

Establishment of Method for Analyzing Radiation Noise in Intake System

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ABSTRACT

Radiation noise in an air cleaner is determined by acoustic excitation due to internal pressure and also by the structural resonance characteristics. A calculation method was developed for predicting radiation noise by acoustic and structural coupling calculation analysis, and for designing the structure of the air cleaner to be as light as possible. This method was applied to the development of a new air cleaner. As a result, it was verified that the prediction accuracy of the radiation noise was within 300 Hz, which was adequate, and also it was possible to reduce the weight of the air cleaner by 12%, thus proving the effectiveness of this method.

1. Introduction

The need for a requirement to reduce the weight of the intake system has increased with the need to lighten automobiles themselves. Since the air cleaner accounts for much of the volume and weight of the intake system, this is certainly one of the components for which weight reduction should be required. The market appeal of automobiles with lower noise and vibration makes it more important to structure air cleaners to control radiation noise. Formerly, the generally used method for reducing radiation noise was to stiffen the exterior surface of the air cleaner by thickening the plate, adding reinforcing ribs, and other approaches. These tended to increase the weight of the air cleaner. Thus, there tends to be a contradiction between the goals of reducing the weight of the intake system and of reducing the radiation noise from it.

A simulation method was developed for predicting radiation noise from the air cleaner by an acoustic-structural coupled analysis, based on its acoustic and structural characteristics. In addition, a method was constructed for optimizing the structure for reduced weight while accomplishing the primary goal of a specified level of radiation noise.

2. Factors Affecting Radiation Noise Characteristics

The noise radiated from an air cleaner is usually generated in the following process: Pulsations of the intake air occur in the intake passage, which give rise to pressure fluctuations, which propagate through the passages and provide the energy for acoustic inputs in the air cleaner.

An air cleaner was installed in a rig for a component test under acoustic excitation to analyze its characteristics that influence the radiation noise. The correlation between its vibration and radiation noise was examined.

2.1. Initial Component Test under Acoustic Excitation

In order to identify factors affecting the characteristics of radiation noise from air cleaners, a test air cleaner was removed from a completed vehicle and installed in a rig so that the acoustic excitation test could be carried out in a simpler manner with lower interference from other noise sources. The correlation between the results of this test and those from a test on a completed vehicle were examined.

Figure 1 compares the findings for the sound pressure level of the radiation noise from the air cleaner during engine

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firing while installed in an actual vehicle and the sound level near the air cleaner in a component acoustic excitation test. The spectrum in the actual vehicle test was virtually the same as that in the component test. It was verified that the radiation noise characteristics of the air cleaner in an actual vehicle could be assessed using component tests.

2.2. Correlation between Air Cleaner Surface Vibration and Radiation Noise

Air cleaner surface vibration and the characteristics of radiation noise were compared in a component test to look for a relationship. The vibration characteristics of the surface were observed under vibration excitation (inertance) and under acoustic excitation (acoustic inertance).

2.2.1. Vibration due to vibration excitation and radiation noise characteristics

A comparison of inertance under vibration excitation and the frequency characteristics of radiation noise indicated that although the resonance peaks in the inertance were at frequencies neighboring the radiation noise peaks, these did not always occur together; the inertance could not really be described as showing the same frequency response as the radiation noise (Fig. 2). There was, at best, a minimal relationship between surface vibration due to vibration input into the air cleaner and radiation noise.

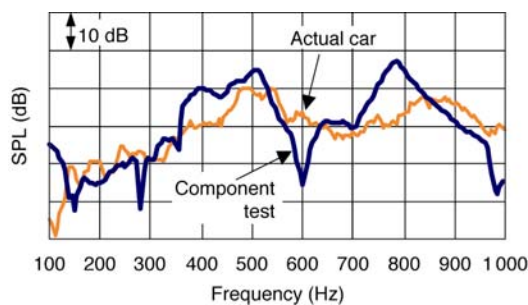


Fig. 1 Comparison of results between specification test and acoustic excitation test

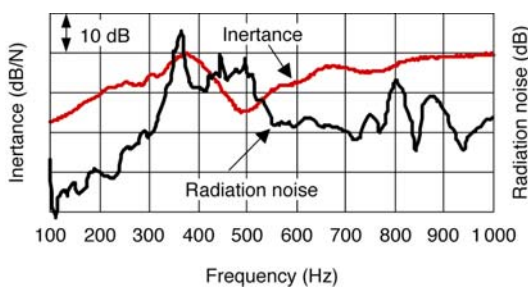


Fig. 2 Comparison of inertance and radiation noise

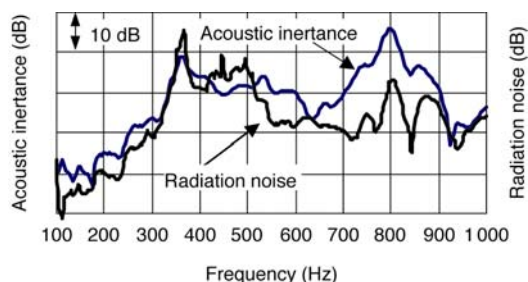


Fig. 3 Comparison of acoustic inertance and radiation noise

2.2.2. Surface vibration due to acoustic excitation (acoustic inertance) and radiation noise characteristics

Figure 3 compares the vibration frequency response under acoustic excitation (acoustic inertance) and the spectrum of radiation noise. These results show two matching peaks in the spectra, a high correlation between the acoustically-excited vibration and the radiation noise frequency response. It therefore seems necessary to analyze coupling between the internal acoustic input and the response due to vibration in the air cleaner radiation noise.

2.3. Examples of Generation of Air Cleaner Radiation Noise

Figures 4 – 7 present examples of air cleaner radiation noise. As shown in Fig. 4, during engine firing, the main components of the radiation noise from the air cleaner were between 300 and 400 Hz and above 500 Hz. Figure 5

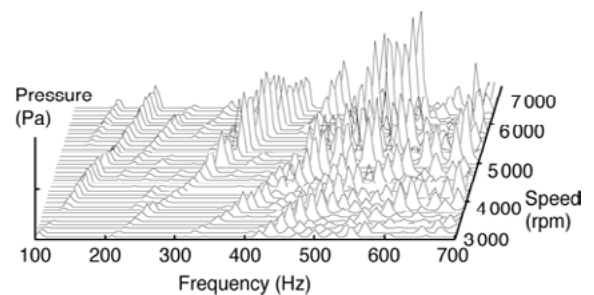


Fig. 4 Radiation noise spectrum

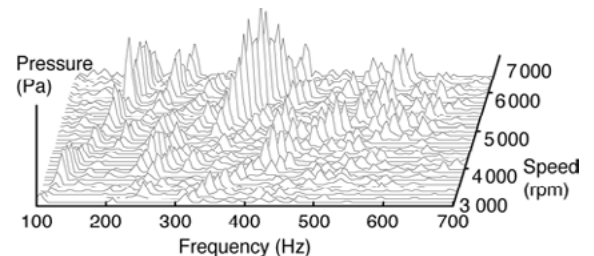


Fig. 5 Cabin noise spectrum including radiation noise

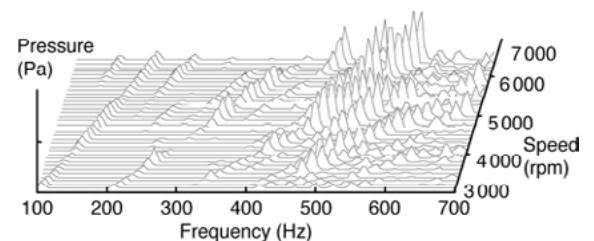


Fig. 6 Spectrum of reduced radiation noise spectrum

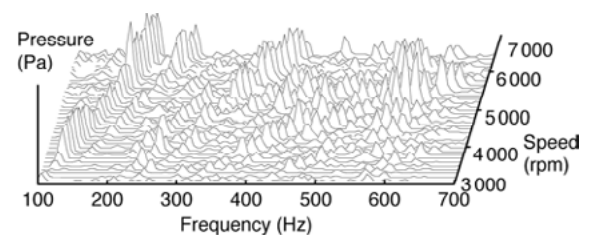


Fig. 7 Cabin noise spectrum including reduced radiation noise

demonstrates the noise occurring in the cabin at the same time. When the air cleaner in the engine compartment was covered with noise insulation to thoroughly mask its contribution to cabin noise, the spectrum changed by the magnitudes shown in Fig. 6; Fig. 7 shows the actual spectrum in the cabin, featuring much lower noise levels in the 300 – 400 Hz range. This indicates that the air cleaner is the source for much of the cabin noise in the 300 – 400 Hz range.

Thus, it was determined to concentrate on the region below 400 Hz in this study.

3. Construction of the Analytical Method

The radiation noise from an air cleaner was calculated in the method described below. This method uses acoustic-structural coupled analysis between the acoustic characteristics of the air intake passages and the vibration characteristics of the air cleaner.

3.1. Acoustic Characteristics of Air Intake Passages

The acoustic model of the entire air intake system shown in Fig. 8 was created with solid elements. It extended from the engine side, the excitation source, to the intake port. The excited panel (Fig. 9), which exerted an acceleration equivalent to the acoustic input, was made of shell elements and attached to a cross section of the throttle section of the intake system where it connected to the engine side. The excited panel was constrained in all but one direction so that its translation was in a direction parallel to the passages.

An acoustic input P_{in} was applied to the excited panel, and the pressure $P_{(n)}$ corresponding to the pressure acting on the air cleaner wall was calculated using the transfer function $H_{ac(n)}$:

$$P_{(n)} = H_{ac(n)} P_{in} \quad (1)$$

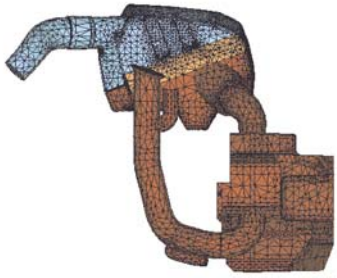


Fig. 8 Acoustic model

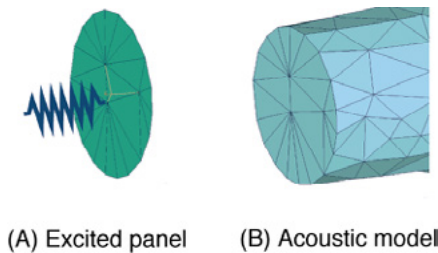


Fig. 9 Model of excited panel and acoustic model

3.2. Vibration Characteristics of the Air Cleaner

A shell model of the air cleaner structure was constructed of finite elements. The exterior structure of the case and cover as well as the rubber seals, filter, and fastener locations for the cover were made of fine shell models in order to improve calculation accuracy.

3.3. Creation of the Model of the Acoustic-Structural Boundary

In order to create the acoustic-structural model boundary, it is essential for the elements at the boundaries between the two models to meet up with each other one-for-one. Ordinarily, however, the structural model is made with a much finer mesh than the acoustic model. This makes it unlikely for the elements to match up with each other at the boundary. Therefore, it is necessary to use a large number of matrices (coupling matrices, defined in Eq. (2)) in order to approximately compensate the mismatches in the boundary where the acoustic model and structural model are in contact. In other words, the force $V_{(m,n)}$, exerted on every element in the structural model, is given by the product of this coupling matrix $M_{(m,n)}$ with $P_{(n)}$, as depicted in Fig. 10.

$$V_{(m,n)} = M_{(m,n)} P_{(n)} \quad (2)$$

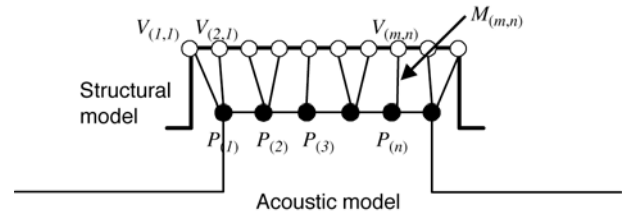


Fig. 10 Coupling matrix

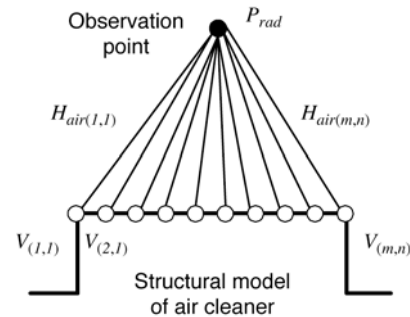


Fig. 11 Acoustic transfer function

Observation point ●

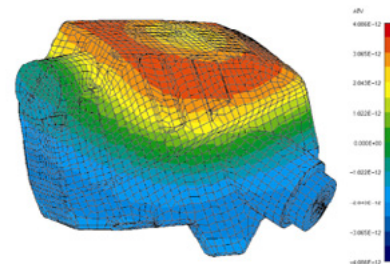


Fig. 12 Example of calculation of acoustic transfer function

3.4. Calculation of the Acoustic Transfer Function

In order to find the noise P_{rad} radiated by the air cleaner surface at the observation point, as shown in Fig. 11, the acoustic transfer functions $H_{air(m,n)}$ from each element of the model surface to the observation point are calculated. Figure 12 demonstrates some results using the acoustic transfer functions for an actual air cleaner. The locations showing high contributions are colored in red. In this example, it is clear that there are high contributions from the upper surface down onto the sides.

3.5. Calculation of Radiation Noise

The radiation noise at the observation point can be calculated using Eq. (3), inserting the air intake path transfer function H_{ac} , the coupling matrix $M_{(m,n)}$, and the acoustic transfer functions $H_{air(m,n)}$.

$$\begin{aligned} P_{rad} &= \sum H_{air(m,n)} V_{(m,n)} \\ &= \sum [H_{air(m,n)} M_{(m,n)} H_{ac(n)} P_{in}] \end{aligned} \quad (3)$$

4. Optimization Calculations

In the previous sections, the radiation noise from an air cleaner was seen to be determined by the acoustic transfer function of the passages in the intake system and the structural characteristics of the air cleaner. Thus, one can develop two methods for optimizing an air cleaner to accomplish both an objective radiation noise level and a reduced weight air cleaner. One method is to improve the acoustic characteristics, while the other method is to improve the structural characteristics of an intake passage system. For this study, it was decided to optimize the structural characteristics, rather than the acoustic characteristics, to obtain reduced radiation noise and reduced weight.

This method consists of tuning the vibration eigenvalues of a system, avoiding coupling with acoustic resonance. It assumes that there exists an optimized structure capable of low radiation noise; the optimization calculations seek both the objective function for the radiation noise and the objective function for reduced weight.

For the variables in the optimization calculations, the plate thickness of the air cleaner exterior wall and the reinforcing material were used. In the first stage, the weight of the air cleaner was constrained to seek the structure which yielded the desired sound pressure level of the radiation noise in the target frequency band. In the second stage, the radiation noise level was constrained while seeking a structure of minimal weight. A β mesh was used for the optimization algorithm in order to minimize the peak sound pressure level within the frequency band of interest.

The exterior wall and reinforcing rib thickness, which were used as parameters, were each divided into several sections. An example is shown in Fig. 13. This section was

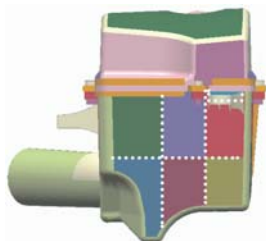


Fig. 13 Example of divided sections

divided with reference to parameters from the acoustic transfer function (Fig. 11) and the modes of vibration of the structural model.

5. Application Results

An example of application of these analytical method and optimization calculations to radiation noise and weight reduction in an air cleaner during development of a new intake system is described below.

5.1. Verification of Precision of Calculated Radiation Noise Level

Figure 14 presents a comparison of the calculated radiation noise and the measured results in an acoustic excitation test. Below 300 Hz, the characteristics were well reproduced by the simulation. This showed that the method described above is able to predict radiation noise.

5.2. Application to Optimization Calculations

The structure model of an air cleaner was sectioned in accordance with its modes of vibration and optimized for light weight while meeting radiation noise performance requirements.

As shown in Fig. 15, the first stage concerned the initial acoustic response: Setting objective levels in an objective function for radiation noise; optimizing the wall thickness of each section; and identifying the structure which met the objective levels. In this example, the ninth iteration achieved the radiation noise targets. The optimized structure obtained in the first stage was used as the initial structure for the second stage, and the radiation noise level was constrained. A

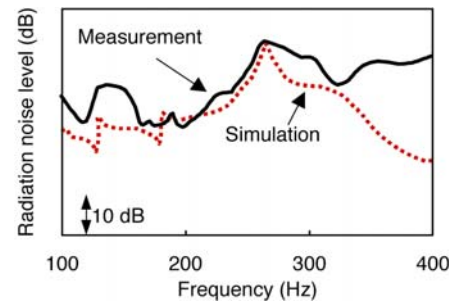


Fig. 14 Correlation of experimental and simulation results

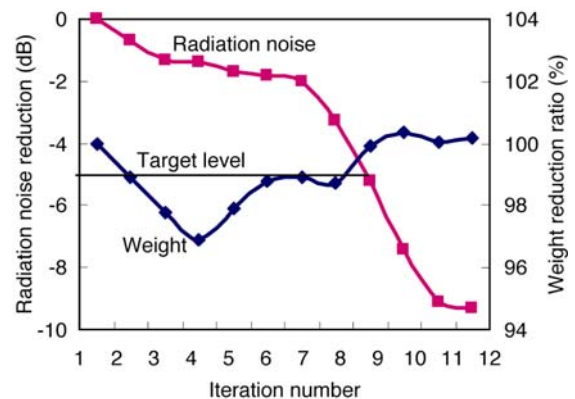


Fig. 15 First step of optimization

structure with reduced weight was obtained, as shown in Fig. 16; in this example, the final weight was about 85% of the initial weight.

5.3. Verification of Optimization Results

The brackets and other fittings attached to the air cleaner described in the previous section were manufactured and the weight and radiation noise level of the actual air cleaner were checked. The results are shown in Fig. 17; the radiation noise level was reduced by 8 dB, and the total weight by 12% in a completed vehicle.

6. Conclusion

The internal acoustic characteristics of an air cleaner and its structural characteristics were used in an acoustic-structural coupled analysis to predict the noise radiated from the air cleaner. A method was constructed to optimize the structure and the following results were obtained.

- (1) This calculation method allowed prediction of radiation noise at frequencies below 300 Hz.
- (2) This method was verified to enable development of new air cleaners meeting radiation noise targets while maintaining low component weight.

Also, this method was used to develop a new air cleaner whose radiation noise met the objective and which was 12% lighter than the initial design.

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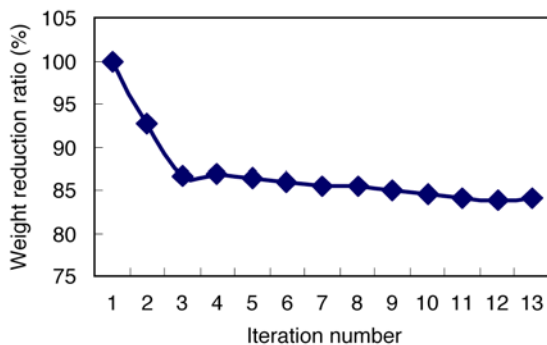


Fig. 16 Second step of optimization

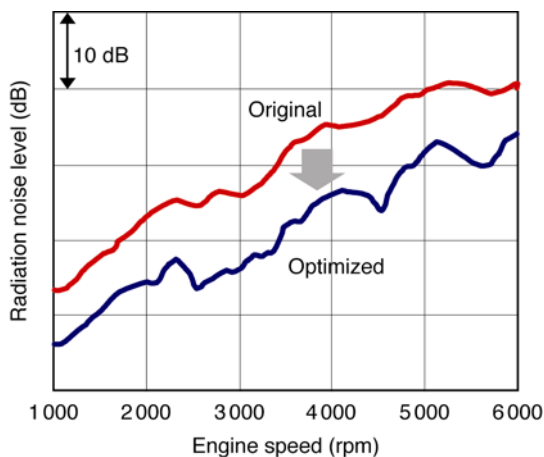
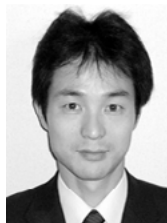


Fig. 17 Radiation noise reduction effect in the vicinity of actual car

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