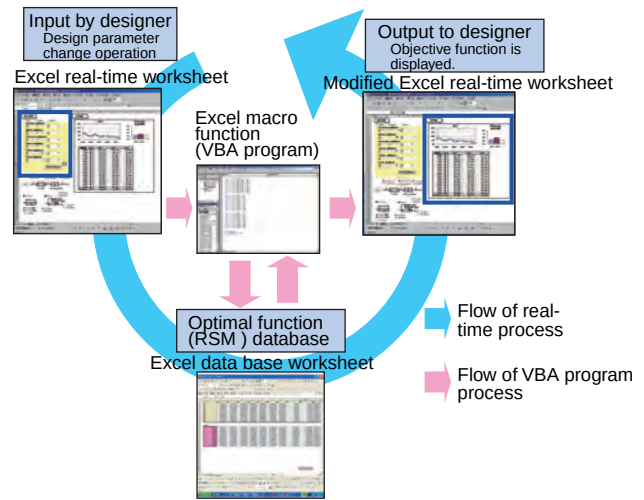


Fig. 13 Block diagram of real-time process

These optimum functions can be used to instantaneously and continuously display the relationship between design parameters and target values. Figure 13 shows a block diagram of real-time analysis.

This process enables designers to analyze in real-time whether input design parameters enable the achievement of specific target values.

4. Examples of Application as a Development Support Tool

The technology discussed in the preceding sections was developed as a practical development support tool for designers. The following points were stressed in this development:

- (1) Simplicity of use, such that designers did not require specialized knowledge of CAE operation.
- (2) Reduction of pre-processing time by enabling designers to choose from models pre-recorded as parametric models.
- (3) Post processing of results using Microsoft Excel, and presentation in a diagrammatic form that is easy for designers to understand.

4.1. Input Interface

To provide a development support tool that was easy for designers to use and that did not announce itself as a light CAE tool, a specialized interface was developed using Sun Microsystems' Java as the software language (Fig. 14). Figure 15 shows an example of the menu sheet, in this case for the basic layout of an exhaust system. The diameters, lengths, etc. of pipes in the exhaust system (composed of the engine, catalyzer, silencer, etc.) can be freely input as parametric numerical values, enabling design parameters to be set.

Figure 16 shows the silencer menu sheet. In this case again, design parameters can be set by freely inputting the silencer diameter, total length, length and diameter of inner pipes as parametric numerical values.

When all the conditions required for calculations have been input, design parameters are displayed as a pull-down menu. This enables designers to set the range of the parameters, median point and upper and lower limits, following which the calculations are executed (Fig. 17). E-mail addresses can also be input for forwarding of calculation results.

4.2. Real-time Analysis Interface

A VBA program using Excel's macro command function is used to display the calculation results. In the worksheet shown in Fig. 18, design parameters are shown as the slide bars at the left, exhaust

orifice noise is shown as the line graph in the upper middle, and exhaust gas flow rate is shown as the bar graph at the upper right.

As designers input values in the design parameter slide bars, they are able to view real-time changes in the graphs of exhaust orifice noise and exhaust gas flow. This enables them to easily analyze the sensitivity and prepotency of the design parameters against target values.

This real-time analysis is enabled by the ability to determine optimum functions for the relationship between parameters and target values provided by the combination of light CAE and optimization technology.

5. Conclusion

A light CAE system that is easy for designers to use in the initial stage of design has been developed.

- (1) The accuracy of light CAE in predicting exhaust orifice noise was enhanced by correcting the associated flow noise using test results based on Lighthill analogy.
- (2) Optimization technology and light CAE were combined to allow the relationship between design parameters and target values for exhaust orifice noise and gas flow to be expressed as approximation functions, enabling designers to execute analyses in real-time.

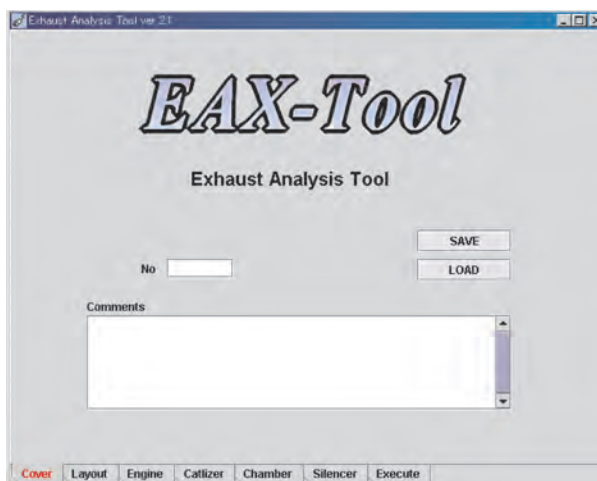


Fig. 14 Opening worksheet

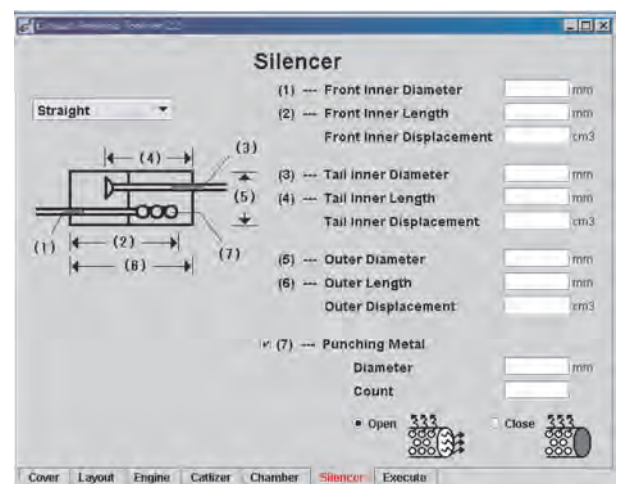


Fig. 16 Silencer system layout menu

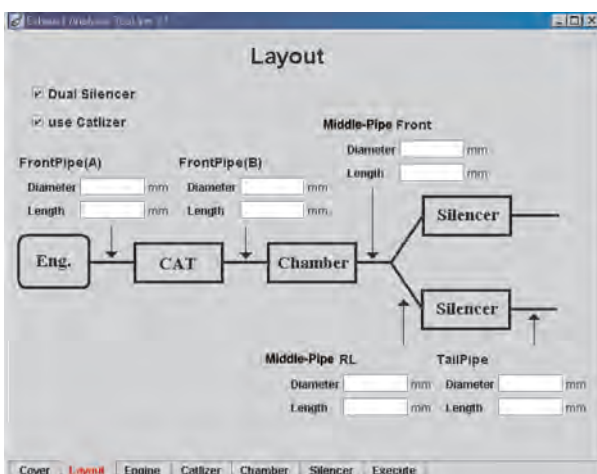


Fig. 15 Exhaust system layout menu

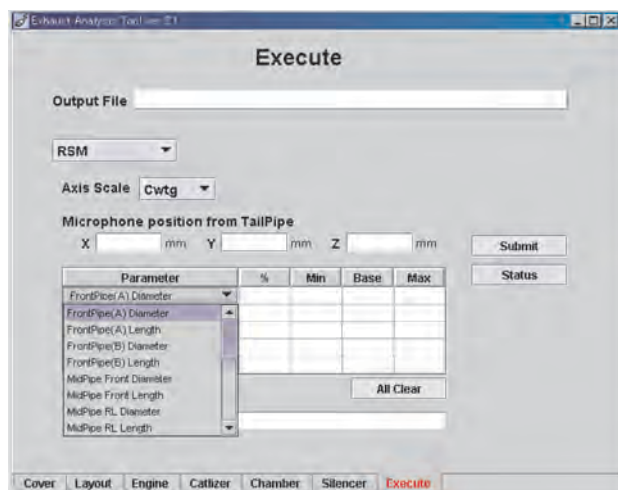


Fig. 17 Execution worksheet

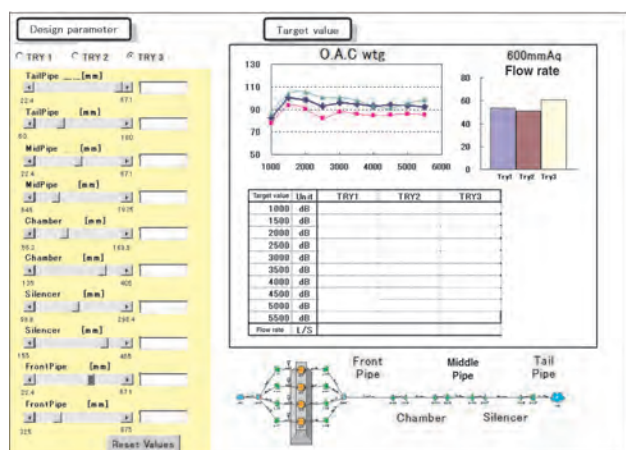


Fig. 18 Real-time analysis worksheet

- (3) The technologies discussed in (1) and (2) above were packaged as a light CAE system (calculation time: less than 1/10 that of power CAE) to provide designers with a development support tool.

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