

Understanding Ignition over Pressure During Start Up of Typical Scaled Down Solid Rocket Motors

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Abstract

The Ignition Over Pressure (IOP) is an unsteady pressure wave generated by the ignition of solid rocket motor during launch vehicle lift-off. This wave behaves as a blast or a shock wave followed by a low frequency excitation characterized up to 40 Hz, would cause severe damage to the launch vehicle, its structures and surroundings. However, in case of huge propulsion system, having two solid rocket motors as its boosters, due to the skew in their ignition, during lift-off, the phase difference of the wave from one side of the vehicle to the other could cause a severe moment, which is detrimental to the vehicle. The present paper deals with the occurrence of such blast waves during the testing of various scaled down solid rocket motors. Also, an attempt has been made experimentally to characterize and understand the propagation of the IOP wave causing unsteady pressure oscillations and transient pressure rise in the vicinity of a solid rocket motor. The spectral and directional characteristics of the IOP wave are also highlighted. Typical scaled-down solid rocket motors with and without nozzle shutters have been tested in horizontal firing configuration and the results are compared to study their effect. The resulting shock wave propagation has axial downstream as well as angular directivities. The pressure rise rate in the chamber is found to be directly correlated to the over pressure measured at various locations at the downstream of the nozzle.

Keywords: Directionality, Ignition Over Pressure, Ignition Transient, Shock Wave Propagation, Solid Rocket Motor

1. Introduction

During the ignition transient of solid rocket motors, unsteady pressure waves are generated in the combustion chamber. These pressure waves emanate through the conventional Convergent-Divergent (C-D) nozzle and propagate outward and interact with the launch vehicle and its surroundings. This will result in spatial and time dependent pressure disturbances. The pressure disturbance (ΔP) could be defined as,

$$\Delta P(x, y, z, t) = P(x, y, z, t) - P_\alpha$$

where, $P(x, y, z, t)$ is the transient pressure at any location

(x, y, z) and time (t), and P_α is the atmospheric pressure. This pressure disturbance is termed as the IOP with its shock front propagates to a large distance initially at supersonic speeds but gradually reduces to subsonic speeds and also in magnitude.

A typical IOP signal measured during the static testing of typical scale down solid rocket launch motor is shown in Figure 1. It gives the time versus Amplitude (IOP) and as per the definition of IOP wave in open literature, the negative half sine wave is considered for frequency evaluation (not through FFT means).

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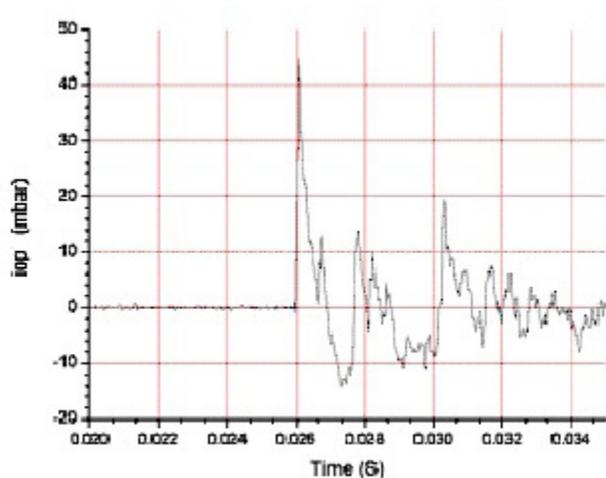


Figure 1. Typical Ignition Over Pressure (IOP) Signature during the Solid Rocket Motor Testing.

The time taken for the half sine wave multiplied by two and inverse of the time is taken as frequency content of the IOP wave. It is evident that the pressure fluctuation of IOP corresponds to a low frequency large amplitude pulse. The frequency may typically lie in the range of 20-40 Hz. However, for the scaled solid rocket motors, the frequency gets shifted as per the Strouhal number criterion ($Str\ No = f De/U_e$; f is the source frequency, De is the nozzle exit diameter and U_e is the nozzle exit velocity) as evident in the literature. The exact cause for the existence of such a fluctuation has been the subject of interest to the launch vehicle community and mitigating efforts are being critically taken up. In the present paper, an effort has been made to throw some light in order to bring in some clarity related to the IOP behaviour and its typical signatures and also its propagation characteristics with the help of experiments conducted using scaled down solid rocket motors. Also, this paper shows the effect of pressure rise rate on IOP characteristics. The main motivation for the understanding the IOP signature is as follows. Depending upon the maximum over pressure, the disturbance wave may induce unsteady pressure fluctuations at low frequencies on the vehicle structure and more significantly injure the payloads in the encapsulated assembly of the launch vehicle. Hence, determination of the maximum IOP is further more necessary in order to protect the payload area and launch vehicle structure and its vicinity.

The first analytical model for Ignition Over Pressure has been devised by Broadwell and Tsu¹ using one dimensional linear wave theory using gas dynamic principles.

It requires two empirical constants; one accounts for combustion in the exhaust gases and the other for momentum loss. NASA observed a very low frequency (approximately 5 Hz) ignition overpressure wave during the lift-off of Space Transportation System-1 (STS-1). The magnitude of ignition overpressure wave has been suppressed with suitable mitigating measures such as water injection during the STS-2 launch². NASA has employed a "FIX", i.e., a thin balloon with water on the jet deflector duct. During lift-off, the unsteady pressure wave travels at supersonic speed at initial period and would impinge on the thin balloon. Water gushes out instantaneously and absorbs the IOP energy and there by propagation is restricted. Lai and Laspesa³ conducted experiments for full scale and sub-scale models. It has been observed that full scale models have been characterized by low frequency overpressure waves whereas subscale models have been characterized by high frequency pressure oscillations. Canabal and Frendi⁴ developed an inviscid flow model for Silo and Minuteman launchers using the finite element method (2002). Their numerical results agree well with experimental data. Canabal and Frendi⁵ studied the ignition overpressure suppression using water injection (2004). The study demonstrated that ignition overpressure is strongly affected by the cooling of the plume and the extent of obstruction which restricts the expansion of the plume. Dougherty et al.⁶ conducted tests for 6.4% model of STS-1 (Space Transportation System-1) to suppress the IOP levels using water injection. Model and full scale launch data were compared and trends were studied for each type of IOP suppression technique used. Walsh and Hart⁷ conducted experiments on a full scale Titan vehicle. Sub-scale model (Titan III) tests were also evaluated on a 7.5% scale model by NASA. The resultant correlation of the sub-scale with full-scale data produces a scaling parameter. Varnier⁸ conducted experiments on small solid propellant rocket engines in order to examine the ignition phase (2002). Downstream from the nozzle, the recorded ignition overpressure appears as a sudden shock front, which is caused by the breaking of the nozzle shutter at high pressure. This overpressure seems to be related to this breaking pressure, but also correlated with the apparent size and brightness of the gaseous "fire ball" which characterizes the unsteady state of the jet. Therefore, it has been assumed that the re-ignition in air of some combustion products constitutes an amplification factor of the shock front. Secondary shock fronts may

randomly appear during the second chamber pressure increase, which come from the powder grain combustion (initial pressure increase is principally due to the igniter charge). Varnier⁹ conducted experiments for small scale motors and medium scale motors using “kulite” type sensors (2005). Motors were tested with and without propellant grain. During the ignition transient, breaking of the nozzle shutter of these motors gives rise to pressure peaks due to shocks, in the recorded signal of field pressure sensors. Nozzle shutter breaking is followed by the main chamber pressure rise and flow oscillations. The shock amplitude appears more or less correlated with the breaking of the nozzle shutter and with the pyrotechnic load of the igniter, but it does not depend on the slope of the chamber pressure rise. This shock wave has a maximum directivity in the axial downstream direction. It has been concluded that the origin of the blast wave is the developed gaseous cloud outside the nozzle. Blast waves occur for medium scale motors, when the chamber pressure rise rate is more than of 0.9 bar/ms. Various studies have been conducted experimentally and also numerically by ONERA, France and NASA, USA and ISRO, India¹⁰⁻¹⁶. In this paper, an experimental study has been initiated to understand the IOP effect produced by typical scaled down solid rocket motors during its transient phase. The resulting IOP field and its directionality, propagation characteristics has been studied extensively for various cases and has been verified with reference to the open literature pertaining to launch vehicle lift-off in particular and its detrimental effect on the launch vehicle and its surroundings.

2. Experimental Set-up and Instrumentation Details

In the present study, an attempt has been made experimentally, to understand the propagation of the blast wave causing unsteady pressure oscillations. Typical scaled-down solid rocket motors of different sizes, with and without nozzle shutters have been tested in horizontal firing configuration. Different types of solid motors have been tested, viz., small size motors with nozzle shutter, small size motor without nozzle shutter and a medium size motor with nozzle shutter. Figure 2 shows the test facility for the measurement of IOP during the static testing of scaled solid rocket motors.

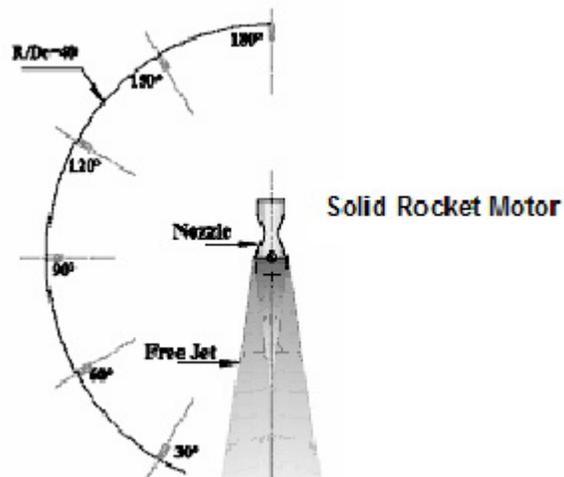


Figure 2. Schematic of the measurement of IOP during the static testing of scaled down solid rocket motors.

The supersonic jet is directed outside and “Kulite” type piezo resistive pressure sensors of 0.18” size with 5 psi and 15 psi range have been used to capture the pressure oscillations in the far field. One pressure sensor is kept inside the combustion chamber to record the chamber pressure. The nozzle center plane is kept at 1.35 m over the concrete ground. The data acquisition rate is 100 Ksamples/s/channel and the accuracy of the Kulite type unsteady pressure sensors is being + 0.4% of full scale for both 350 milli bar & 1035 millibar range sensors used. The position of the sensors is also shown in Figure 2. The ballistic properties of the small size motor with nozzle shutter, small size motor without nozzle shutter and medium size motor with nozzle shutter used for the present study are listed in the following Table 1.

Table 1. Thermo physical properties of typical scaled down Solid Rocket Motor

Chamber stagnation pressure (P_0)	42 bar
Chamber stagnation Temperature (T_0)	3415 K
Specific heat ratio ($\gamma = C_p/C_v$)	1.2
Nozzle exit diameter (D_e)	144 mm
Nozzle throat diameter (D_t)	62 mm
Nozzle Area ratio (A_e/A_t)	5.26
Nozzle Exit area to the Throat area	
Jet exhaust mach number (M_e)	2.81
Propellant mass flow rate (Averaged)	8 Kg/s

3. Result and Discussion

3.1 Small Size Motors with Nozzle Shutter

Figure 4 shows the signals recorded by the main chamber pressure sensor in combustion chamber and overpressure amplitude of the shock front recorded in the free field kept in front of the nozzle at a radial distance of 2.8m. In the plot, the rise of the chamber pressure is suddenly interrupted by the nozzle shutter breaking approximately in the range of 10 to 15 bar. After shutter breaking, chamber pressure rise due to propellant grain burning is quite smooth.

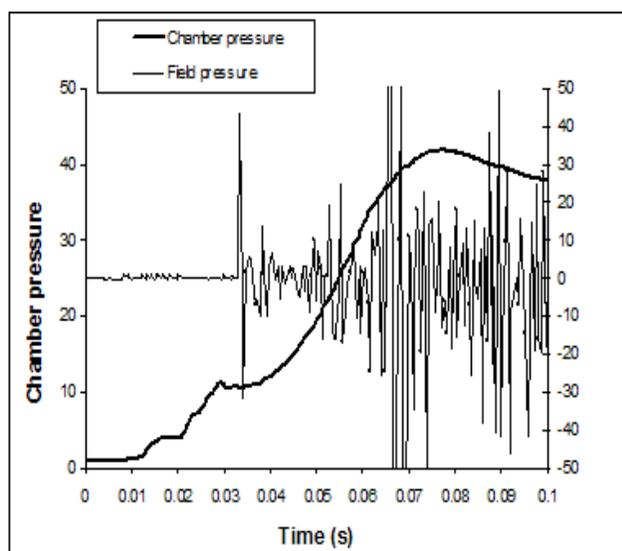


Figure 3. Measured signals from chamber pressure sensor & field pressure sensor from the nozzle exit of small size motor with nozzle shutter.

(Location : at 300 & 18De Shock front velocity =762 m/s, Shock front Mach number = 2.1; Shock front amplitude = 43 mbar, Nozzle shutter breaking pressure = 11 bar, Maximum chamber pressure rise rate = 1.76 bar / milli s)

During the ignition transient, breaking of the nozzle shutter of these motors gives rise to pressure peaks with the associated shocks, in the recorded signals of field pressure sensors and they are followed by some flow oscillations also. The shock wave travels at supersonic speed in the down stream direction of the nozzle. The maximum chamber pressure rise rates of the motors are in the range of 0.28 to 11.52 bar/millis. Even for these higher range of pressure rise rates, the scaled down rocket motors do not exhibit any distinct low frequency blast wave

signatures. This particular effect was observed by Varnier⁹. This phenomenon is quite likely in the case of smaller size of motors, where, the pressure fluctuations during the ignition period could not be distinguished from the oscillations arising from nozzle shutter breaking and the pressure oscillations arising due to flow.

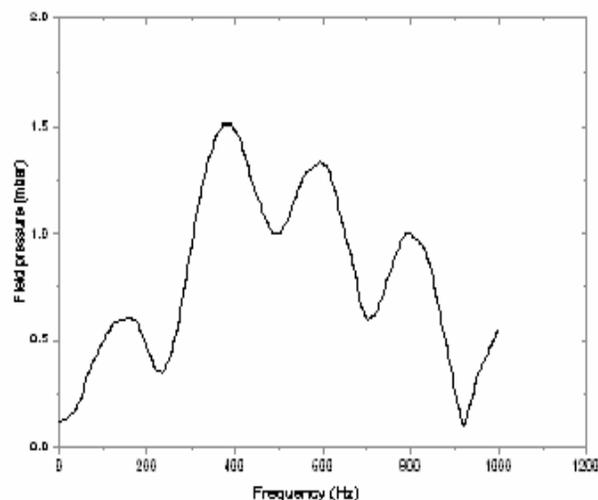


Figure 4. Fast Fourier Spectrum (FFT) of recorded signal of IOP at 300& 18De.

Also the, amplitudes of these oscillations are small (of the order of a few mbar) in the near field and they are still smaller in the far field due to its decay characteristics. The frequency components are also typically in the range of few hundred Hz. From the Figure 4, it is evident that smaller motors do not exhibit any distinct low frequency blast wave preceding the flow. Similar kind of experiments have been conducted by Lai and Laspesa³ for STS-1 and 6.4% of STS-1 subscale model. Very low frequency blast wave region (approx. 5 Hz) was observed for STS-1 and fluctuations were observed in the frequency range of few hundreds Hz for 6.4% subscale model of STS-1.

To understand the IOP phenomena further, motors have been tested by keeping four field pressure sensors at same radial distance from the nozzle exit and at different angles. Figure 5 shows the amplitude and velocity of the shock front. The amplitude of the shock decreases when the angle from the nozzle axis increases. From this, it can be inferred that the shock wave coming out of the motor shows clear angular directivity. However, the shock wave reaches all the sensors at the same time, which indicates that the shock wave is spreading spherically in the down-stream direction.

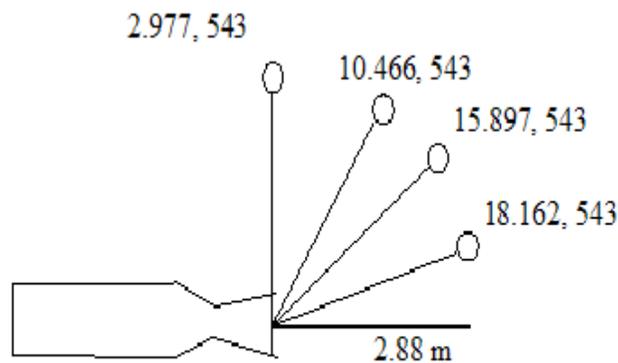


Figure 5. Amplitude and velocity of the shock front at various Angles for a Radial distance of 2.88 m. (IOP in milli bar, Velocity Amplitude in m/s at that location).

But, the strength of the shock front along its curvature is not the same. The higher strength prevails at the centre of the shock front and it decreases both sides of its curvature. This trend also confirmed from the firing of small size motors by Varnier⁸.

3.2 Small Size Motor without Nozzle Shutter

A small size motor without nozzle shutter has been tested experimentally to understand the effect of nozzle shutter on ignition overpressure. This motor has shown chamber pressure rise due to igniter mass burning, a long ignition delay up to 0.8 seconds (not shown in Figure) and it is followed by the main chamber pressure rise as shown in Figure 6. The maximum chamber pressure rise rate of this motor is 13.3 bar/ms. These signals are also not showing any distinct blast wave peak even for high chamber pressure rise rate. The pressure fluctuations arise due to the igniter charge and the flow oscillations (after motor exhaust emerges out of the nozzle) are in the range of few hundred Hz. The analysis shows dominant frequency is in the range of 100-200 Hz. From this, it can be concluded that small motors can be characterized by high frequency fluctuations as compared to full size motors which show a low frequency blast wave as discussed above. Similar trends were also observed by various authors as seen in open literature^{1,3,8,9} with their experiments on full size and small size motors.

3.3 Medium Size Motor with Nozzle Shutter

One medium size motor has been tested with nozzle shutter as a part of experimental programme.

The overpressure amplitude recorded by the field pressure sensor is shown in Figure 7 for the case 90° & 1.5De radius from the nozzle exit. This signal recorded by the pressure sensor shows the occurrence of a shock at around $t = 0.16$ s due to igniter mass flow followed by shutter breaking. This is followed by another shock wave between $t = 0.16$ s to $t = 0.19$ s which has an amplitude and duration considerably larger than shutter breaking shock wave. Hence it can be termed as a “blast wave”. The dominant frequency of these fluctuations is seen to be significantly lower (20 Hz) as compared to the cases of the smaller motors. The medium size motor has a tendency to form a blast wave, but still it is not a pressure oscillation of large magnitude (Figure 8). The larger size motors, on the other hand, known to exhibit low frequency blast waves which precedes the flow.

3.4 Full Size Rocket Motor

Experimental studies have also been carried out for the full size motor for a location of 23Deg angle for various radii of 10De, 18De & 22De. From the studies, it has been inferred that hot gaseous products first occupy the combustion chamber volume and they push out the stagnant air inside the combustion chamber (it was noticed in CFD results also and it is not shown here). This transient pushing action generates a blast wave which spreads spherically outside the nozzle as shown in the filed pressure measurements presented in Figure 9. The transient pressure measurements in this figure clearly illustrate that most of the energy of the blast wave is radiated in the downstream direction of the nozzle (Figure 9) for the radial distance of 10De case with an IOP magnitude of 45 millibar at T+ 35 milli seconds. The blast wave decays as it propagates downstream, i.e., for the 18De and 22De, the magnitude were measured around 15 milli bar at T+410 milli seconds and 420 milli seconds respectively. It is clear that ignition overpressure wave is followed by the gaseous flow and the IOP wave emerges out of the nozzle much before the flow, i.e. before the nozzle attains full flow condition. Based on the analysis of entire data obtained, it is evident that the blast wave has a characteristic frequency of ~50 Hz approximately, which is also similar to the experimental results of the Lai and Laspesa³ for STS-1³.

4. Concluding Remarks

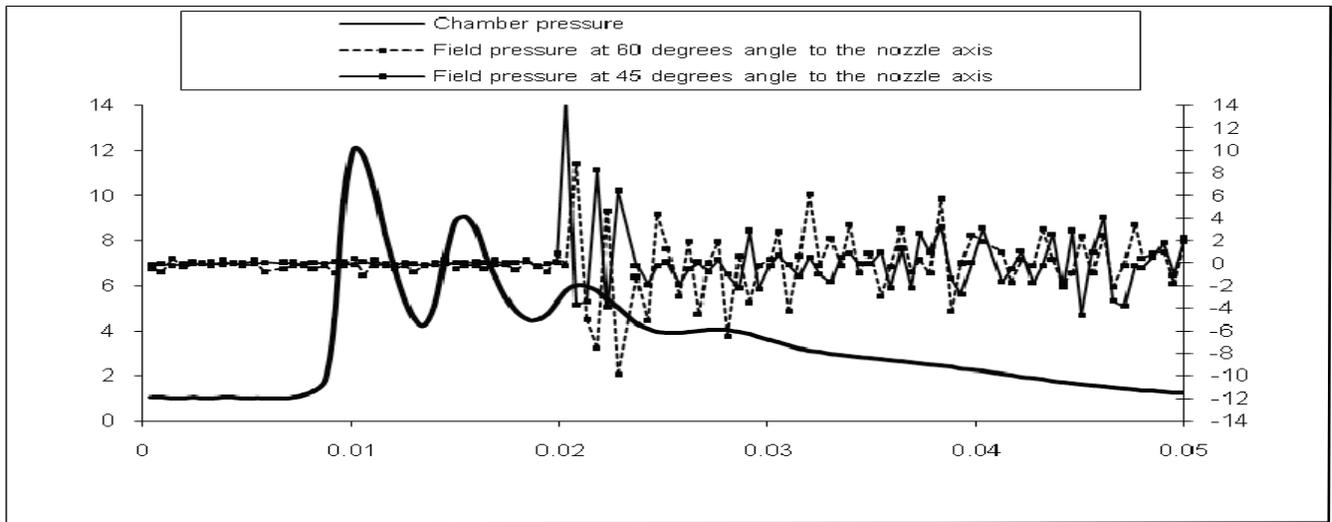


Figure 6. Recorded signals from chamber pressure sensor & field pressure sensor (IOP) from the nozzle exit of small size motor without nozzle shutter. (Location : 60° & 45°).

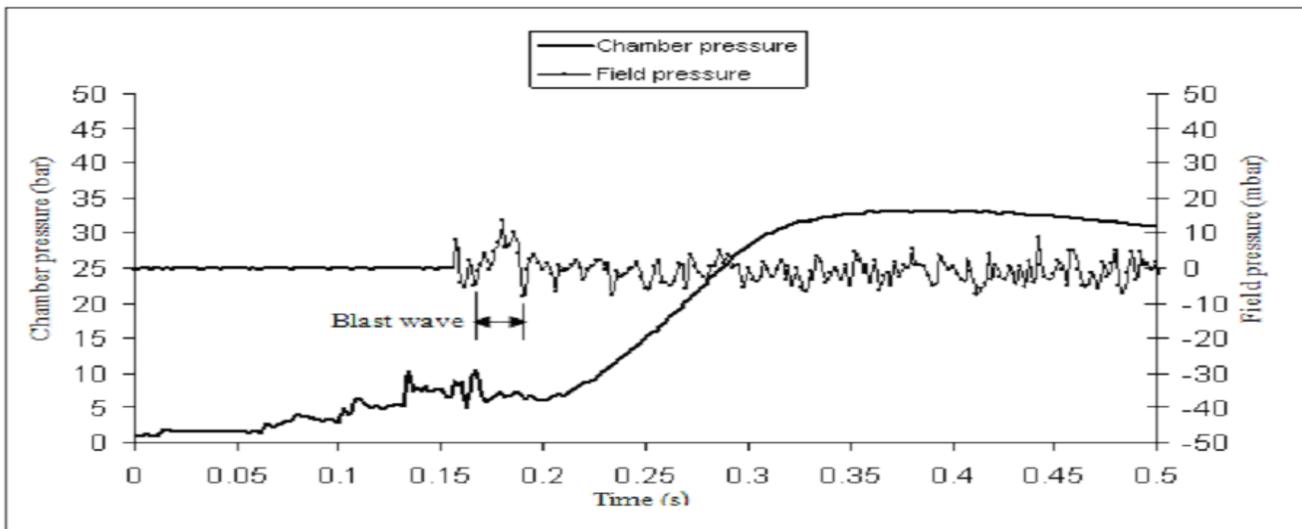


Figure 7. Measured signals from chamber pressure sensor & field pressure sensor (IOP) from the nozzle exit of medium size motor (Location : 900 & 1.5De radius from the nozzle exit of medium size motor; Chamber pressure rise rate = 2.5 bar/millisecond, Velocity = 892 m/s, Mach number = 2.66; Nozzle shutter breaking pressure = 10.25 bar & Shock front amplitude = 13 milli bar).

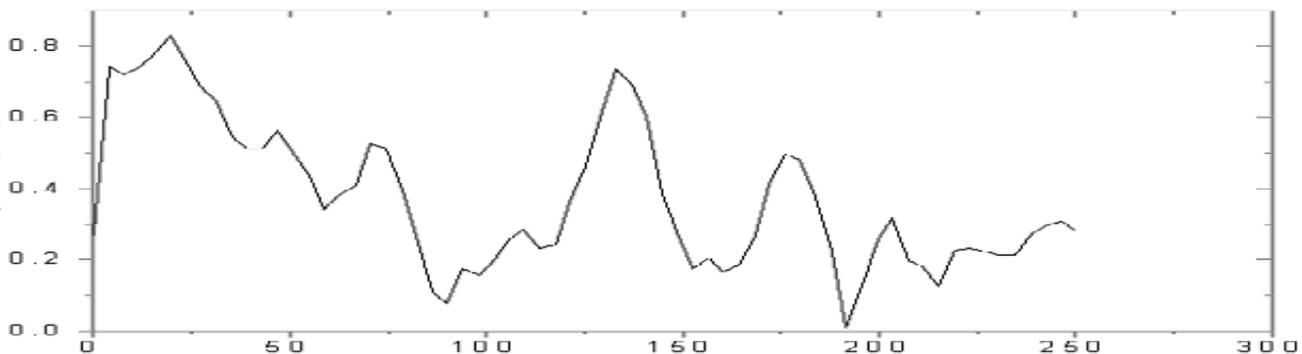


Figure 8. Spectra for field pressure sensor at 900 & 1.5De radius from the nozzle exit of medium size motor.

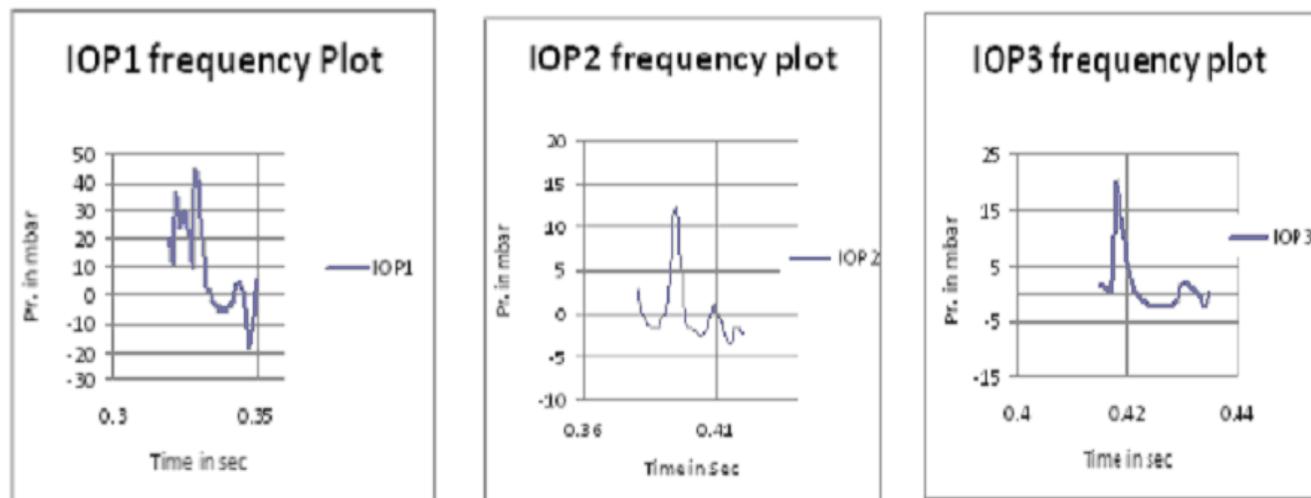


Figure 9. Typical IOP signatures measured for the large Solid Rocket Motor case for various transient periods of 350milli seconds, 410milli seconds & 420milli seconds ; Location = 23 deg & 10De,18De & 22De).

Experimental studies have been conducted to understand and characterize the Ignition Over Pressure (IOP) of the solid rocket motors during the ignition transient. Small, medium and full scale motors have been investigated with and without nozzle shutters in order to understand the IOP signatures and its low frequency content. Small size motors do not exhibit distinctly any low frequency and high amplitude distinct blast wave. However, the frequency of the wave is in the range of few hundred Hz, due to the Strouhal number shift especially for the small rocket motors. Testing of various small motors without and with nozzle shutter indicate that the IOP has definite directivity, which is brought out by the simultaneous IOP measurements at a typical radial distance and at various angles in front of the nozzle. The medium size motor has tendency to show a low frequency blast wave with very small amplitude compared to the full size motor. The experimental investigation of full size motor show the spherical nature of the blast wave and the strength of the shock wave varies along its curvature. The pressure rise rate plays a very major role in the IOP magnitude and the shape of the spherical wave. As for the spectral content is concerned, the frequency of the IOP wave for the full scale motor is in the range of 50 Hz, as indicated in open literature measured for the STS vehicle. This study has made an effort to understand the IOP characteristics of solid rocket motors of various sizes, which is very critical for the launch vehicle lift-off loads assessment and its mitigating mechanisms, possibly achieved through water injection.

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