음향인텐시티법을 이용한 4기통 가솔린 엔진의 소음원 검출에 관한 연구

A Study on the Identification of Noise Sources of the 4-Cylinder Gasoline Engine by using Acoustic Intensity Method

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요지

본 연구에서는 음향 인텐시티법을 가솔린 엔진에 직접 적용하여, 각각의 중심주파수별 음향 인텐시티 응답특성을 1/3 옥타브 밴드로 구하였고, 오버올 레벨 및 최대 인텐시티레벨을 갖는 중심주파수에서의 음향 인텐시티 방사특성을 등고선 및 3차원 표시로 나타내었다. 또한 그 결과를 분석 및 고찰하여 엔진의 중요 소음원을 검출하므로서 이 수법이 소음대책에 유효하다는 것을 검증하였다.

연구 결과, 오버올 레벨에서는 아이들링 상태의 경우 엔진 전면부에서, 2,000 rpm 상태의 경우 엔진 우측부에서 가장 높은 음향 인텐시티가 방사되었으며, 최대 인텐시티레벨을 갖는 중심주파수에서는 오일팬과 흡·배기매니홀드가 100 Hz에서 가장 높은 음향 인텐시티를 나타내었다.

ABSTRACT

Acoustic intensity method is applied to a 4-cylinder gasoline engine in order to identify the noise sources and the response characteristics. Acoustic intensity is analyzed by 1/3 octave band filter for each center frequency. Radiational characteristics of acoustic intensity at overall and the maximum intensity level are represented by using the contour and three-dimensional plot. It is verified that this method is effective to the assessment of engine noise.

It can be found that the maximum intensity is radiated from the front side of the engine under idling condition and the right side of it under 2,000 rpm running with no loading condition at overall level, and also that the maximum intensity is radiated from the oil pan and the intake and exhaust manifold at the center frequency of 100 Hz.

1. INTRODUCTION

Recently, high techniques have been requested to the noise problem of automobiles due to the demand of output efficiency, energy efficiency, light weight, etc. For exam-

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ple, more delicate techniques of noise assessment are necessary, which suggests a rapid consideration for the reduction of the engine noise problem.

Conventional techniques which have been used to identify the noise sources are as follows [1] [2]; (1) lead wrapping approach, (2) laser holography, (3) modal analysis. But these method are time consuming, expensive and unable to analyze the wanted results directly. Therefore, the development of new techniques for identifying and estimating noise sources in addition to the experimental method become indispensable.

The highly developed digital analyzer enables to measure directly the flow of sound [3] [4] [5], that is, the sound strength; these methods measure simultaneously the acoustic pressures of two closely spaced microphones, and calculated the acoustic intensity by the use of the cross-spectrum of them [6] [7] [8] [9].

The above mentioned analytical methods are able to obtain exact results by using a computer, but there are many difficulties in applying them practically. In this study, the acoustic intensity method is applied to the 4-cylinder gasoline engine in order to identify the exact noise sources. Also, the efficient approach method is developed for solving the noise problems, and the softwares are devised to display the contour and three-dimensional plot by which we can determine the noise source visually.

2. THEORY

2.1 Basic theory of acoustic intensity

In elasto-acoustic system, the acoustic intensity is a vector quanity defined as a product of the acoustic pressure and the corresponding particle velocity at a given point.

When there is no flowing, the 1-dimensional equation of motion is

$$\rho \frac{\partial u(t)}{\partial t} + \frac{\partial p(t)}{\partial r} = 0 \qquad (1)$$

where ρ is the density of air, u(t) is the particle velocity in r-direction. If the acoustic pressure are $p_1(t)$ and $p_2(t)$ measured at two closely-spaceded points in r-direction, then the gradient of acoustic pressures is approximately represented as

$$\frac{\partial p(t)}{\partial r} = \frac{p_2(t) - p_1(t)}{\triangle r} \qquad (2)$$

where $\triangle r$ is the distance between two points where the acoustic pressures were measured. Then the approximate particle velocity is

$$\begin{aligned} u(t) &= -\frac{1}{\rho} \int_{-\infty}^{t} \frac{\partial p(t)}{\partial r} dt \\ &= -\frac{1}{\rho \triangle r} \int_{-\infty}^{t} \{p_2(t) - p_1(t)\}\, dt \qquad (3) \end{aligned}$$

and the acoustic pressure P at the center of two points can be approximated as $p(t) = \{p_1(t) + p_2(t)\}/2$. Therefore the acoustic intensity, I becomes

$$\begin{aligned} I &= \lim_{T \to \infty} \frac{1}{T} \int u(t) \cdot p(t) dt = \langle p(t) \cdot u(t) \rangle \\ &= -\frac{1}{\rho \triangle r} \left\langle \frac{p_1(t) + p_2(t)}{2} \int_{\infty}^{t} \{p_2(t) - p_1(t)\}\, dt \right\rangle \end{aligned} \qquad (4)$$

where < > denotes a time average. By the stationary and ergodic process of signals $\langle p_1(t) \int_{-\infty}^{t} p_2(t) d\tau \rangle$ becomes zero, and using the relation of $\langle p_1(t) \int_{-\infty}^{t} p_2(t) d\tau \rangle = \langle -p_2(t) \int_{-\infty}^{t} P_1(t) d\tau \rangle$, the acoustic intensity of equation (4) can be rewritten as

$$I = -\frac{1}{\rho \triangle r} \langle p_1(t) \int_{-\infty}^{t} p_2(\tau) d\tau \rangle \qquad (5)$$

By computing Fourier transforms of equation (5), acoustic intensity $I(f_1-f_2)$ in frequency domain is expressed as

$$I(f_1-f_2) = -\frac{1}{2\pi\rho\Delta r}\int_{f_1}^{f_2}\frac{\mathrm{Im}\{G_{12}(f)\}}{f}df \quad (6)$$

where Im is the imaginary part of a complex number and G_{12} (f) is cross spectral density function of the acoustic pressures at the two points.

Hence acoustic intensity can be determined by measuring the imaginary part of cross-spectrum between the pressures P_1 and P_2 measured at closely-spaced points. In this paper, the 2-channel F.F.T. analyzer was used to compute the acoustic intensity in frequency domain.

2.2 Directional characteristics of microphones for measuring acoustic intensity

Acoustic intensity is a vector quantity which describes the amount and direction of net flow of acoustic energy at a given point. If the real value of acoustic pressure is P_{rms}, and particle velocity is U_{rms}, then the acoustic intensity component is

$$I = \mathrm{Re}\,(p^* \cdot u)\cos\alpha \quad (7)$$

where p* is the complex conjugate of P, α is the angle between the direction of acoustic radiation and normal line of surface where the sound passes. Equation (7) represents that the vector component of acourstic intensity in the direction is theoretically equivalent to cosine function of intensity vector. In practice, acoustic intensity probe is made to measure the acoustic pressures and the component of pressure gradient along a line joining the centers of the microphones. The value of acoustic intensity passing the probe is the vector component of an intensity. Equation (7) shows that when α is o°, or 180°, then the intensity value, I is maximum, and when α is 90°, or -90°, then I is minimum. Fig.1 shows that the directional characteristics of acoustic intensity makes the shape of Arabic numeral "8".

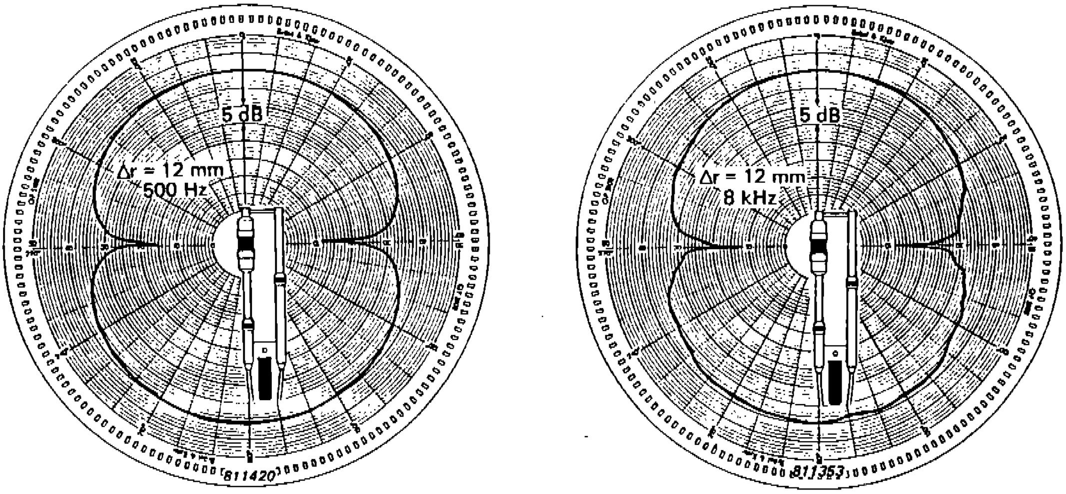


Fig. 1 Directional Characteristics at 500 Hz and 8 kHz for the intensity probe fitted with 1/2″ microphones and a 12 mm spacer

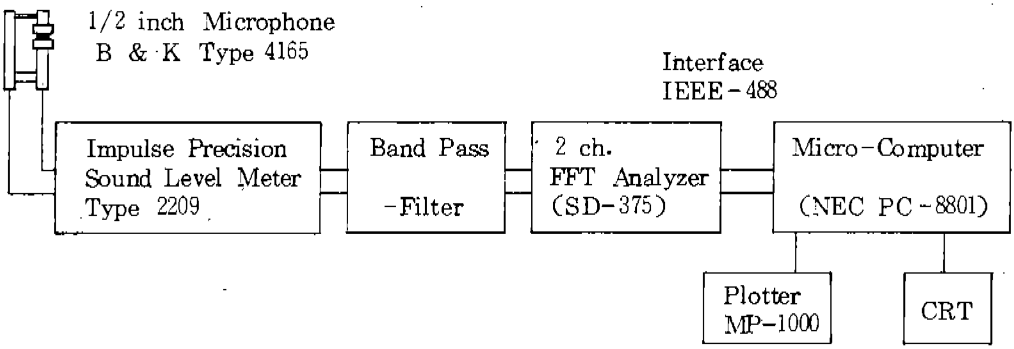


Fig. 2 Blockdiagram of the two microphone technique used for the acoustic intensity measurement

3. EXPERIMENT

3.1 Experimental apparatus and measuring system

A gasoline engine (GWE-80, 1500cc, Nissan), can control it's loading condition and revolution speed by a dynamometer, is used in this experiment. Fig.2 shows the block diagram of the measuring system and signal processing.

All the measurements are performed with two 1/2” condensor microphones and a 12 mm spacer. In this space, the measurable frequency range is 125 Hz – 5 kHz. The two microphones are mounted by face to face and the phase error between the microphones is calibrated by a piston phone. The F.F.T. analyzer and the micro-computer are interfaced by the IEEE-488 interface bus line.

3.2 Experimental method

The experiment in this study is carried out by measuring acoustic intensity about five sides of the engine under idling (700 rpm) and 2,000 rpm running state with no loading condition. In order to identify the accurate source of noise, we measure and analyze each side of the engine by dividing 36(6x6) points. The results are represented by the contour and three-dimensional plot to identify the accurate noise source of the engine visually.

4. EXPERIMENTAL RESULTS AND CONSIDERATIONS

4.1 Directional characteristics for acoustic intensity probe

Fig.3 represents the directional characteristics at 125 Hz for the acoustic intensity probe with a 12mm spacer.

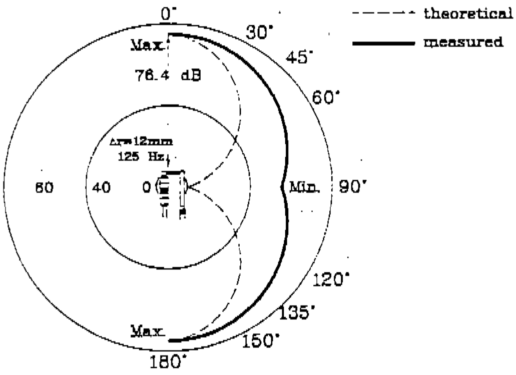


Fig. 3 Directional characteristics at 125 Hz for the prove with a 12 mm spacer over the cooling fan under idling state

Table 1. Differences in Ir between the theoretical and measured for the probe orientation

|Ir| \ α (degree)	0	30	45	60	90	120	135	150	180
theoretical (dB)	76.4	68.1	58.1	44.9	0	44.9	58.1	68.1	76.4
measured (dB)	76.4	75.1	72.5	67.2	52.2	66.9	72.4	75.3	76.6
difference (dB)	0	7	14.4	22.3	52.2	22	14.3	6.2	0.2

As shown in the figure, we come to know that the directional characteristics for the intensity probe makes the shape of Arabic numeral "8" and the intensity level is minimum when α is 0° or 180°, maximum when α is 90° or -90°. The comparisions between the theoretical and measured Ir for probe orientation are shown in Table 1, and it can be estimated that the differences are come from the sound radiational characteristics at all sides of the engine.

4.2 Response characteristics of acoustic intensity for each center frequency using 1/3 octave band

Fig.4 shows the results analyzed by the 1/3 octave band for the acoustic intensity under idling and no loading state of the engine.

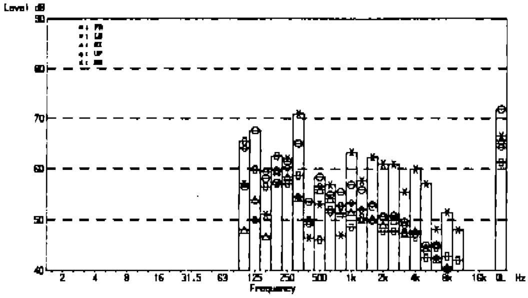


Fig. 4 Acoustic intensity level in 1/3 octave band over each side of the engine under idling state

As shown in the figure, the acoustic intensity radiated from each side of the engine has varied a lot and radiated or absorbed at high level comparatively. And the response characteristics came out in order like this; the front side, upper side, left side, right side and rear side. The highest level of acoustic intensity at the front side is assumed to be the effect of the cooling fan, especially this phenomenon is remarkable from 100 Hz to 500 Hz. At higher than 500 Hz, the acoustic intensity radiated from the front side, left side, right side and upper side are in almost same level, and the rear side is higher to the extent of 5-10 dB.

On the other hand, the frequence response characteristics of the acoustic intensity under 2,000 rpm running and no loading state are shown in Fig.5.

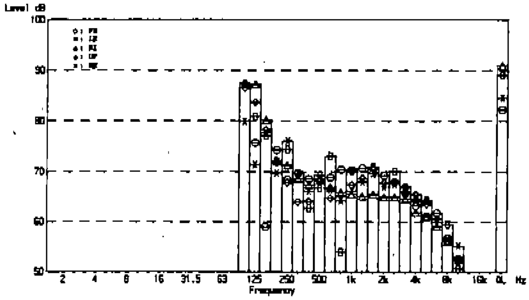


Fig. 5 Acoustic intensity level in 1/3 octave band over each side of the engine under 2,000 rpm running state

At lower than 500 Hz, the response characteristics of the acoustic intensity radiated from each side of the engine came out in order like this; the right side, left side, upper side, rear side and front side. Especially from the viewpoint of higher level at 100 – 500 Hz, it is assumed that there will be important sound sources in this range. At higher than 500

Hz, the levels of the acourstic intensity radiated from each side of the engine take rank with each other. And it can be known that the level due to the increment of revolution speed of the engine becomes higher to the extent of 15-20 dB.

Next, the comparisions of the overall level of the acoustic intensity radiated from each side of the engine are shown in Table 2. From the results, it can be found that the acoustic intensity radiated at the highest level from the front side under idling state, the right side under 2,000 rpm running state and that the increment of acoustic intensity level due to the revolution speed was remarkable at the left side of the engine. Therefore, it is found that the dominant sound sources would exist in the front, right and left side of the engine.

Table 2. Comparisions of overall level of the acoustic intensity radiated from each side of the engine under idling and 2,000 rpm running state

rpm	sound intensity level (dB)				
	FR	LE	RI	UP	RE
Idling	71.8	60.3	65.5	63.8	66.0
2,000	82.2	89.1	91.0	89.1	84.5

4.3 Sound sources and sound radiational characteristics of the gasoline engine

Fig.6 and Fig.7 show that the noise source in the overall level and the sound radiational characteristics of the front side of the engine are represented as the contour and the three-dimensional plot of the acoustic intensity under idling and 2,000 rpm running state respectively.

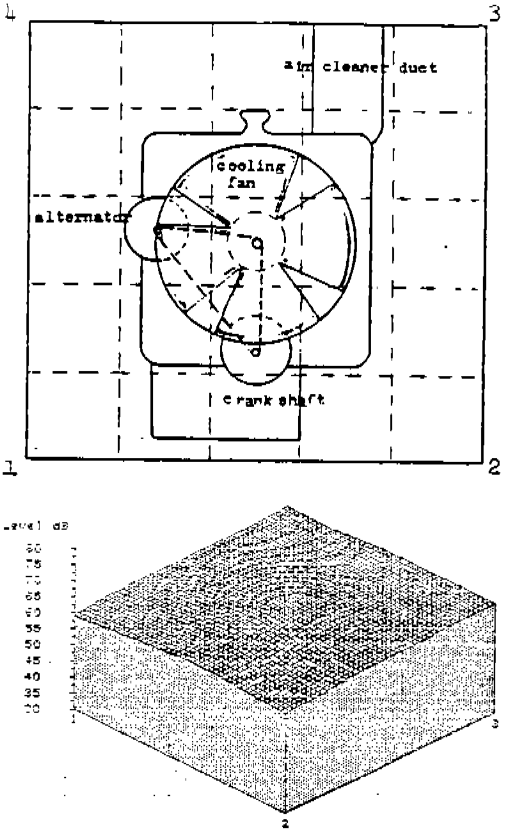
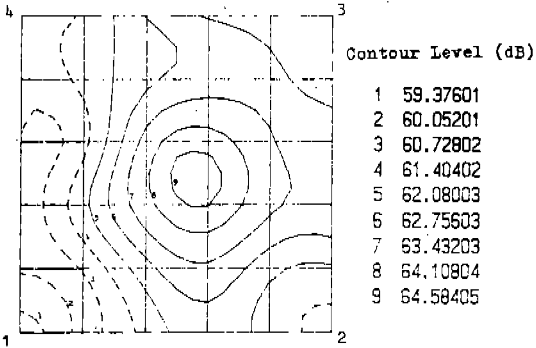
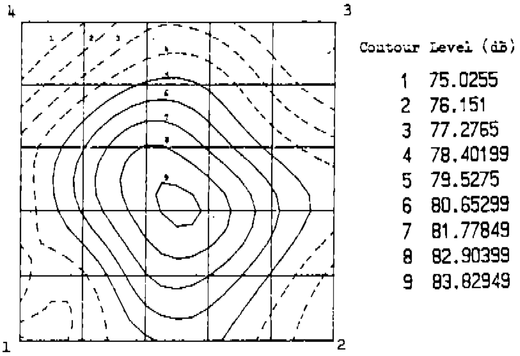
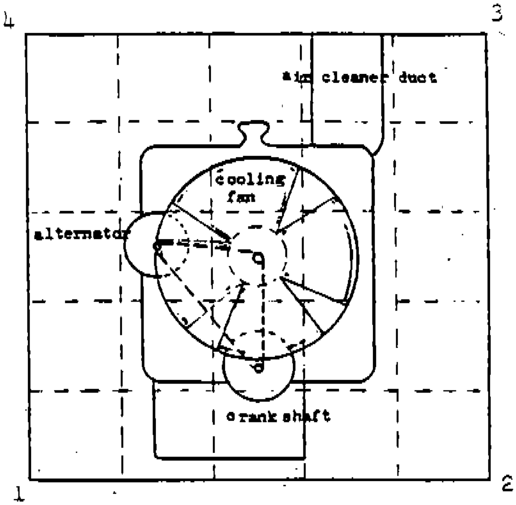


Fig. 6 Acoustic intensity plot measured with a 12mm spacer over the front side of the engine at overall level under idling state







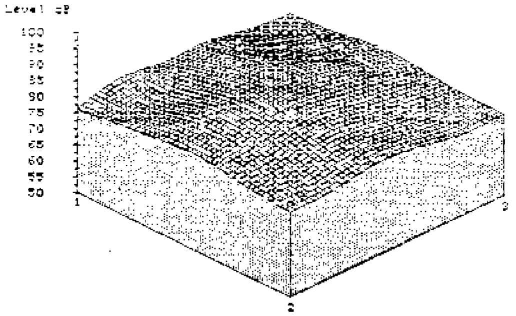


Fig. 7 Acoustic intensity plot measured with a 12mm spacer over the front side of the engine at overall level under 2,000 rpm running state with no loading condition

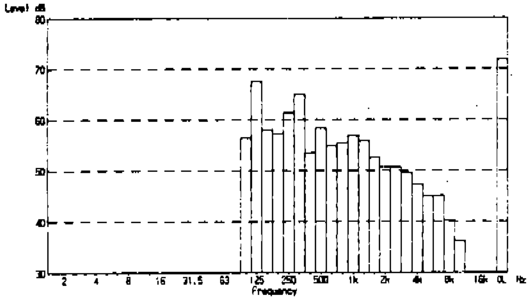


Fig. 8 Acoustic intensity level in 1/3 octave band over the front side of the engine under idling state

As shown in the figures, it can be known that the acoustic intensity of the front side of the engine is radiated at around the cooling fan. Also when we measure the acoustic intensity for each center frequency using the 1/3 octave band filter under idling and 2,000 rpm running state respectively, the results are the same as shown in Fig.8 and Fig.9.

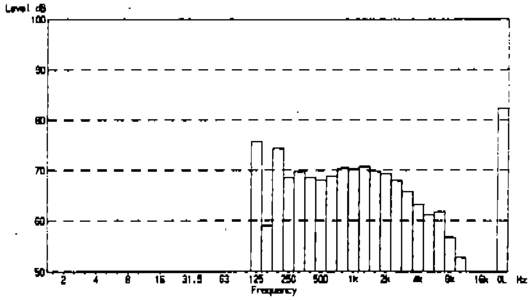
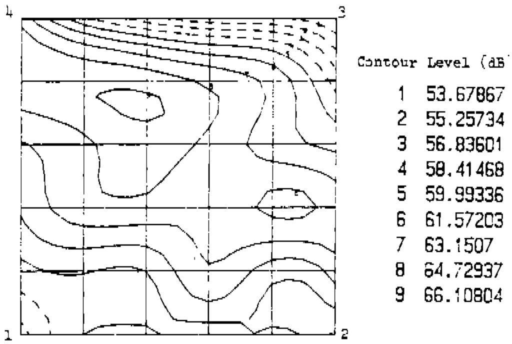
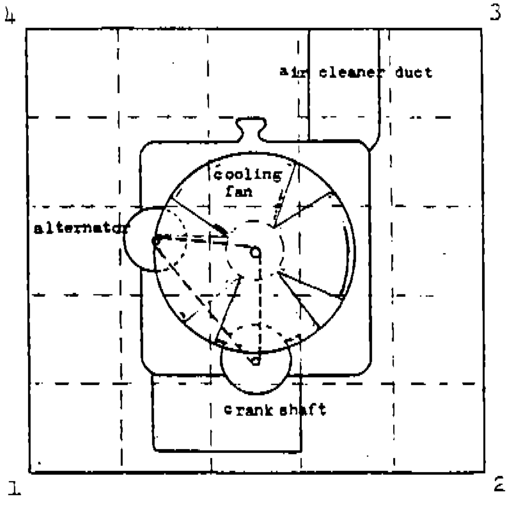


Fig. 9 Acoustic intensity level in 1/3 octave band over the front side of the engine under 2,000 rpm running state with no loading condition





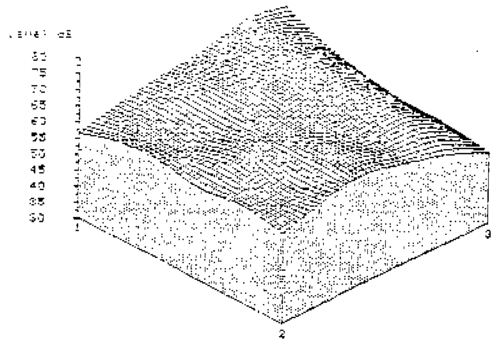
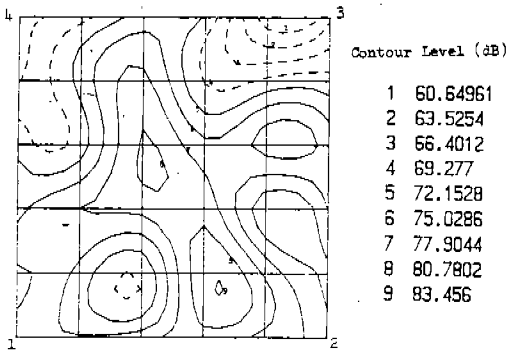
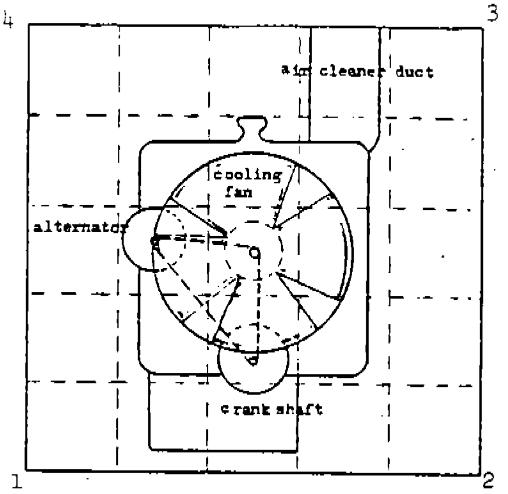


Fig. 10 Acoustic intensity plot measured with a 12 mm spacer over the front side of the engine at 125 Hz under idling state

The acoustic intensity of the front side of the engine under idling state has the maximum level at around 125 Hz, and the contour and three-dimensional plot of the acoustic intensity for this frequency are the same as shown in Fig.10. As shown in the measurement result of the acoustic intensity, it is assumed to be the effect of the alternator located on the left-upper point of the cooling fan that the maximum level is shown at the engine exists at the left-upper point.

On the other hand, as the acoustic intensity of the front side of the engine has the maximum level at 125 Hz as shown in Fig.9 under the 2,000 rpm running state, so it can be known that the dominant noise source of the front side of the engine exists at around 125 Hz.





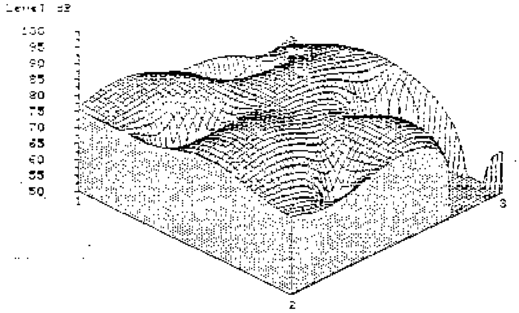


Fig.11 Acoustic intensity plot measured with a 12mm spacer over the front side of the engine at 125Hz under 2,000 rpm running state with no loading condition

Fig.11 shows the contour and three-dimensional plot of the acoustic intensity for 2,000 rpm running state at around 125 Hz. As shown in the figure, the sound is absorbed from four points and radiates from three points around the center, then it can be estimated that the sound radiation is caused by the rotating noise of the cooling fan, alternator and crank shaft.

Besides, from the experimental results over the left side of the engine, it can be known that the intake and exhaust manifold are the dominant noise sources and the absorption of sound is occurred around the air cleaner duct

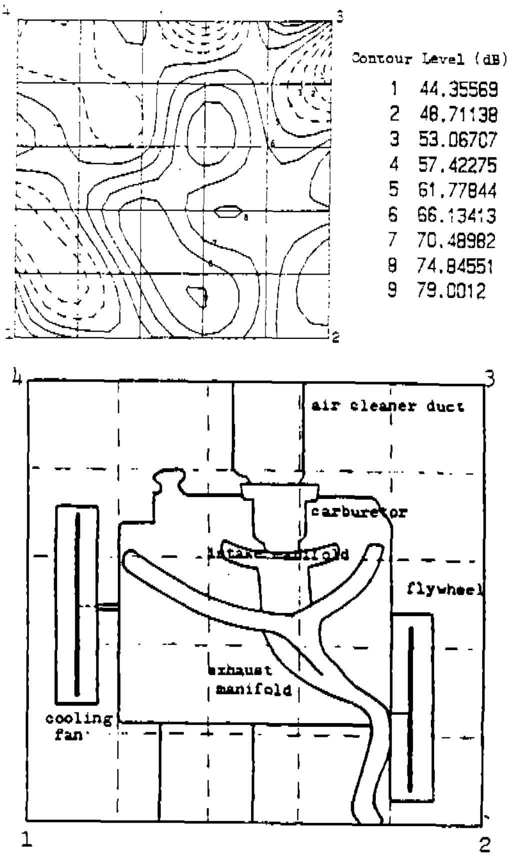


Fig. 12 Acoustic intensity plot measured with a 12 mm spacer over the left side of the engine at 100 Hz idling state

under idling state. Also that the dominant noise source is formed around the exhaust manifold under 2,000 rpm running state. The acoustic intensity for each center frequency using 1/3 octave band filter under idling and 2,000 rpm running state are analyzed. Under idling state, the acoustic intensity of the left side of the engine have the maximum level at 100 Hz and the contour plot for this frequency, as shown in Fig.12, shows high level of sound radiation at the intake manifold. Also under the 2,000 rpm running state, the maximum level at 100 Hz and the highest level of sound radates at the intake and exhaust manifold. Thus it is found that the dominant noise of the left side of the engine is caused by the effects of the intake and exhaust manifold.

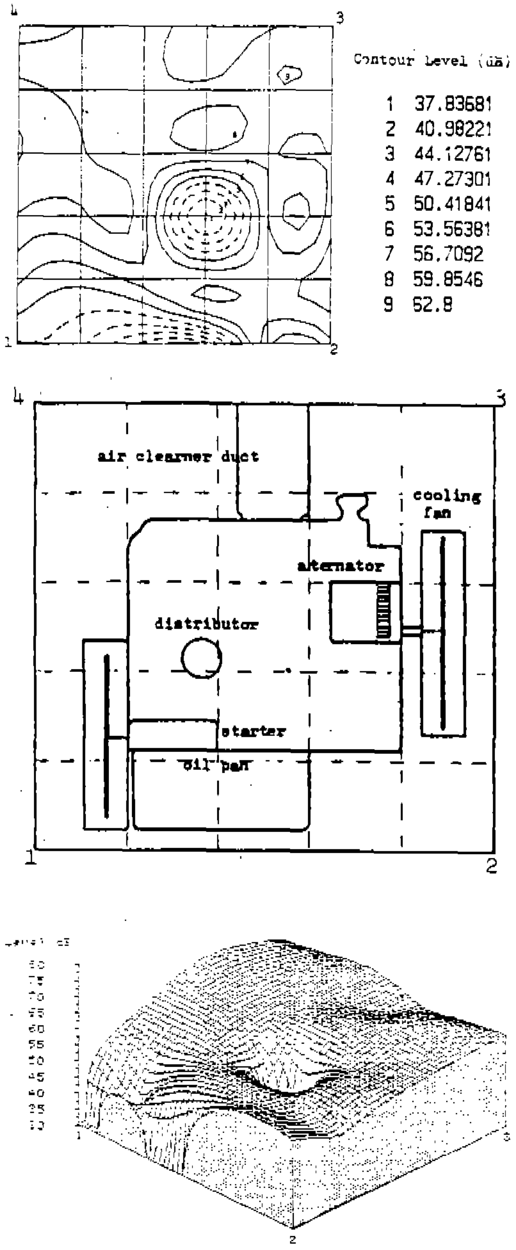


Fig. 13 Acoustic intensity plot measured with a 12 mm spacer over the right side of the engine at 200 Hz under idling state

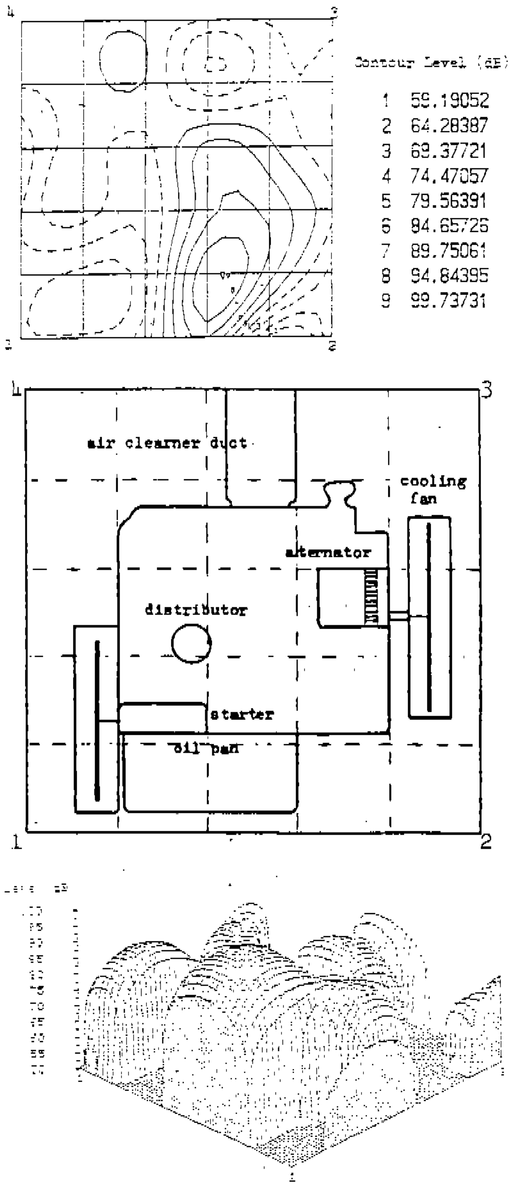


Fig. 14 Acoustic intensity plot measured with a 12 mm spacer over the right side of the engine at 100 Hz under 2,000 rpm running state with no loading condition

Identification of noise sources and sound radiational characteristics are carried out under idling and 2,000 rpm running state for overall level on the right side of the engine. Acoustic intensity radiates constantly from the whole right side of the engine under idle running state and some higher sound level radiates from around the flywheel of the left center. The oil pan located at the lower side is evaluated as a dominant noise source at 2,000 rpm. Under idling state, the acoustic intensity of the right side of the engine have the maximum level at 200 Hz and the contour and three-dimensional plot for this frequency shows high level of sound radiation at the upper part of the flywheel and sound absorption at the center part as shown in Fig.13. Also under 2,000 rpm running state, the maximum level at 100 Hz and very high level of sound radiation is occurred at the right part of the oil pan as shown in Fig.14. Therefore, the dominant noise source on the right side of the engine with the partial absorption and radiation of sound results to the oil pan.

5. CONCLUSIONS

The important thing to reduced noise level of the gasoline engine is to identify the principal noise source by analyzing the coherence and radiational characteristics of each noise source. From the considerations of the experimental results, following conclusions were obtained.

(1) By identifying the noise source and sound radiational characteristics of the gasoline engine visually using acoustic intensity method, it was verified that this method was useful to the engine noise problem.

(2) From the results of noise source identification for GWE-80 gasoline engine, it was shown that the cooling fan at the front side, the intake and exhaust manifold at the left side and the oil pan at the right side were the dominant noise sources of the engine.

(3) At overall level, the highest level of

the acoustic intensity were radiated from the front side under idling state and the right side under 2,000 rpm running state. And in the center frequency of the highest intensity level, the oil pan and the intake and exhaust manifold radiated the highest level of the acoustic intensity at 100 Hz.

ACKNOWLEDGEMENT

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