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Measuring Projectile Velocity using Shock Wave Pressure Sensors

Sankarsan Padhy*, and Susmita Panigrahi
Proof and Experimental Establishment, DRDO, Chandipur-756 025, India
**E-mail: spadhy55@gmail.com*

ABSTRACT

This paper deals with development of velocity measurement methodology based on projectile shock wave pressure measurements. The measurement principle is based on the fact that, whenever a projectile moves with supersonic velocity, shock wave fronts are produced along the trajectory of the projectile. Measurement configuration has been developed for measuring the shock wave pressure associated with projectile in flight, and hence, projectile velocity has been calculated. This paper covers various aspects of shock waves, generation of N Waves, feasibility study for capturing shock wave using dynamic microphone. Finally, suitable piezo-electric sensor has been selected and deployed in the trials and shock wave signature has been captured. From shock wave pressure, the projectile velocity has been computed.

Keywords: Shock wave, piezo-electric sensors, velocity measurement

1. INTRODUCTION

Shock waves are generally mechanical waves of finite amplitude and arise when matter is subjected to rapid compression. In an ideal fluid, large perturbations to fluid dynamical variables inevitably evolve to form a divergently large velocity gradient–a shock wave front. When the gradients become large, the viscous stress can no longer be ignored. In case of shock wave front, viscous stress converts the kinetic energy into thermal energy. Shock wave estimation and detection details are presented by Sadler[1], *et al*. Propagation details of shock waves through atmosphere are covered in Henry[2], *et al*. Modelling of shock wave force is presented by Acharya & Naik[3]. Applications of piezo-electric sensors as hydrophone are presented by Kharat[4], *et al*. Supersonic projectile identification using acoustic signature are given in Loucks[5], *et al*.

This paper presents details of shock wave characteristics, generation of N waves, and feasibility of capturing shock wave phenomena using dynamic microphones and its limitation, selection of suitable sensor for capturing shock wave, deployment of sensor in dynamic firing conditions and analysis of measured results.

2. SHOCK WAVE CHARACTERISTICS

Compared to acoustic waves, a shock waves is characterised by some of its unusual properties like pressure-dependent supersonic velocity of propagation, formation of a steep wave front with abrupt changes in all thermodynamic quantities, for non-planer shock waves, a strong reduction of propagation velocity with increasing distance from the centre of the origin and non-linear reflection and interaction properties.

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2.1 Thermodynamic Quantities in Upstream and Downstream Flows

For an adiabatic shock, the three requirements of mass, momentum, and energy conservation, collectively known as Rankine-Hugoniot relations, enable to create the downstream flows and their thermodynamic variables to their upstream counterparts. Taking the reference frame in which the shock front is at rest and assuming that upstream flow is normally incident upon shock front, Rankine-Hugoniot relations take the form

$$\rho_2 \upsilon_2 = \rho_1 \upsilon_1 = j \quad (1)$$

$$p_2 + \rho_2 \upsilon_2^2 = p_1 + \rho_1 \upsilon_1^2 \quad (2)$$

$$h_2 + \tfrac{1}{2}\upsilon_2^2 = h_1 + \tfrac{1}{2}\upsilon_1^2 \quad (3)$$

where j is the mass flux, which is determined by upstream flow. ρ, υ, p represent density, velocity, and pressure of the flow and subscripts 1, 2 are used to denote quantities measured ahead and behind the shock, respectively. Taking the case of projectile moving with supersonic speed, conservation of mass, momentum, and energy should be considered. In case of projectile, time to pass through the shock is so short that the flow can be regarded as stationary. In a stationary flow, mass flux is always constant as there is no new way to create new mass. In case of energy, there are three ways that a change in energy flux could occur. First, the energy may be added to the flow by chemical or nuclear reaction that occurs in shock front. Secondly, if gas is heated to high temperature, it will lose energy. Thirdly, energy may be conducted by super thermal particles so as to preheat the incoming gas. In case of shock waves due to projectile, these three things don't occur, and hence, energy flux is constant. Hence in case of a projectile, the momentum part is important and should be considered.

Due to supersonic flow, air particles get compressed, hence

$\rho_2 >> \rho_1$, and $\upsilon_2 << \upsilon_1$ (4)

as from Eqn. (1), product of $\rho\ \upsilon$ is constant. Equation (2) can be written as

$p_1 + (\rho_1\ \upsilon_1).\ \upsilon_1 = p_2 + (\rho_2\ \upsilon_2).\ \upsilon_2$ (5)

From Eqns (4) and (5), it is clear that $p_2 >> p_1$ and in our measurement setup, this change in pressure is sensed.

2.2 Formation of Mach Cone Due to Supersonic Projectile

The shock waves formed by a supersonically moving body are complex close to the body and depend on its detailed shape, Reynold's number, etc. However far from the body, the leading shock has the form of Mach cone, as shown in Fig. 1.

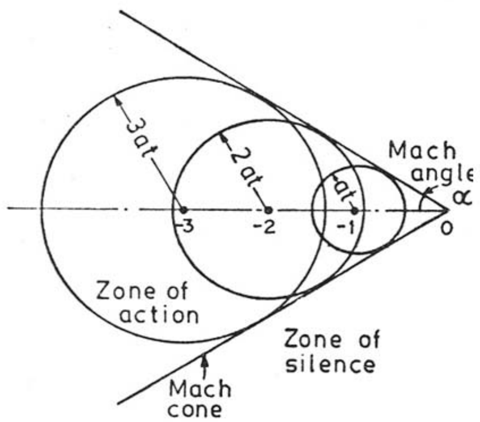

Figure 1. Construction of Mach cone formed by a supersonic projectile.

In the above figure, the cone angle is $\alpha = sin^{-1}\ (1/\ M)$, where $M = \upsilon_p/a$ is the Mach no. of the projectile. υ_p is the projectile velocity, and a is the speed of sound in the medium. The shock is the boundary between that fluid which is sound-based casual contact with the projectile and that which is not. This boundary is mapped out by (conceptual) sound waves that propagate into the fluid from the projectile at the ambient sound speed a. When the projectile is at the indicated position, the envelop of these circles is the shock front and it has the shape of Mach cone. Usually there will be two such shock cones, one will be attached to the projectile bow shock and the other will be formed out of the complex shock structure in its tail region. The pressure must jump twice, one across each of these shocks and will therefore form an N wave which propagates away from the projectile.

Let Δp denote the pressure jump at the start of the N wave and p_{at} denote the ambient atmospheric pressure, we have from Sadler[1], *et al.*

$$\Delta p/p_{at} = (0.53\ d)(M^2-1)^{1/8}/(x^{3/4}\ l^{1/4}) \quad (6)$$

where d = Diameter of the Projectile
l = Length of the Projectile
x = Perpendicular distance from the projectile trajectory to the sensor
M = Mach number

3. FEASIBILITY STUDY WITH DYNAMIC MICROPHONE

Initially feasibility experiment was conducted to sense shock wave pressure signature using standard dynamic microphone. Other instruments used were Hand-held Digital Storage Oscilloscope (Make Fluke), low-noise cables. The microphone was placed directly under the trajectory and the output was recorded in the oscilloscope using cables. Sensitivity of the microphone used was 2 mv/Pa.

Figure 2 shows shock wave signature pattern of diameter 30 mm and length 127 mm projectile. The pattern shows the actual shape but the recorded value is different from that expected. This would be due to the saturation of the standard microphone. From this feasibility experiment, it was concluded that the shock wave signature exists whenever a projectile moves at supersonic speed. Then the next goal was to identify a suitable shock wave pressure sensor and capture and measure the shock wave pressure.

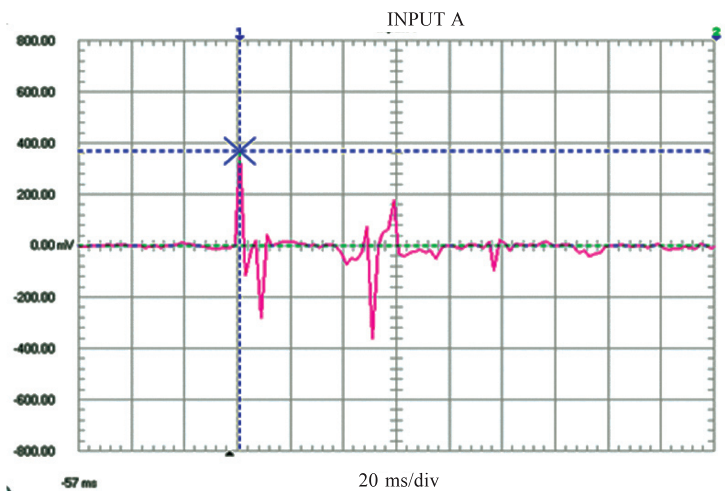

Figure 2. Shockwave signature captured using dynamic microphone.

4. MEASUREMENT RESULTS WITH SHOCK WAVE PRESSURE SENSOR

The measurement was carried out for a projectile of length 396 mm and dia. 28 mm. The shock wave sensor is a piezo-electric sensor and its details are given below: dynamic range 0.001 psi to 8.3 psi, sensitivity 300 mv/psi, resolution 0.0001 psi, resonant frequency 60 KHz, rise time 9 µs. The measurement layout and results are given in Figs 3 and 4, respectively.

The sensor is placed about 1.05 m below the trajectory as shown[6] in Fig 3. The output of the sensor is connected to

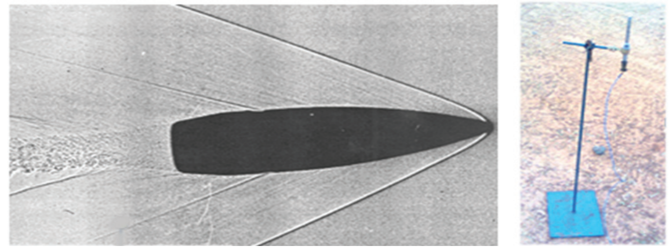

Figure 3. Shockwave measurement layout.

the data acquisition system using special low-noise cable. Using values of length, diameter of the projectile, and distance between trajectory and sensor in Eqn. (6), velocity of the projectile is obtained as shown in Fig. 5.

In Fig. 4, as expected the *N* wave has been obtained and two peaks are also observed. Behind the first shock, the density and pressure drop off gradually by more than the first shock's compression. As a result, the fluid flowing into the second shock has a lower pressure.

From Fig. 4, the value of shock wave pressure was 1.59 psi and from Fig. 5, the Mach number was 4.53. Speed of sound was 349.8 m/s for ambient temperature of 30 ^{o}C, hence the projectile velocity corresponding to that of shock wave pressure was 1584.59 m/s which is in the expected range.

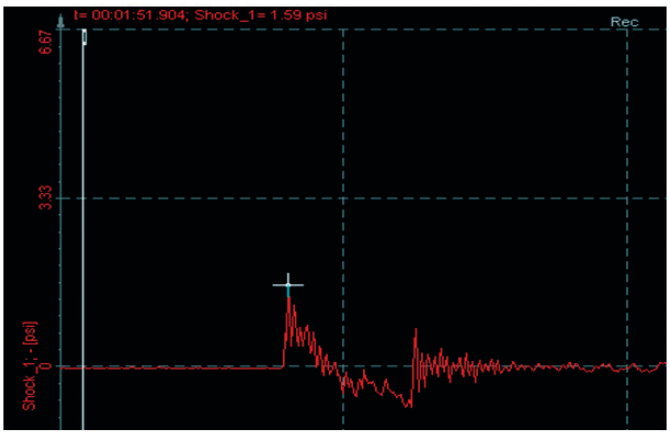

Figure 4. Measured results.

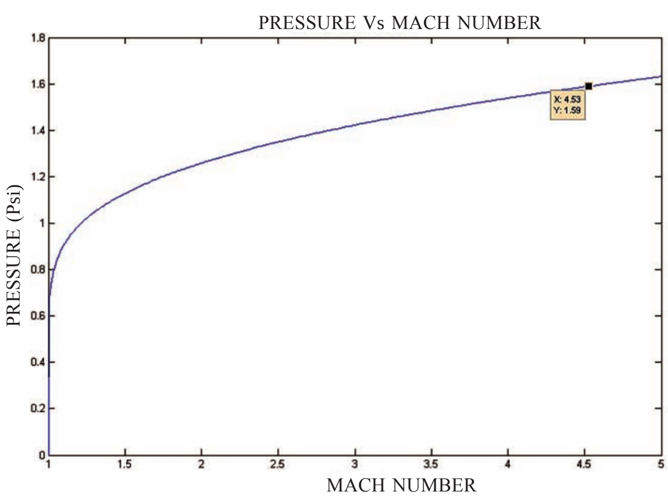

Figure 5. Shock wave pressure versus Mach number plot.

5. CONCLUSION

In this paper, a velocity measurement methodology based on projectile shock wave pressure measurements has been developed. Measurement configuration has been developed for measuring/observing the shock wave pressure associated with projectile in flight, and hence, projectile velocity has been calculated. Using suitable piezo-electric sensor, shock wave signature has been captured, and from shock wave pressure, the projectile velocity has been computed. This is one of the inexpensive methods for measuring velocity at any given point along the trajectory. Using an array of sensors, portions of trajectory can also be computed with suitable measurement methodology.

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CONTRIBUTORS

Mr S. Padhy is presently working as a scientist in DRDO, PXE, Chandipur. He completed his MTech in Radio Frequency Design Technology from Indian Institute of Technology (IIT) Delhi. He is a life member of IETE and Society of EMC engineers. His area of interest includes radar cross section (RCS) prediction and measurement of different targets, RCS reduction by applying radar absorbing materials, ballistic instrumentation and radar signal processing. He has received silicon and titanium medals from DRDO in 2004 and 2010, respectively. He was awarded Laboratory Scientist of the Year Award in 2012.

Ms Susmita Panigrahi obtained her diploma in Electronics & Telecommunication Engineering from Women's Polytechnic, Bhubaneswar in 1992. She joined PXE, Chandipur in 1994. She has more than 20 years of experience in the field of Doppler radars, acoustics and piezo-electric based instrumentation setups.