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Measurement of Strong Shock Pressure

This paper deals with measurement of a strong shock pressure like an imploding detonation of over 1 GPa which cannot be measured directly with currently available commercial pressure transducers. After the transfer functions of three kinds of materials were measured using a shock tube, Teflon was selected as a shock absorber. As an example of pressure beyond the limit of the pressure transducer, we tried to measure pressure at the center of an imploding detonation. From this measurement, we could estimate the pressure peak of about 1.7 GPa.

INTRODUCTION

Ultra high pressure like a shock wave, an imploding detonation or pressure in an explosion over 1 GPa are used industrially to make diamonds from graphite (Glass and Sharma, 1976) and for other products. In such cases, it is necessary to know the precise value of the high pressure, but it cannot be measured directly with commercially available pressure transducers. Imploding shock waves were studied by Perry and Kantrowitz (1951) and by Lee (1967). Cylindrical or spherical implosions were studied by Bach and Lee (1969) and Glass and Chan (1974). These papers presented mainly the production or propagation of shock waves, the high pressure, however, has never been measured.

We have tried to obtain such a high pressure pulse, and then it is necessary to set a shock absorber between the pressure transducer and an imploding detonation in a combustion chamber so that the transducer cannot be damaged by the great shock. We attempt to develop the measurement technique to derive the time history of a high pressure pulse like an imploding detonation whose pressure pulse cannot be measured directly, thus, we can use the transducer without the fear of destruction in industrial applications.

In this paper, a strong shock pressure derivation technique is presented. The high pressure value can be derived using the damped pressure through a shock absorber set between the pressure transducer and the shock wave.

SELECTION OF SHOCK ABSORBING MATERIAL

The shock absorber we use is cylindrical and has a 5 mm diameter and a 30 mm length. The absorber and

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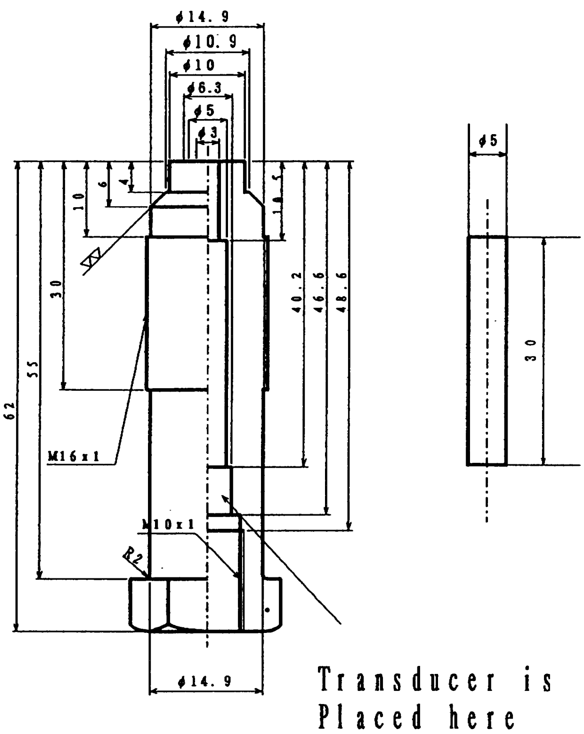

FIGURE 1 Holder and shock absorber for pressure measurement.

its holder are shown in Fig. 1. The space for the absorber has a 5 mm diameter and a 29.7 mm length and the length is shorter by 0.3 mm than that of the absorber. Thus any gap is avoided between the absorber and the pressure transducer. If there is any gap, the absorber may shift in axial direction. Therefore, it is necessary to fix the absorber tightly.

The holder for the shock absorber is mounted in the end wall of the driven section of a shock tube. The driver section of the shock tube, as shown in Fig. 2, is 3.22 m long and the driven section of it is 3.26 m long. We use a reflected shock wave to obtain a high pressure pulse. In the shock tube we selected reflected shock pressures of 1.5 MPa and 2.6 MPa because we can measure these pressures directly. Using the measurement, we obtained the transfer function of the shock absorber. Two piezo-electric pressure transducers (No. 4 in Fig. 2) are set to measure the incident shock velocity of the shock wave from the time interval between the two transducers. They were made in our laboratory using barium titanate. We do not measure the pressure using these transducers. By using the incident shock velocity we calculated the reflected shock pressure P_5 in the shock equations (Gaydon and Hurle, 1963).

On the other hand, two PCB pressure transducers (PCB Piezotronics, Inc., Model M109A02 S/N 3085; No. 2 in Fig. 2) are set to obtain the transfer function of the shock absorber.

The pressure P_1 in front of the shock wave and the pressure P_2 behind the shock wave are related by the following expression (Gaydon and Hurle, 1963)

$$\frac{P_2}{P_1} = 1 + \frac{2\kappa_1}{1+\kappa_1}(M_s^2 - 1), \qquad (1)$$

where κ_1 is the ratio of the specific heats in the driven section and M_s is the Mach number of incident shock wave.

Usually the pressures P_2 and P_5 are used in a shock tube for calibration purposes. The wave diagram of the shock tube in shown in Fig. 2(b), the subscripts of the pressures refer to the areas of constant properties in the diagram. The incident shock wave is reflected from the tube end wall, and the pressure in the reflected shock pressure rises suddenly from P_1 to P_5 at the end wall and then region 5 holds a constant pressure for a certain period, as one can see from Fig. 2(b).

The pressure P_5 is calculated from the following expression (Gaydon and Hurle, 1963),

$$\frac{P_5}{P_2} = \frac{P_{21}(\alpha_1 + 2) - 1}{\alpha_1 + P_{21}}, \qquad (2)$$

where P_{21} is defined by P_2/P_1, and α_1 is defined by $(\kappa_1 + 1)/(\kappa_1 - 1)$.

The instantaneous wave recorded on the memory of an oscilloscope, and the frequency characteristics were analyzed by complex FFT using a sampling frequency of 1 MHz. The pressure transducer has 500 kHz natural frequency and 1 μs rise time. The gain spectra were plotted for four cases: (1) with no shock absorber; (2) with a steel shock absorber; (3) with a brass shock absorber; and (4) with a Teflon shock absorber. The results for two kinds of shock absorber (steel and brass) and the gain spectrum without a shock absorber are shown in Fig. 3. The brass absorber can reduce the value by about 10 dB in comparison to the no absorber case. The reduction of 10 dB means only about one third (1/3.16).

Very high or ultra high pressure pulses, which we mean here, indicate order of GPa. We want to know the value, and thus a reduction of one third is not enough for a transducer which has a measurement limit of 840 MPa of static or quasi-static pressure. We want to develop a measurement technique for an ultra high pressure pulse.

From these values, Teflon was selected as the shock absorber we use. The transfer ratio of the Teflon shock absorber is much smaller than that of the other materials, therefore it does not appear in Fig. 3 for the frequencies under 1500 Hz.

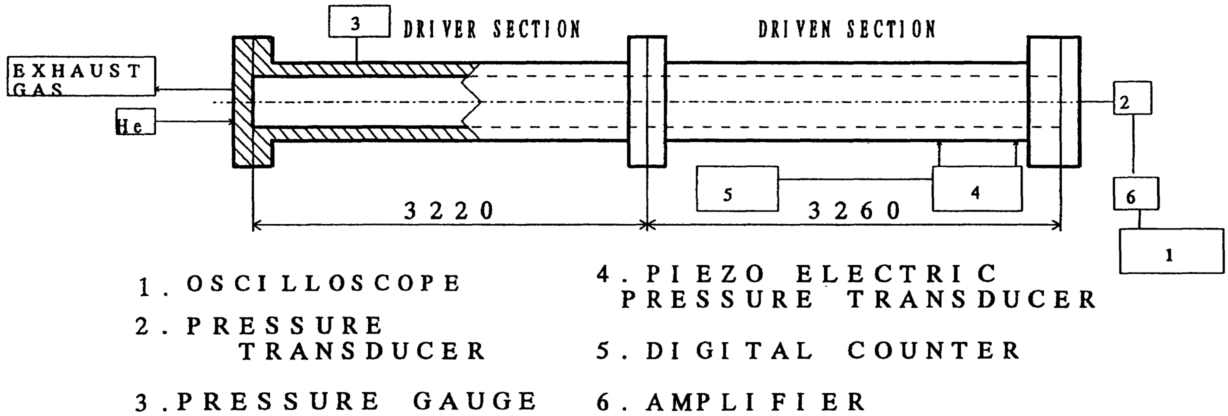

FIGURE 2(a) Shock tube configuration.

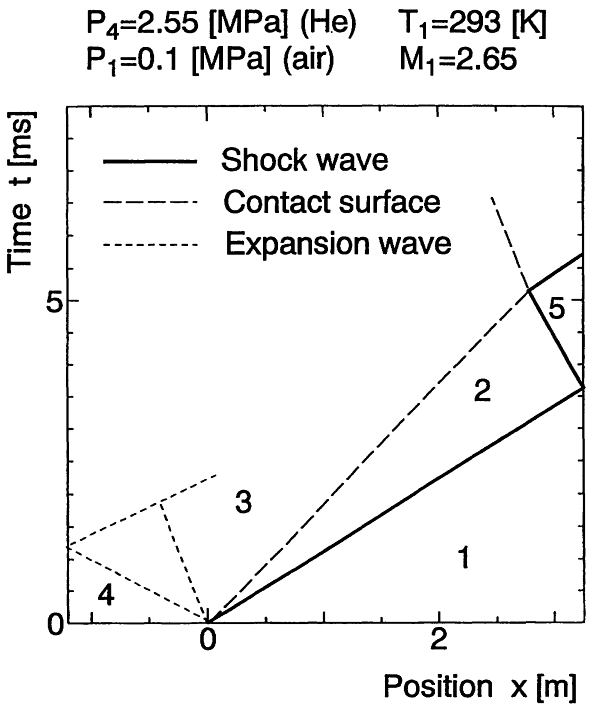

FIGURE 2(b) Wave diagram.

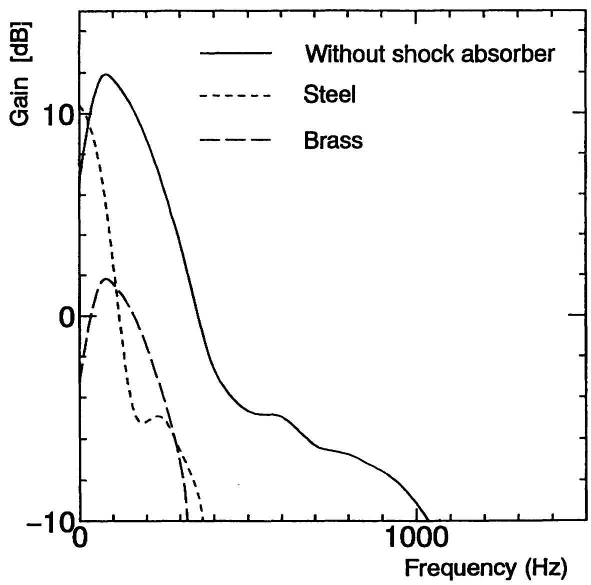

FIGURE 3 Power spectra of shock absorbers.

The transfer ratio for Teflon is shown in Fig. 4. The input data to obtain the transfer ratio are the pressure wave data which the shock absorber receives. The input data which rise from the initial condition (0.1 MPa) to 1.5 or 2.6 MPa can be measured directly with one of the PCB transducers because they are not so high. The output data are the pressure pulse data through the shock absorber. They can be obtained with the other one. The calculated data using FFT are plotted with circles or squares on the frequency domain, and we use a spline curve fit to draw Fig. 4.

The effect of the shock absorber on the pressure profile wave is shown in Fig. 5. The values of 2.6 and 1.5 MPa were used as a known pressure in the shock tube to confirm the complex transfer ratio of the shock absorber. The characteristics in the case of 2.6 MPa are similar to that of 1.5 MPa, and so we determined that pressure over 1 GPa can be measured if the shock absorber is deformed within the elastic limit.

To confirm that the shock absorber is deformed elastically we tried to derive a very high pressure value several times. As a result, the same values are always obtained, and so it is determined that the shock absorber is deformed within the elastic limit during receiving a shock and that it has not been deformed after receiving the shock.

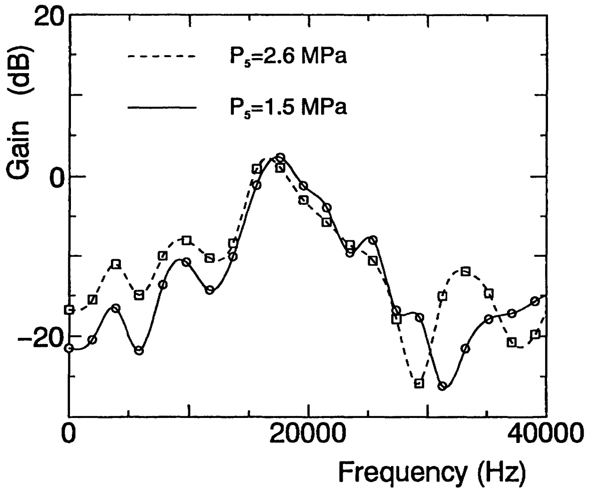

FIGURE 4(a) Transfer function of shock absorber; Gain versus frequency. Conditions: $P_1 = 0.1$ MPa, Driver gas: Air.

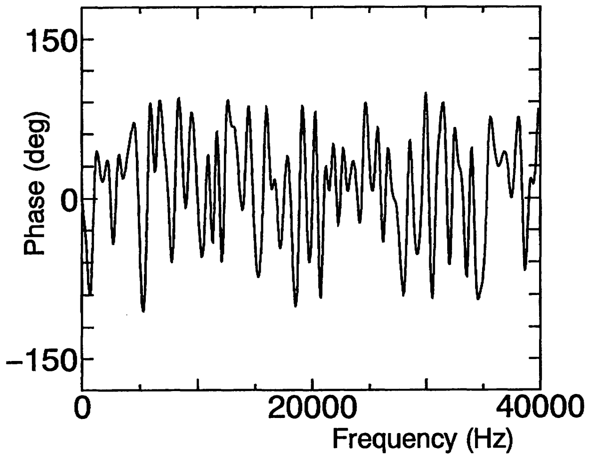

FIGURE 4(b) Transfer function of shock absorber; Phase versus frequency.

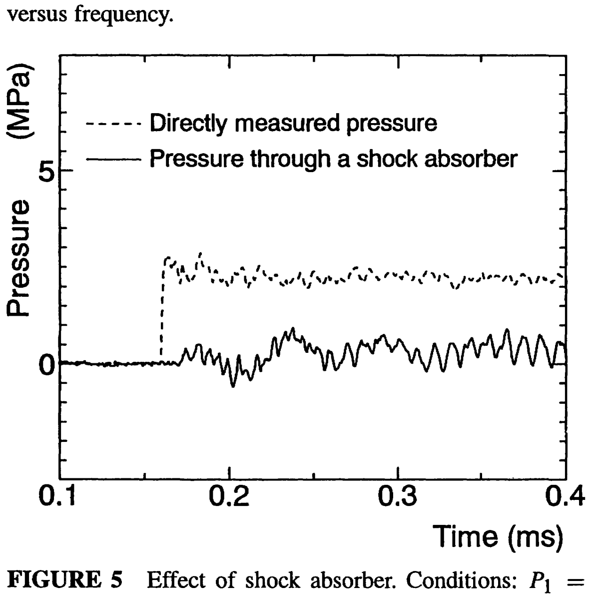

FIGURE 5 Effect of shock absorber. Conditions: $P_1 =$ 0.1 MPa, $P_5 = 2.6$ MPa, Driver gas: Air.

The phase characteristics should be considered together with the gain characteristics, as one can see in Fig. 4(b). Thus, the complex transfer ratio of the shock absorber was obtained.

REPRODUCTION OF UNKNOWN PRESSURE IN SHOCK TUBE

Our procedure is shown in Fig. 6. In the first stage, a known pressure is measured directly and through the shock absorber at the same time. The shock tube is used to confirm the transfer ratio as mentioned above. The spectra of the both pressure are obtained by complex FFT. The complex transfer ratio is calculated from the spectrum comparison between the direct pressure and the damped pressure.

In the second stage, the spectrum of an unknown pressure through the shock absorber is obtained by FFT. The spectrum of the pressure we want to know is calculated by dividing by the transfer ratio. And, the calculated pressure profile is obtained by the inverse FFT software. In this way, the high pressure we cannot directly measure can be derived. As mentioned above the shock absorber is not deformed non-elastically, and so the shock absorber has a linearity within the elastic deformation. Owing to the linearity we can derive the high pressure pulse value using the transfer function.

The spectra of the damped pressure (the pressure through the shock absorber) P_{5D} are shown in Fig. 7. The pressure is measured using a shock tube. This figure indicates two cases: the pressure P_5 values are 2.6 MPa and 1.5 MPa. The pressure P_5 which should be 2.6 MPa is calculated from the damped pressure P_{5D} of 2.6 MPa using the transfer ratio of 1.5 MPa. The result is shown in Fig. 8. The solid line represents the derived pressure and the broken line is the directly measured pressure. In the measurement or derivation of ultra high pressures or strong shock pressures like in this study, the measurement or the derivation error is large, usually 50 $\sim$ 100%. From this result, however, it is found that the real pressure wave is derived and that the transfer ratio can be trusted within an error of 50 $\sim$ 100%.

REPRODUCTION OF IMPLODING DETONATION PRESSURE

We tried to derive the shock pressure of an imploding detonation as a sample of ultra high pressure which is unable to be measured directly. The experimental apparatus is shown in Fig. 9. An oxygen-propane gas

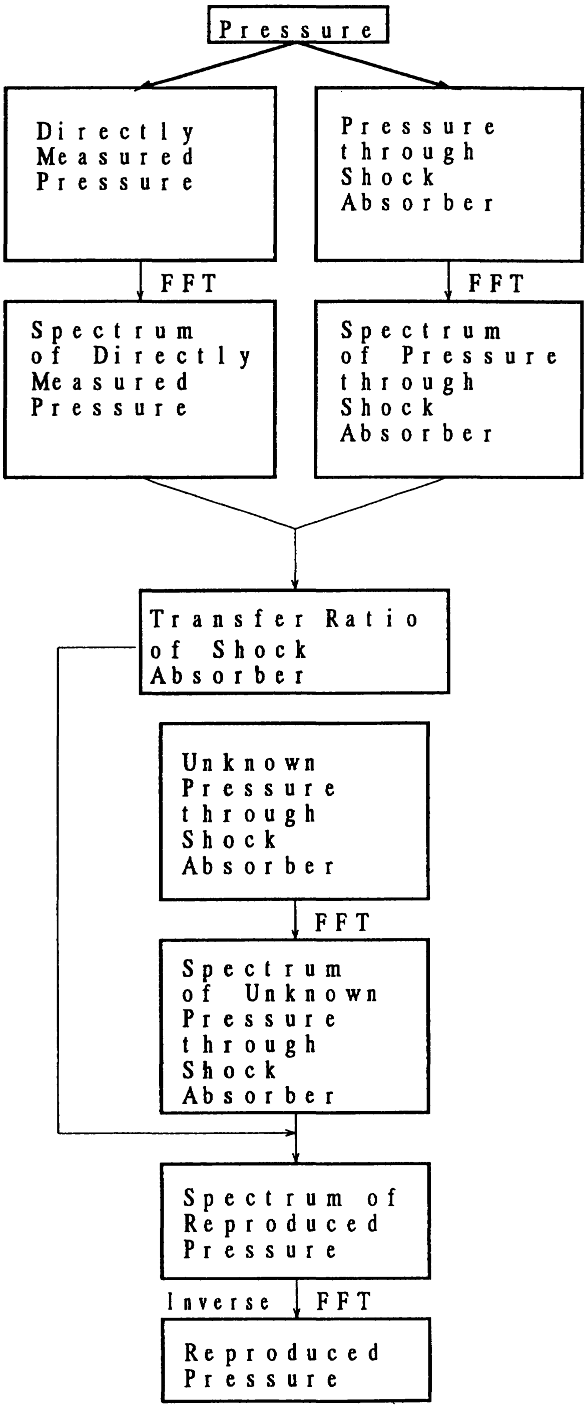

FIGURE 6 Flow chart.

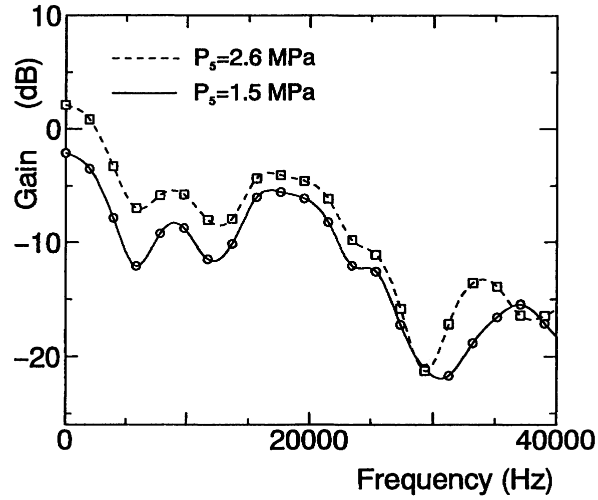

FIGURE 7 Power spectrum of damped pressure. Conditions: $P_1 = 0.1$ MPa, Driver gas: Air.

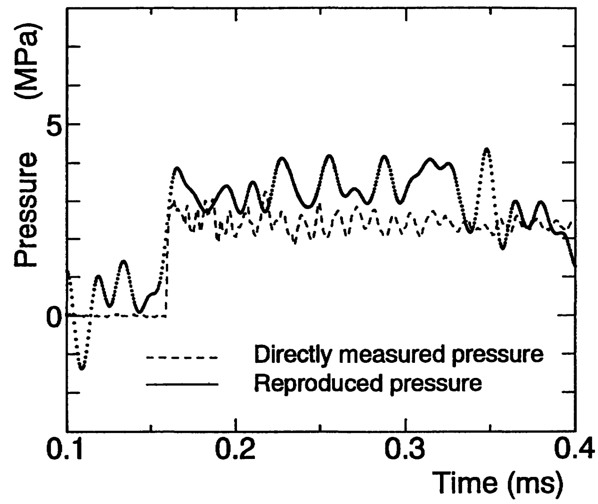

FIGURE 8 Reproduced pressure using inverse FFT. Conditions: $P_1 = 0.1$ MPa, $P_5 = 2.6$ MPa, Driver gas: Air.

mixture is enclosed in the combustion area where the initial pressure value in the imploding denotation P_0 is 53.3 kPa (400 Torr). The detonation is generated by the ignition plug at the upper part of the apparatus, and converges to a point in the area A. The shock pressure in the detonation is assumed to be over 1 GPa. To avoid destroying of the pressure transducer, a new long cylindrical Teflon shock absorber was made.

The technique to obtain the transfer function of the long shock absorber is the same as that of the shorter one. The damping of the longer one is larger than that of the shorter one. The method to derive a very high pressure is the same as that in the case of the shorter one.

The transfer ratio of the long shock absorber is shown in Fig. 10. In comparison to the ratio of the short shock absorber, the damping effect of the long one is much larger than that of the shorter one. Attempts were made to derive the center pressure of the imploding denotation, as shown in Fig. 11. It is confirmed by the propagation velocity through the steel

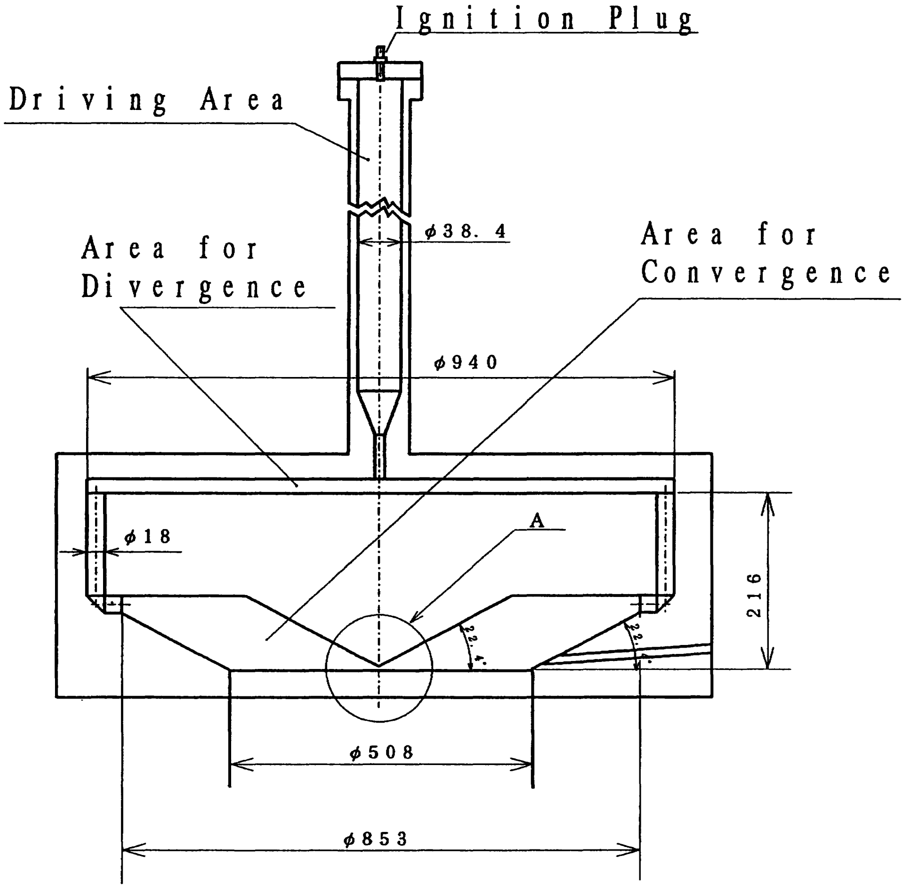

FIGURE 9 Apparatus for imploding detonation.

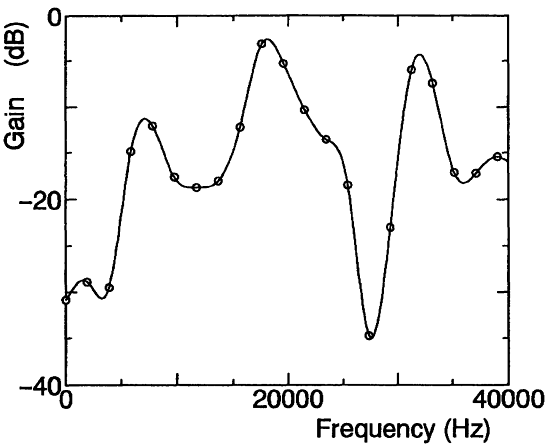

FIGURE 10 Transfer function of long shock absorber. Conditions: $P_1 = 0.1$ MPa, $P_5 = 2.6$ MPa, Driver gas: Air.

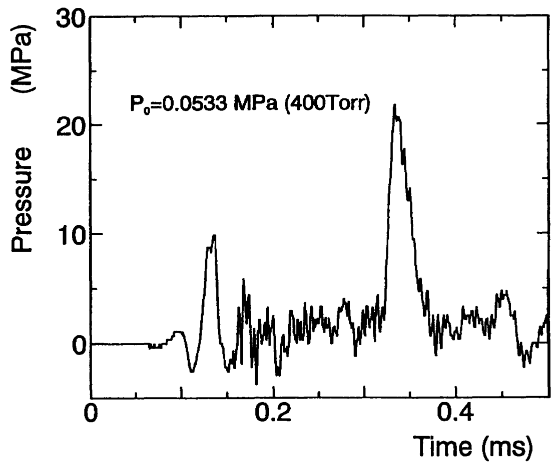

FIGURE 11 Derived center pressure of imploding detonation.

holder that the pressure peak appearing at time 0.13 ms is the pressure propagated through the steel holder shown in Fig. 1. The pressure propagated through the long shock absorber appears at 0.34 ms, from which the pressure wave is derived, as shown in Fig. 12. In this figure, the time axis is independent of that of Fig. 11. Figure 12 indicates the derived peak pressure value is about 1.7 GPa, and the center pressure of the

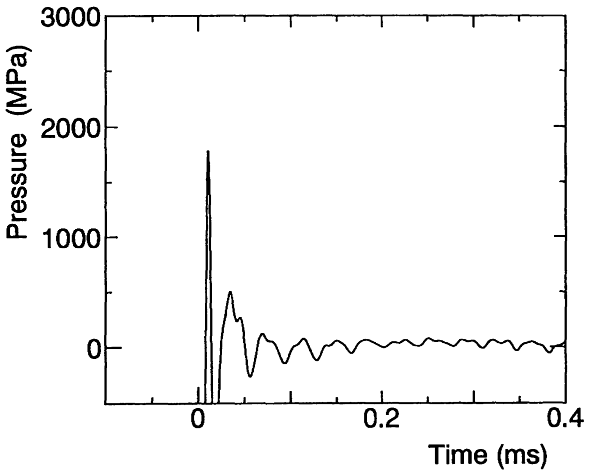

FIGURE 12 Reproduced pressure of imploding detonation.

imploding detonation is derived to be 1.7 GPa. We derived that this value has 50 $\sim$ 100% error as mentioned above.

The negative pressure in Fig. 12 was considered to result from two sources: (1) the characteristics of PCB transducer; and (2) a high noise floor in the transfer ratio. At this point, we are now developing the calculation to reduce the noise and the error. As a result, we found it is possible to measure an ultra high pressure like a strong shock pressure or an imploding detonation. Actually, after several measurements of an imploding detonation, the pressure cannot be measured directly by a commercial transducer correctly even if the pressure the transducer receives is less than the maximum pressure value described in the catalog.

CONCLUSIONS

An ultra high pressure has been measured for a shock wave and an imploding detonation. The shock absorber made of Teflon makes it possible to measure pressures over 1 GPa. The shock absorber made of other materials, steel and brass, were tried but they could not be used because the transfer ratios were not so small. The spectrum of an unknown pressure was calculated by the transfer ratio and the unknown pressure wave can be reproduced by inverse FFT software. We found it is possible to measure an ultra high pressure like a strong shock pressure or an imploding detonation though the reproduced pressure is slightly higher than the directly measured pressure. The pressure measurement of the imploding detonation was tried as a sample whose pressure cannot directly be measured. As a result, the pressure peak is estimated to be about 1.7 GPa.

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REFERENCES

Bach, G. G., and Lee, J. H., 1969, "Initial Propagation of Impulsively Generated Converging Cylindrical and Spherical Shock Waves," *J. of Fluid Mech.*, Vol. 37, Part 3, pp. 513–528.

Gaydon, A. G., and Hurle, I. R., 1963, *The Shock Tube in High-Temperature Chemical Physics*, Chapman and Hall, London, pp. 1 and 26.

Glass, I. I., and Chan, S. K., 1974, "Strong Planar Shock Waves Generated by Explosively-Driven Spherical Implosions," *AIAA J.*, Vol. 12, No. 3, pp. 367–374.

Glass, I. I., and Sharma, S. P., 1976, "Production of Diamond from Graphite Using Explosive-Driven Implosions," *AIAA J.*, Vol. 14, No. 3, pp. 402–404.

Lee, B. H. K., 1967, "Nonuniform Propagation of Imploding Shocks and Detonations," *AIAA J.*, Vol. 5, No. 11, pp. 1997–2003.

Perry, R. W., and Kantrowitz, A., 1951, "The Production and Stability of Converging Shock Waves," *J. of Applied Physics*, Vol. 22, No. 7, pp. 878–886.