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Measurement of Combustion-Chamber Volume Using an Acoustic Resonance Technique

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Abstract— This paper describes a method to measure the combustion-chamber volume of automotive engines by using an acoustic resonance technique. In this method, two resonance frequencies are used as follows; one is produced by the Helmholtz resonator formed by a combustion -chamber and acoustic tube, the other is one of the parasitic resonance frequencies arising in the resonator. And the speed of sound can be canceled by the ratio of them to eliminate temperature sensitivity. Furthermore a PLL (Phase-Locked Loop) can help to measure them precisely and quickly. Measuring systems using this method can be applied to measure the volume of combustion-chamber of assembled engine and of combustion-chamber in the cylinder head in isolation .

1. INTRODUCTION

The volume of the combustion-chamber is one of the important parameters determining the performance and quality of an automotive engine. Several methods have been tried to date for measuring the volume of the combustion-chamber [1][2]. We have devised an acoustic resonance technique that provides a simpler and more accurate method of measuring the combustion-chamber volume. In the present work, this technique was incorporated into a system for measuring the combustion -chamber volume in the cylinder head in isolation. As a further application of this acoustic resonance technique, a system has been developed for measuring the volume of the combustion-chamber of an assembled engine through the spark plug hole in a simple, accurate and quick operation. This paper describes these measuring systems and presents typical examples of the measured results.

2. MEASUREMENT THEORY

2.1 Helmholtz resonator

The technique presented here uses the theory of a Helmholtz resonator to measure the volume of the combustion-chamber. A Helmholtz resonator consists of an enclosed cavity with a small opening which is connected to a straight acoustic tube (Fig. 1). Helmholtz resonance frequency is given by

$$f_1 = \frac{c}{2\pi}\sqrt{\frac{S}{LV}} \tag{1}$$

where c is the speed of sound, S and L are the cross -sectional area and length of the tube, respectively, and V is the volume of the cavity.

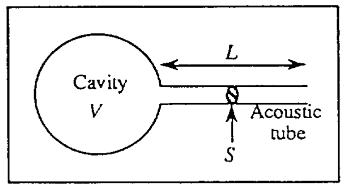

Fig. 1. Helmholtz resonator

Since the speed of sound varies according to the ambient temperature, temperature compensation must be provided in order to obtain accurate measurements. While there are various possible temperature compensation methods, with our technique temperature compensation is accomplished by using the parasitic resonance generated in the acoustic tube of the Helmholtz resonator. Its resonance frequencies are given by

$$f_2 = \frac{nc}{2L} \quad (n = 1,2,3\cdots) \tag{2}$$

Accordingly, the ratio of these two resonance frequencies can be used to cancel out the effects of variation in the speed of sound, thus yielding (n =1)

$$V = \frac{LS}{\pi^2}\left(\frac{f_2}{f_1}\right)^2 \tag{3}$$

As a result, the cavity volume V can be determined from the frequency ratio of f_2/f_1 [3] .

2.2 Resonance frequency measuring circuit

A PPL is used with this technique to obtain quick and highly precise measurements of the resonance frequencies. This type of closed circuit generates a signal which is synchronized with the phase and frequency of an input signal.

An example of the transfer function of the Helmholtz resonator is shown in Fig. 2. A resonance peak is seen in each of the resonance frequencies f_1 and f_2 and the phase is inverted. Since these characteristics are used by the measuring circuit, the input signal, the phase of which reverses at the resonant point, thus coincides with the locked frequency of the PPL.

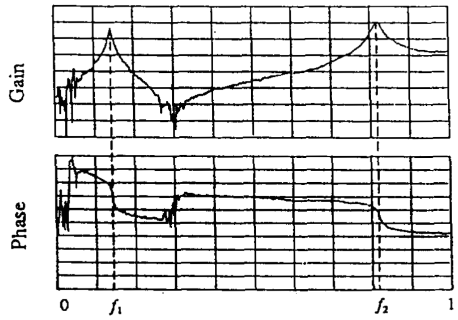

Fig. 2. Example of transfer function of Helmholtz resonator

3. COMBUSTION-CHAMBER VOLUME MEASURING SYSTEM

3.1 Main specifications

Table 1 gives the main specifications of the system incorporating the foregoing measurement theory which has been developed to provide an accurate way of measuring the combustion-chamber volume of the cylinder head in isolation. The appearance of the system is shown in Fig. 3. It consists of three main components: a sensor head, a volume calculation unit and a master chamber. When the system is used exclusively for engines of the same type, it provides high measurement accuracy with repeatability (3σ) of ± 0.05 [cm^3]. The system is also easy to operate, which means that stable measurements can be obtained every time without assigning specific individuals to perform the task (personal error).

TABLE 1
MAIN SYSTEM SPECIFICATIONS

Repeatability ($\pm 3\sigma$)	Within ± 0.05[cm^3]
Response	Less than 10 sec/cylinder (externally adjustable)
Range of engine application	Dedicated use with same type of engine
Volume resolution	0.01[cm^3]
No. of cylinders measured	1 cylinder
Temperature range	Approx. 10~40[℃]
Calibration (regular inspection)	Performed with a master chamber. The volume calculation unit automatically determines the constants.
Master chamber	Aluminum casting having a known volume (3 castings of differing volumes are used)

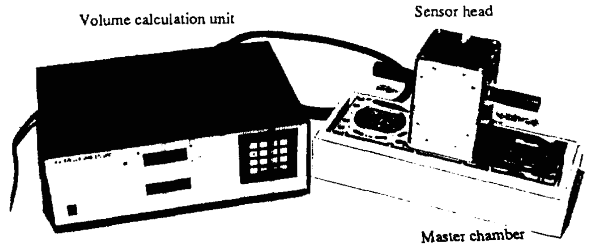

Fig. 3. The appearance of the system

3.2 Hardware configuration

One end of the acoustic tube is connected to the combustion-chamber to be measured, which is assumed to represent the cavity (volume V) of a Helmholtz resonator. To obtain stable generation of resonance, a soundproof enclosed cavity (volume V') is attached at the other end of the tube to form the sensor head of the system. The acoustic tube, a speaker and microphones are positioned along the center axis of the combustion-chamber.

3.3 Volume calculation equation

Connecting the sensor head and combustion-chamber cavity to the acoustic tube forms a type of acoustic resonator, making it possible to measure the combustion -chamber volume. Since this acoustic resonator has two cavities (V, V') connected in parallel, one on either end of the acoustic tube, its resonance frequency is given by

$$f_1 = \frac{c}{2\pi}\sqrt{\frac{S}{L\left(\frac{VV'}{V+V'}\right)}} \tag{4}$$

where $(VV'/(V+V'))$ is the combined volume of the two parallel cavities.

The volume V' of the soundproof cavity of the sensor head is approximately 1,400 [cm^3], which is sufficiently larger than the combustion-chamber volume (V = 20~80 [cm^3]) to be measured. However, when the theoretical equation represented by Eq. (3) is applied, it is necessary to take the effect of V' into account. The measuring system was calibrated using a casting having a known volume. From the volume and resonance frequencies measured at that time, the following approximation equation was then obtained by the least-squares method:

$$V = a_1\left(\frac{f_2}{f_1}\right)^4 + a_2\left(\frac{f_2}{f_1}\right)^2 + a_3 \tag{5}$$

where a_1, a_2 and a_3 are constants determined on the basis of the calibration test. Equation (5) was thus adopted as the expression for calculating the combustion-chamber volume.

3.4 Evaluation results

Typical results obtained in evaluations of the measuring system are shown in Figs. 4 and 5. The results in Fig. 4 were obtained when the system was placed in a constant temperature tank and the ambient temperature was varied uniformly. The data confirm that temperature compensation was accurately provided in relation to a baseline value (38.80 [cm^3]). It is seen that the measured values move upward and to the right with increasing temperature. That characteristic indicates the adjustment made in consideration of the thermal expansion (dashed line) of the aluminum cylinder heads being measured.

The results in Fig. 5 show the correlation between the combustion-chamber geometry and measured volume for different cylinder head variations. When different cylinder head variations are measured using the same set of calculation constants (a_1,a_2 and a_3), maximum error of 0.2 [cm^3] may occur in a few cases. However, by using a different set of constants for each type of engine measured, it is possible to obtain measurement accuracy of ±0.05[cm^3] for each engine variation.

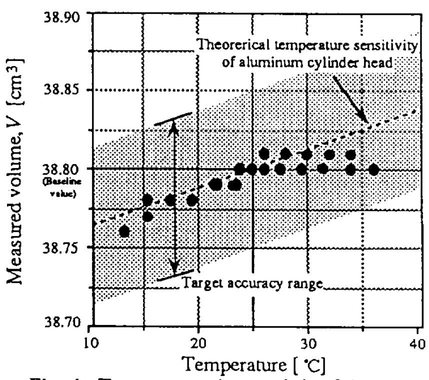

Fig. 4. Temperature characteristic of the system

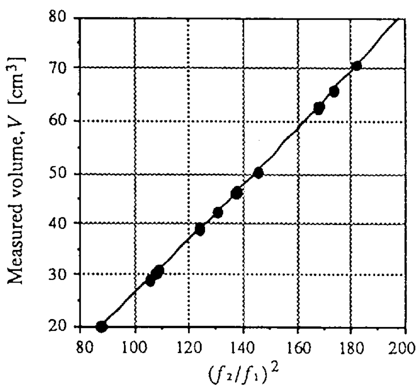

Fig. 5. Evaluation results for different combustion-chamber variations

4. MEASUREMENT OF COMBUSTION-CHAMBER VOLUME OF ASSEMBLED ENGINE

4.1 Sensor head configuration

As an example of the application of this acoustic resonance technique, a system was developed for measuring the combustion-chamber volume in an assembled engine without dismantling the engine. A cross-sectional view of the sensor head used to obtain volume measurements with this system is shown in Fig. 6.

As indicated in the figure, the spark plug was removed and the sensor head, including an acoustic tube and a cylindrical cavity, was installed in its place to form an acoustic resonator .

The construction of the engine used did not allow any extra space for installing the speaker and microphone in such a close position. The portion having extra space in this system was the cylindrical cavity. Consequently, the volume (V') of the cylindrical cavity was reduced to approximately 34.2 [cm^3] to allow the resonance frequency to be detected at the cylindrical cavity,and the speaker and microphone are positioned at the upper cylindrical cavity.

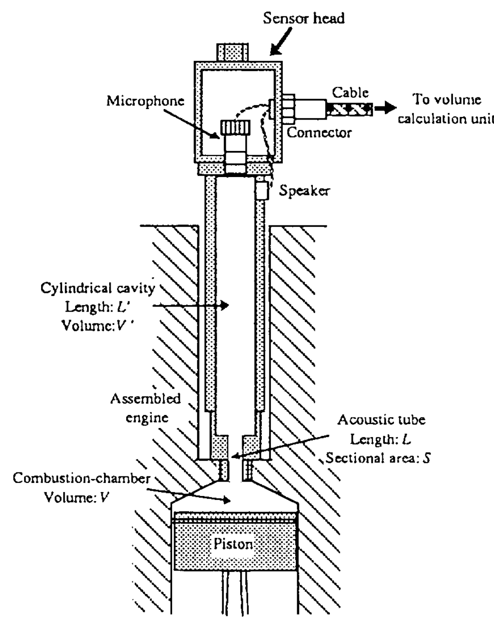

Fig. 6. Schematic diagram of sensor head for use with assembled engines

4.2 Temperature compensation

To reduce the measurement error described in *3.4* (Fig.5), the resonance generated by the cylindrical cavity , which was not directly connected to the combustion -chamber, was used as the basis for providing temperature compensation. This cavity had a sufficiently larger diameter than the acoustic tube and sharp edges were formed at the interface where the cylindrical cavity and acoustic tube were connected. As a result, both ends of the cavity could be considered as a closed acoustic tube. Its resonance frequency was given by the following expression, similar to Eq. (2):

$$f_2' = \frac{nc}{2L'} \qquad (n = 1,2,3\cdots) \tag{2'}$$

4.3 Volume calculation equation

As mentioned earlier, Eq. (5) for calculating the combustion-chamber volume does not provide sufficient accuracy with this system, because the volume (V') of the cylindrical cavity is not sufficiently larger than the volume (V) of combustion-chamber to be measured. For that reason, a term representing the combined volume of two parallel cavities was added to the left-hand side of Eq. (5) to create Eq. (6), which assured sufficient calculation accuracy.

$$\frac{VV'}{V+V'} = a_1\left(\frac{f_2'}{f_1}\right)^4 + a_2\left(\frac{f_2'}{f_1}\right)^2 + a_3 \tag{6}$$

4.4 Evaluation results

Eight different cylindrical dummy combustion -chambers were prepared and their volumes were measured to investigate the effect of differences in engine configurations and piston positions on measurement accuracy. The dummy chambers had differing heights and diameters and their volumes were known. Typical results are shown in Fig. 8. The maximum measurement error is seen to be ±0.5 [cm^3] in a few cases. Converting this value to a compression ratio equivalent yields a maximum error of approximately 0.1.

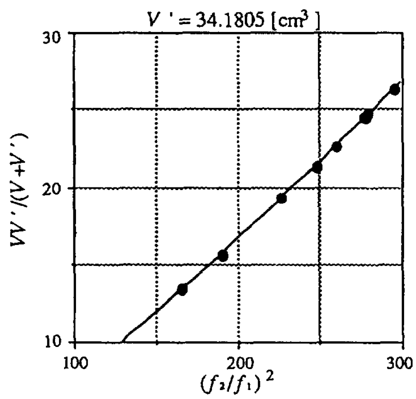

Fig. 7. Evaluation results

4.5 Technical issues

The cylindrical cavity attached to the acoustic tube in parallel with the combustion-chamber to be measured lacks a sufficiently large volume (V') relative to that (V) of the combustion-chamber. Thereby lowering the sensitivity of the system to the volume (V) of the combustion-chamber to be measured. Furthermore, as the volume (V) becomes larger, the cylindrical cavity, rather than the cavity of the combustion-chamber, and the acoustic tube tend to function as the Helmholtz resonator. Consequently, specifications that facilitate accurate volume measurement when the piston is at top dead center tend to result in lower measurement accuracy as the piston descends toward bottom dead center.

In addition, a temperature gradient sometimes occurs in the sensor head because of its long vertical construction, as shown in Fig. 6. This tends to result in greater measurement error than with the system explained earlier that is used to measure the volume of the combustion-chamber in isolation. Accordingly, in order to obtain accurate volume measurements, both the sensor head and the combustion-chamber to be measured must undergo a sufficient heat soak in advance.

5. CONCLUSIONS

A technique has been developed for measuring the volume of the combustion-chamber by means of acoustic resonance. The results of this study are summarized below.

(1) The acoustic resonance technique was incorporated in a system for measuring the combustion-chamber volume of a cylinder head in isolation. This system provides a highly accurate volume measurement in a quick and simple operation.

(2) As a further application of this acoustic resonance technique, a system was developed for measuring the volume of the combustion-chamber in an assembled engine.

Because this measurement technique is based on the acoustic resonance generated in a closed space, it is exclusively effective in measuring the volume of enclosed cavities. In addition, the sensor head is simple in construction and allows a wide range of application. Because of these advantages, this acoustic resonance measurement technique is expected to find widespread use in future.

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