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OPTICAL METHOD FOR DETECTING SHOCK PROPAGATION

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The ability to measure the speed of propagation of a shock is crucial in a number of applications such as in characterizing the test flow of short duration facilities, and in detonation and combustion research. A new optical technique is developed which is able to resolve the shock speed accurately. A salient feature of this device is its low cost because it uses a helium-neon laser and optically multiplexes the signals to an ultrafast photodetector.

Nomenclature

a = acoustic speed
h = enthalpy
K = Gladstone-Dale constant
l = distance between shock tube diaphragm and photodetector
M = Mach number
n = refractive index
p = pressure
t = triggering pulse duration
u = speed
w = shock speed
γ = specific heat ratio
θ = angle between light ray and the line normal to shock front
ρ = density
τ = time interval between light pulses

Subscripts
1, 2 = upstream and downstream of propagating shock front
s = shock

Introduction

Accurate measurement of the speed of a propagating shock is important in a number of applications. In short duration facilities such as shock tubes and tunnels, the shock speed in the driven tube must be known accurately for determining the state of the test gas. Similarly, in detonation and combustion research, the speed of the propagating detonation wave or flame front is an important parameter for establishing the thermodynamic state of the downstream gas via a detonation adiabatic.[1] Common methods of obtaining shock or detonation wave speeds include using an array of fast-response pressure transducers or microphones,[2] heat flux gauges[3] or ionization gauges.[3] These methods have temporal resolutions of about 1 μs. Also, the sensors are usually placed 0.1-1 m from each other. The further the sensors are, the poorer will be the measurement because the shock speed is attenuated by viscous effects.

Optical methods involving laser light sources have been used. In typical optical arrangements, pairs of light sources and detectors line the driven tube, again with separation in the 0.1-1 m range.[3] The theoretical response of optical sensors is extremely short, being in the nanosecond range. In fact, the response of the entire measurement system is limited by external electronics, namely, by the signal conditioning and data acquisition system. Although existing optical techniques possess superior temporal resolution, the large separation distance yields an inaccurate measurement due to the previously mentioned shock speed attenuation. Ideally, the array of light rays should be as close as possible to provide a "point" measurement, such as, for example, in interferometric methods.[4]

The existing optical or non-optical methods indicated above rely on miniature transducers or lasers and are expensive. In this paper, we report the development of a low-cost optical sensor which provides an accurate measurement of shock speed. In initial testing of the technique, a helium-neon laser provides the light source but high-powered light emitting diodes (LEDs) would be used later. Beams of laser light intercepted by the passage of a shock wave will be disturbed by the shock front. These distur-

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bances are then picked up by the photodetector on the receiving side of the optical setup. The signals from the disturbances are multiplexed to an ultrafast photodetector connected to an oscilloscope. The discussion of the experimental technique involved are detailed in the section following a review of the principles involved.

Shock Speed Sensing

Optical Principles

When a shock wave propagates through a compressible fluid, it induces a density change. This change in density also causes the refractive index of the fluid to change. Other than very dense gases, the relationship between the refractive index and the density of a gas is known as the Gladstone-Dale law:

$$n - 1 = K\rho, \tag{1}$$

where K, the Gladstone-Dale constant, is a function of the fluid properties and the wavelength of light. As a result of the refractive index change, a ray of light passing through the fluid will be disturbed by the shock wave. Such a disturbance can be exploited in devising a time-of-flight technique to determine the shock propagation speed. Combining Eq. (1) with Snell's law

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}, \tag{2}$$

where light is shining from upstream to downstream of the propagating shock front as shown in Fig. 1, yields

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{\frac{1}{\rho_1} + K\frac{\rho_2}{\rho_1}}{\frac{1}{\rho_1} + K}. \tag{3}$$

If the properties of a gas, assumed perfect, upstream of the shock front is known, from Eq. (3) we can see that the relation between the incident and refraction angle of a monochromatic light ray is a function of the density ratio ρ_2 / ρ_1 which in turn is a function of the shock speed M_s only. Since the value of K for air with different wavelengths of light at room temperature is around 0.00023 m^3/kg, the ratio between the angle of incidence and that of refraction will be very close to 1. This means that a light ray will not be deflected a lot even if the shock speed is as high as Mach 5. In fact, a sensitive optical setup is needed in order to detect the

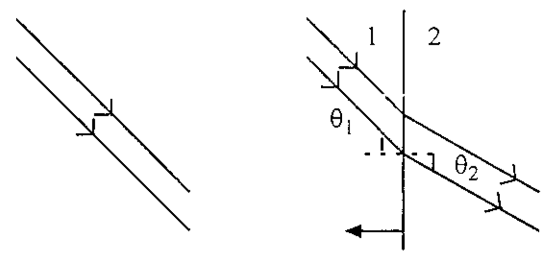

Fig. 1. Shock induced light deflection

deflection of the ray and to produce a signal. With such an optical setup, a pulse train will be detected when a shock wave, propagating past an array of light rays, disturbs each ray in sequence. Moreover, by optically multiplexing the signals, a single photodetector can detect a train of pulses. This yields a substantial cost saving. The shock speed is computed through a knowledge of the spacing of the light rays and the time delay between the pulses.

Shock Wave Propagation in Gases

The governing one-dimensional equations for a shock moving with speed w into a stagnant gas are:

$$\rho_1 w = \rho_2 (w - u_2) \tag{4}$$

$$p_1 + \rho_1 w = p_2 + \rho_2 (w - u_2)^2 \tag{5}$$

$$h_1 + \frac{w^2}{2} = h_2 + \frac{(w - u_2)^2}{2}. \tag{6}$$

In general, these equations must be solved numerically. However, if we assume a calorically perfect gas, the density ratio across a shock wave becomes a function of the pressure ratio, namely,

$$\frac{\rho_2}{\rho_1} = \frac{1 + \frac{\gamma+1}{\gamma-1}\left(\frac{p_2}{p_1}\right)}{\frac{\gamma+1}{\gamma-1} + \frac{p_2}{p_1}}. \tag{7}$$

Further, the shock speed is given by the relation

$$w = a_1 \sqrt{\frac{\gamma+1}{2\gamma}\left(\frac{p_2}{p_1} - 1\right) + 1} \tag{8}$$

from which one can obtain the shock Mach number

$$M_s = w / a. \tag{9}$$

Equations (7) and (8) indicate that, given initial conditions for determining a_1, the speed of sound in the initially stagnant gas, a knowledge of the shock speed or shock Mach number enables the pressure and density ratios to be computed. Hence, the thermo-dynamic state of the gas downstream of the shock is determined completely. Although the above discuss-ion assumes a perfect gas, in principle, thermodynamic properties of real gas flows can also be determined.[1]

Shock Speed Calculation

The time-of-flight technique that is presently implemented provides a simple means of determining the shock speed. The array of light sources separated by a distance d will produce a pulse train of period τ or frequency f, assuming no attenuation of the shock speed. The shock speed is then given by

$$w = d / \tau \qquad (10)$$
$$= fd . \qquad (11)$$

Moreover, Eq. (8), and Eq. (10) or (11) identify that an accurate determination of either w or p_2 rests critically on an accurate determination of τ or f.

Experimental Techniques

A schematic of the experimental arrangement is shown in Fig. 2. A shock wave is generated by a micro shock tube. This shock tube consists of an aluminum driver section and a glass driven section. Since one end of the glass tube is open and the other end is connected to the driver tube, the air inside the tube is at room conditions. The aluminum driver tube, on the other hand, is pressurized to 4.14 MPa. Theoretically, the shock wave generated is estimated to travel down the glass tube at Mach 2.4. The glass tube has a square section, and it has 1 mm thick walls with an outer dimension of 5 mm by 5 mm. The light source is a 5 mW He-Ne laser emitting red light at a wavelength of 632.8 nm. The laser beam is directed into the glass tube at an

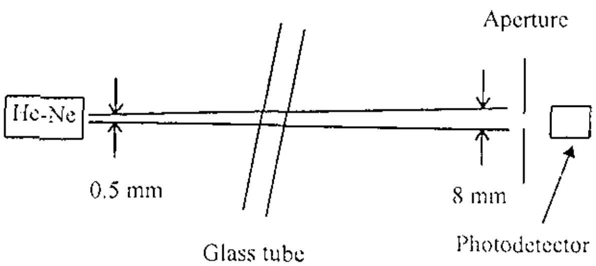

Fig. 2 Shock speed detection

angle of 2 deg from the normal to one side of the tube. The gaussian beam has a waist of 0.5 mm. At a distance of 1 m, the beam diverges to yield a waist of 8 mm. At the receiving end, a diaphragm aperture is placed in front of a high speed photodetector. The diaphragm aperture is used to control the intensity of the beam shining onto the photodetector. When a shock wave propagates down the tube, the beam becomes deflected, and the change in intensity is measured by the photodetector.

In order to measure the shock speed, a beam splitter can be used to direct two laser beams into the glass driven tube. With the same principles, the beams will be deflected in turn when the shock wave propagates down the tube. The light of the two beams are multiplexed together and this produces a pulse train at the output of the photodetector. By knowing the separation between the beams, and the time interval between the pulses, the time-of-flight technique can be used to determine the shock speed accurately.

To obtain accurate shock speed measurements, not only must the separation distance between the laser beams be kept as small as possible, but the photo-detector must have a fast response time. In fact, ultra-fast photodetectors have response times far shorter than those of pressure transducers or heat flux gauges, which provides a motivation for developing the present technique. A United Detector Technology ultrafast photodetector PIN-HS-040 with a response time of 0.8 ns is used. In addition to the fast response time, this photodetector also has the advantage of low dark currents and low capacitance. Since a high bandwidth is required for detecting the high speed of the shock wave, the detector is operated in the photoconductive mode. In this mode of operation, reverse bias of the photodetector is needed. A higher reverse bias voltage will give a lower junction capacitance that results in a higher bandwidth of operation. The photodetector is reverse biased at 45 V. An op-amp functioning as a current-to-voltage converter is designed to convert the current generated by the photodetector to measurable voltage levels. The op-amp we use is a Harris HA-5160 wideband, uncompensated op-amp. Together with the photodetector, the whole circuit is estimated to yield a 30 MHz bandwidth with good signal-to-noise ratio. With such a large bandwidth, the separation between two light rays can be further reduced to increase the accuracy of the shock speed measurement if required.

Since the shock passage is a short event, the data acquisition system must also be fast. We use a Hewlett-Packard Model 54201A digital storage oscilloscope with 50 MHz bandwidth for single-shot digital storage, sampled at 200 megasamples/s. The oscilloscope must be triggered at an appropriate moment. An in-house triggering circuit is used to create a signal to trigger the oscilloscope and to fire the shock tube. Fig. 3. shows the present configuration. The triggering circuit consists of a type 555 timer and is connected in such a way that when we press the push button, a 6 V square pulse of duration t is produced. A time delay t can easily be adjusted by changing the resistance of a potentiometer in the circuit.

The shock tube is fired by opening a valve electromagnetically and not by breaking a diaphragm. For timing purposes, an International Rectifier Series CS60 ChipSwitch solid state relay is used. The DC control input of the relay is connected to the output of the triggering circuit and the AC output is connected to the solenoid valve of the shock tube. When the push button is pressed, the valve is opened for a duration of t which initiates the run. At the same time, the trigger signal is transmitted to the external trigger input of the digital storage oscilloscope. However, we do not want the oscilloscope to start recording too early because there is a distance l between the photodetector and the "diaphragm" location. The shock wave needs to travel a distance l before it causes any disturbance which can be picked up by the photodetector. As a result, we set a time delay l / w in the oscilloscope to account for the distance traveled by the shock wave. The oscilloscope will then start recording after this time delay.

Since the HP54201A is a digital storage oscilloscope with full HP-IB programmability, a personal computer equipped with a HP-IB card can be used to download the digitized waveform from the oscilloscope. To do this, an instrument driver for the oscilloscope is written using the Driver Writer's Tool in

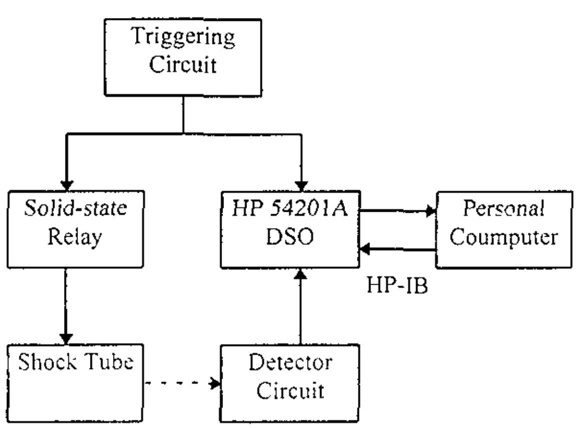

Fig. 3. Signal and data flow

the Hewlett-Packard Visual Engineering Environment (HP VEE). With the HP VEE software and the interface card, the oscilloscope can be set to operate in the single sweep storage mode using the personal computer via HP-IB. Each time the shock tube is fired, the oscilloscope digitizes the recorded signal into a waveform of 1000 points. The whole waveform is transferred to and saved in the personal computer for further manipulation.

The present system is much faster than the fastest mechanical transducers. For the highest shock speeds of practical interest, say, 8 km/s, Eq. (10) shows that an overall response of merely 2 MHz using the present arrangement is necessary. (A much higher sampling rate, still within the range of common oscilloscopes, is obviously necessary to resolve the pulse train.) If the separation between beams of laser light is decreased to provide better accuracy, a higher sampling rate is also needed, although other difficulties such as crosstalk may become significant. At present, the temporal pulse separation τ is used to compute w according to Eq. (10) whereas an averaging Fourier transform technique to obtain f and computing w according to Eq. (11) should improve accuracy.

Ongoing tests are being made to replace the He-Ne laser by a high-powered AlInGaP LED (Hewlett-Packard Model HLMA-CH00) which emits red light at a wavelength of 615 nm. If this is used, optical fibers will be needed to distribute the light and microlenses will be used to collimate the light before they reach the glass driven tube. The main technical advantages of this LED are that it has a very high luminous intensity, typically 3000 mcd at a current of 20 mA, and a narrow viewing angle of only 7 deg. The electrical power drawn by the LED is 1 W which is also more than common LEDs. The LEDs are less costly than the He-Ne laser, and can provide a more compact and rugged design.

Discussion and Conclusions

By having a rough idea of the speed of the shock wave before each measurement, the delay time in the oscilloscope can be set. By knowing the approximate speed of the shock wave and the separation between the two laser beams, the time base necessary to capture the whole event can also be set. However, in real situations, it will be more difficult to capture the signal at the right time because the estimated shock speed may not be available. The correct delay time and time base for the oscilloscope will not be easily determined.

Since the development of this shock speed measurement method is still in progress, the proof of concept, including sources of error and an estimate of sensor accuracy will be reported in the future.

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References

[1]Landau, L. D. and Lifshitz, E. M., Fluid Mechanics, Pergamon Press, Oxford, U.K., 1959, Chapter 14.

[2]Bogdanoff, D. W., Zambrana, H. A., Cavolowshy, J. A., Newfield, M. E., Cornelison, C. J. and Miller, R. J., "Reactivation and Upgrade of the NASA Ames 16 Inch Shock Tunnel; Status Report," AIAA Paper 92-2855, 1992.

[3]Sharma, S. P., Ruffin, S. M., Gillespie, W. D. and Meyer, S. A., "Nonequilibrium Vibrational Population Measurements in an Expanding Flow Using Spontaneous Raman Spectroscopy," AIAA Paper 92-2855, 1992.

[4]Merzkirch, W. and Erdmann, W., "Measurement of Shock Wave Velocity Using the Doppler Principle," Applied Physics, Vol. 4, 1974, pp. 363-366.