CHAPTER – 6

EXPERIMENTAL RESULTS & DISCUSSION FOR
HORIZONTAL TESTING OF SOLID ROCKET MOTOR

6.0 INTRODUCTION

This chapter describes the experimental results obtained during the ignition overpressure simulation during the start-up of solid rocket motors for various configurations. During the development phase of any launch vehicle, it is necessary to evaluate its performance under all environment conditions (experienced during the flight). During liftoff phase of the launch vehicle, it is expected that severe overpressure environment will be generated by solid rocket motors. This overpressure may cause damage to launch vehicle structure and electronic packages. In general, solid rocket motor create an Overpressure wave during ignition caused by the accelerating gas particles, displacing the air contained in the launch pad and also by the burning of fuel rich gases, this wave behaves as a blast or shock wave characterized by a positive triangular shaped first pulse and negative half sine wave second pulse. The pulse travels upwards towards the launch vehicle and payload. It has the potential to overload the individual elements or excite the overall vehicle dynamics.

6.1 IGNITION OVERPRESSURE DATA FOR THE SMALL SCALE SOLID ROCKET MOTORS IN HORIZONTAL CONFIGURATION

Free field IOP measurement carried out at various locations in the nozzle centre plane. In tests typical locations were selected keeping nozzle centre line and nozzle height from floor constant as in Fig. 4.2. the measurement locations, such as, A1(30°) to A12 (120°) are chosen such that the angles are 30, 40, 50, 60, 70, 80, 90, 100,110,120,130 &140 degrees respectively at Radius(R) of 20De, 25De, 30De ,35De ,40De ,45De ,50De, where De is nozzle exit diameter (i.e.144mm). The results presented here are pertinent to the ignition overpressure (IOP) generated by the typical solid rocket motor (i.e. Agni motor) and its motor pressure-time graph is shown in Fig.6.1 and IOP data along with the motor pressure data is plotted for a typical case of R/De=20 for all the measurement angles (i.e. from 30deg. to 140deg.).
Similar way measurements have been made for other R/De at all the measurement locations.

Fig. 6.1 Typical Pressure –Time history of a small scale solid rocket motor

Fig. 6.2 IOP signature and motor pressure time at R/De=20, angle=30deg

In this experimental series of tests, it is observed that the IOP decreases with respect to angle as shown in Fig.6.2. Here, only IOP peak values are considered, as
shown in earlier figures. The amplitude of the IOP wave decreases with respect to R/De across the nozzle exit as shown in Fig.6.3.

**Fig 6.3 IOP amplitude decay characteristics for various angles in different R/De**

In Fig. 6.3, it noticed that amplitude of IOP is relatively more in nozzle upstream region when compared to downstream. That is the IOP wave pressure intensity is higher in lower R/De and lower propagation angles compared to the higher R/De and higher theta. This IOP behavior is clearly brought out in the subsequent sections. From the Fig.6.4, it is observed that, the IOP propagation velocity from nozzle exit decays as the distance increases in terms of R/De.

**Fig. 6.4 IOP propagation velocity (m/s) Decay characteristics with respect to distance (R/De)**
6.1.1 IOP AMPLITUDE AT VARIOUS DISTANCE (R/DE) WITH PROPAGATION ANGLES (THETA)

The variation in IOP amplitude with propagation angle (Theta = 30 to 140 Degrees) at different normalized distances (R/De = 25 to 50) a typical case with R/De=25 is shown in Fig.6.5 and the effect of distance from the nozzle exit on the IOP amplitude is shown in Fig. 6.6. The decay in the IOP amplitude has been fit with an exponential curve and it clearly indicates that there is an exponential decay in the IOP amplitudes (millibar) with respect to the propagation angles. These results also indicate that the IOP wave is highly directional in nature in the energy front. The IOP characteristics show that the pressure decay of IOP amplitude is varying with Y = 1/x^n. For the cases of R/De 25 and R/De 30, the best fit line has graced through all the data points. The value of n in Y = 1/x^n is varying between 1 to 1.73.

![Graph showing variation of IOP amplitude (mbar) for various Theta at R/De = 25](image1)

**Fig. 6.5** Variation of IOP amplitude (mbar) for various Theta at R/De = 25

![Graph showing IOP amplitude decay characteristics for various angles in different R/De](image2)

**Fig. 6.6** IOP amplitude decay characteristics for various angles in different R/De
6.1.2 IOP AMPLITUDE VARIATION AT VARIOUS THETA FOR R/De

The variation of the IOP amplitudes with normalized distance (R/De) at various propagation angles is shown in Figure 6.7. These results indicate that IOP wave front pressure intensity decays exponentially with varying propagation angles for a given distance R/De for all cases. However, it is observed that the pressure intensity of the wave front varies non-linearly with R/De, which is due to the compression-expansion behavior of the supersonic shock front of IOP wave. This phenomenon is also clearly brought out by CFD computations shown in earlier chapter, where at a time instant (before IOP wave is impinging on the bottom flat plate), the IOP intensity seems to vary non linearly with R/De for a given propagation angle. The experimental results corroborate such IOP characteristics for a solid rocket motor for a non-impinging case.

![IOP Amplitude at various Angles](image)

Fig. 6.7 Variation of IOP amplitude (mbar) for various R/De at all Theta

The pressure front of IOP waves varies widely with respect to the propagation angle (Theta) for all R/De cases. The pressure intensity of IOP spherical wave is higher in the centre of the axis compared to the curvature of the sphere (at higher angles). This shows clearly the IOP directionality while propagating from the nozzle exit. This is a very important result in terms of launch vehicle lift-off, where it is very critical to know how the IOP propagates and interact with the launch vehicle and its structures. The same phenomenon is again brought out clearly by the CFD studies,
where the shock strength and its pressure intensity is more dominant at the centre than at its curvature. These results would indicate the need of mitigating this effect and where to suppress it either actively by water injection or by shielding it through passive means. Also, the “Water Trough” (balloon bag filled with water which absorbs the IOP energy upon impinging on it) location could be even determined by these results in the future.

In the subsequent sections, the IOP propagation velocity characteristics are brought out based on the experimental results. It is very interesting to note that though the IOP energy front is having very high directionality, the velocity front is nearly spherical (constant with angles of propagation). Further, the velocity is found to decay with distance R/De increases. The following results corroborate such phenomenon.

6.1.3 IOP PROPAGATION VELOCITY AT VARIOUS R/DE

The variation of amplitude of the IOP velocity with respect to the propagation angles at different R/De values (20, 25, 30, 35, 40, 45 and 50) are shown in Figures 6.8a and 6.8b. For all these cases, the angles (Theta) are varying from 30 degrees to 140 degrees as measured for small scale solid rocket motors during the static testing.

![Velocity Propagation at Various Angle](image)

**Fig. 6.8a** IOP propagation velocity (m/s) decay characteristics for all Theta
From the above figures, it is understood that the IOP velocity propagation is found to be almost linear in nature till R/De of 35. Beyond, which, the decay in velocity seems to increase and becomes weak shock wave and turns to be subsonic propagation. Also, it is noticed that beyond the propagation angle of 90 degrees (behind the exit plane towards the head end side of the solid rocket motor), the reduction in velocity is more predominant as shown in figure 6.8 and 6.8b. This phenomenon indicates that IOP wave which is supersonic initially has become a weak shock wave and later becomes subsonic in nature, which is similar to the cases beyond R/De >35. It is found that the IOP velocity decay follows almost the second order polynomial fit, which radically changes for the cases R/De >35 and angles theta greater than 90 degrees.

6.1.4 IOP PROPAGATION VELOCITY AT VARIOUS PROPAGATION ANGLES (THETA)

The variation of amplitude of the IOP velocity with respect to the R/De values (20, 25, 30, 35, 40, 45 and 50) for various propagation angles (theta = 30 to 140 degrees) are shown in Figure 6.8b

From the figure 6.9, it is understood that the variation in IOP wave propagation velocity does not alter very much with propagation angle for a given
It is interesting to note that the velocity of the wave front is almost same for a given R/De for any angle showing the curvature of the shock wave front, which is almost spherical in nature as indicated in CFD results provided in the subsequent section. However, the magnitude of the velocity varies with reference to distance (R/De) indicating that the front face of the IOP wave has got higher amplitude in lower R/De from the nozzle exit and decays (almost conforms to second order polynomial) in a specific way as shown in earlier figures.

However, with reference to the propagation angles for a given R/De distance, the velocity is almost linear following a fit of $Y = mX + C$, where the slope $m$ indicates the decay in velocity with respect to angle for a typical R/De, which is almost negligible. The intercept is almost representing the actual IOP wave front propagation velocity for that case. Further, it is noticed that for angle greater than 90 degrees and for R/D > 35, there seems to be the radical change in the IOP characteristics as observed earlier.

![Fig. 6.9 IOP propagation velocity (m/s) decay characteristics for all R/De cases](image)

**6.1.5 SPECTRAL CONTENT OF IOP WAVE PROPAGATION**

The spectral content is computed by marking the half time period of the relaxation of the IOP wave after the peak time. The half time period is converted into the frequency of the IOP wave. This is the general method followed for the frequency
determination of IOP wave front. This is done for all cases and the sample results are being presented here (for R/De = 20, 25 and 30 for all theta values). This is essentially done to understand its spectral content during the propagation of the energy front. However, this analysis assumes more significance as the structural frequency of the launch vehicle and its surroundings has got first mode natural frequency as about 20 - 25 Hz. Further, the small scale solid rocket motors exhibit IOP frequency in the range of 600 to 700 Hz range because of the Strouhal shift criterion. Strouhal number is defined as Str No = f X De / Ue, where f is the IOP propagation front frequency and De is the nozzle exit diameter of the solid rocket motor and Ue is the exit velocity of the Supersonic jet. In the scale model case, De is scaled by geometrical factor and Ue is the same as that of the actual launch vehicle case. Hence, the frequency is shift by the scale model factor, i.e., about 25 times.

IOP spectral content is presented in Fig. 6.10. From these figures, it is understood that the frequency of IOP energy front is about 625 Hz average. This is so for all the cases of R/De with all propagation angles (theta). This data indicates that frequency does not get altered and remains constant along the R/De and also Theta. The whole shock front is moving with the same frequency in a spherical form as a single identity. Further, the Strouhal number shift is very clearly seen with higher frequency value for the scaled down case and when it is normalized with a factor of 25 scales (geometrical model factor), the frequency values converges to about 25 Hz. This is almost in line with the actual launch vehicle IOP wave frequency, which will be dealt in the forthcoming sections and chapter. This IOP frequency is more critical as it would interact with launch vehicle structures and becomes detrimental to the vehicle and its surroundings. And even, the phase differences between the strap-on motors will create moment on the vehicle which in turn demands more controllability during lift-off, where the margins of error is extremely low. This calls for mitigation of IOP through active and passive suppression system. It is to be noted that the slight variation in frequency in the results could be attributed to the time marking during the relaxation during which, the millisecond difference can deviate the frequency value significantly.
Fig. 6.10 Spectral content of IOP wave at R/De = 20, 25 & 30 for all theta

6.2 INTERMEDIATE SCALE SOLID ROCKET MOTOR IOP CHARACTERISTICS

For understanding the Ignition Overpressure characteristics during the initial transients of Intermediate scale solid rocket motor (1m dia class solid rocket motor) Ignition overpressure levels are measured during the static testing of 1m class solid rocket motor. IOP sensors are located in three positions and the polar coordinates of the sensors, time at which the IOP peak was recorded and the velocity of the wave propagation along with the frequency and amplitude of the IOP wave are given in the table 6.1.

Table 6.1. IOP sensor locations, wave amplitude and frequency measured during 1m class solid rocket motor static testing.

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>Polar Co-Ordinates (r, Θ)</th>
<th>Time at Max Peak (ms)</th>
<th>Amplitude of the IOP wave (mbar)</th>
<th>Frequency of the IOP wave (Hz)</th>
<th>Velocity of IOP wave (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOP1</td>
<td>(18, 26)</td>
<td>130</td>
<td>80.4</td>
<td>105</td>
<td>340</td>
</tr>
<tr>
<td>IOP2</td>
<td>(27.7, 27)</td>
<td>160</td>
<td>24.4</td>
<td>107</td>
<td>333</td>
</tr>
<tr>
<td>IOP3</td>
<td>(2, 104)</td>
<td>83</td>
<td>66.25</td>
<td>98</td>
<td>363.6</td>
</tr>
</tbody>
</table>

Photographic view of the solid rocket motor on the test bed during static testing and the sensor location are shown in Fig. 6.11. Sensor height and the solid rocket motor center are maintained the same.
Fig. 6.11 Photographic view of the solid rocket motor during static test

IOP data measured at various locations IOP1, IOP2 and IOP3 are shown in Fig.6.12.

![Photographic view of the solid rocket motor during static test](image)

Fig. 6.12 IOP Signature at location IOP1 during the static test

From the IOP signature graphs and Table 6.1 it is seen that the velocity of IOP wave propagation is near sonic at far of location that is at R/De 20. As the distance from the nozzle increases the velocity of the IOP wave reduces. The location IOP3 is very close to the nozzle and is not in the jet flow direction (location is around the
nozzle throat with a radial distance of 2m). Since the IOP3 sensor distance is less the velocity of the wave is higher, as mentioned in the literature, IOP wave is supersonic initially and as the distance increases the wave transforms into a week shock wave with sub sonic velocity.

Frequency of the IOP wave is in the order of 100Hz. In the case of small solid rocket (Agni motor) motor IOP data, the frequency of the IOP wave is in the order of 625Hz. The scale ratio between the 1m class motor and Agni is 6.9 (Ratio of nozzle exit diameters 1000/144). Considering this scale ratio as the Strouhal factor, the frequency of the IOP wave in 1m class motor should be in the range of 100Hz, which is the frequency measured during the static testing of 1m class solid rocket motor.

6.3 LARGE SOLID ROCKET MOTOR IOP CHARACTERISTICS

Free field Ignition Overpressure measurements are carried during the initial transients of large scale solid rocket motor. Unsteady pressure sensors of Kulite make are used for the measurement of IOP during the initial transients of the motor ignition. All the measurements are at the same height that is at the nozzle center axis. Various locations along the jet flow path are chosen for measuring the IOP levels. Three large solid rocket motor static tests of 20scale of Agni motor are considered for IOP level characteristics analysis. Three tests are named as ST-01, ST-02 and ST-03 (ST-Static Test) in the comparison. IOP levels are initially brought out for the individual tests and then are compared among the tests. The frequency shift with respect to the scale of the solid rocket motor is explained through experimental data in this section. Also, the reasons for variation in IOP levels among the three tests and the dominant factors that can affect the IOP levels for large solid rocket motor are briefed in this section.

6.3.1 MOTOR CHAMBER PRESSURE RISE RATE IN THREE TESTS (ST-01, ST-02 AND ST-03)

Chamber pressure rise rate is the predominant factor contributing for Ignition Overpressure. Average Chamber pressure rise rate is compared for all the three large solid rocket motor Static tests and a minor change was noticed in the motor chamber pressure rise rate between the three static tests. Average Chamber pressure rise rate for ST-01, ST-02 and ST-03 are 15.6MPa/s, 17.2MPa/s and 19.8MPa/s respectively. Fig.6.13 shows the comparison of initial transients in three static tests. Apart from the
Average pressure rise rate values the rate of change of motor chamber pressure in the initial transients is plotted in Fig.6.14. The rate of change of pressure is higher in the initial transients for ST-03. The affect of this on IOP is seen in detail in this section from the IOP data comparison between the three static tests.

Fig.6.13 Comparison of initial transients between ST-01, ST-02 & ST-03

Fig.6.14 Comparison of initial motor pressure rise rate between ST-01, ST-02, & ST-03
6.3.2 IOP MEASUREMENT FOR ST – 01

Three Kulite sensors were mounted at an angle of 23deg. from the thrust axis as per the measurement plan shown in Fig.6.15. Data was acquired at 1Ksamples/s up to T+10s.

![Diagram showing IOP Measurement plan for ST-01]

**Note: All Dimensions in Meters**

**Fig.6.15 IOP Measurement plan for ST-01**

All the sensors are mounted perpendicular to the motor center axis. Same mounting scheme is followed during all the three tests.

Motor Chamber pressure rise rate was 15.6 MPa/s during initial transients of Large solid rocket motor in ST-01. The initial pressure spike is circled using a callout. The second figure is constructed by taking few points showing only the initial pressure spikes from the raw data. These points are joined by a smooth B-Spline. Amplitude of the Overpressure wave is taken from the raw overpressure data, while the frequency is computed from the constructed data. The same procedure is followed for Overpressure analysis in large solid rocket motor IOP characteristics section. IOP levels and frequency of the wave at all the locations is given in Table.6.2. IOP levels at all the locations are shown in Fig.6.16.
### Table 6.2 Comparison of IOP wave at various locations in ST-01

<table>
<thead>
<tr>
<th>Location</th>
<th>Time at IOP peak (s)</th>
<th>IOP Level (mbar)</th>
<th>Frequency (Hz)</th>
<th>Mach No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOP 1 (31m)</td>
<td>0.328</td>
<td>43</td>
<td>39</td>
<td>1.2</td>
</tr>
<tr>
<td>IOP 2 (56m)</td>
<td>0.395</td>
<td>12</td>
<td>42</td>
<td>1.2</td>
</tr>
<tr>
<td>IOP 3 (66m)</td>
<td>0.417</td>
<td>20</td>
<td>45</td>
<td>1.19</td>
</tr>
</tbody>
</table>

![Graph showing comparison of IOP levels between IOP 1, 2 & 3 in ST-01](image)

**Fig. 6.16 Comparison of IOP levels between IOP 1, 2 & 3 in ST-01**

Ignition Overpressure decay characteristics during ST-01 test are compared with the theoretical Overpressure decay characteristics in Fig. 6.17. According to the literature IOP amplitude is inversely proportional to the square of the distance. Theoretical decay is plotted taking the amplitude at location IOP 1 and amplitude of the IOP is predicted with respect to distance at locations IOP2 and IOP3. In the initial phase the comparison of the IOP amplitude decay is very much in line with the $1/X^2$ rule.
The distribution, propagation and mitigation of the energy content in case of the large solid rocket motor are more predictable compared with the small solid rocket motor IOP phenomenon. Frequency of the IOP wave is in the range of 40Hz. And the decay of amplitude of IOP wave with respect to distance is also seen clearly. Similar measurement locations are chosen in ST-02 static test for comparison of Ignition overpressure levels.

6.3.3 IOP MEASUREMENT FOR ST – 02

Four IOP sensors were used for Ignition Overpressure characterization during ST-02 static test. ST-01 locations IOP 1, 2 and 3 are maintained the same and an additional sensor IOP4 was mounted near nozzle exit. IOP measurement plan for ST-02 is shown in Fig.6.18. Data was acquired at 50Ksamples/s up to T+2s.
Similar procedure (followed in ST-01 IOP characterization) is followed for characterization of IOP wave in ST-02. The amplitude of the Ignition Overpressure wave at various sensor locations and the corresponding frequency of the wave are given in table 6.3. IOP data at locations IOP1, IOP2 and IOP3 which are in a straight line are plotted in a same graph and is shown in Fig.6.19.

Motor Chamber pressure rise rate was 17.2 MPa/s during initial transients of motor in Static test. Location IOP 4 is close to the motor (R=4.5m and θ=109deg.). An Overpressure with amplitude of 69mbar was recorded here.

Table 6.3 IOP wave amplitude and frequency at various locations in ST-02

<table>
<thead>
<tr>
<th>Location</th>
<th>IOP Level (mbar)</th>
<th>Frequency (Hz)</th>
<th>Mach No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOP 1 (31m)</td>
<td>30</td>
<td>38</td>
<td>---</td>
</tr>
<tr>
<td>IOP 2 (56m)</td>
<td>33</td>
<td>35</td>
<td>1.04</td>
</tr>
<tr>
<td>IOP 3 (66m)</td>
<td>21</td>
<td>53</td>
<td>1.02</td>
</tr>
<tr>
<td>IOP 4 (4.5m)</td>
<td>69</td>
<td>58</td>
<td>---</td>
</tr>
</tbody>
</table>

From table 6.3, the IOP levels are similar to that observed in ST-01 static test. Frequency is also the similar to that seen in ST-01.
6.3.4 IOP MEASUREMENT FOR ST – 03

For ST-03 static test seven nos. of Kulite sensors and two nos. of Druck sensors were used for IOP characterization. Two Kulite sensors location is identical to ST-01 & ST-02 static test (i.e., IOP2 and IOP3). Two more Kulite sensors were mounted on the free stand and other one on the HPS3 casing which are at an axial distance of 70m from the nozzle exit. Druck sensors were co located with Kulite on the free stands. A new unsteady pressure sensor of make Druck is also used for comparison of IOP data. This new sensor has lower natural frequency compared to Kulite sensor. It was planned to evaluate the minimum sensor requirement for measuring the IOP levels during the static test. Two Kulite sensors were positioned near to nozzle exit similar to LVM3 scale model tests. One Kulite sensor was mounted on Acoustic stand. IOP Measurement plan for ST-03 is shown in Fig. 6.20. Data was acquired at 100K samples/s for duration of one second.
Fig. 6.20 IOP Measurement plan for ST-03

Overpressure levels recorded from all the sensors is listed in table 6.4. Overpressure peak value is taken from the raw data and the frequency is calculated from the constructed data.

Table 6.4 IOP levels measured at locations during ST-03 static test

<table>
<thead>
<tr>
<th>Location</th>
<th>Time (sec)</th>
<th>Pressure (mbar)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOP 8 – Kulite (76m)</td>
<td>0.43</td>
<td>120</td>
<td>77</td>
</tr>
<tr>
<td>IOP 8a – Druck (76m)</td>
<td>0.43</td>
<td>181</td>
<td>42</td>
</tr>
<tr>
<td>IOP 2 – Kulite (56m)</td>
<td>0.38</td>
<td>202</td>
<td>67</td>
</tr>
<tr>
<td>IOP 2a – Druck (56m)</td>
<td>0.38</td>
<td>274</td>
<td>40</td>
</tr>
<tr>
<td>IOP 3 – Kulite (66m)</td>
<td>0.41</td>
<td>160</td>
<td>55</td>
</tr>
<tr>
<td>IOP 4 – Kulite</td>
<td>0.20</td>
<td>172</td>
<td>46</td>
</tr>
<tr>
<td>IOP 5 – Kulite</td>
<td>0.19</td>
<td>146</td>
<td>35</td>
</tr>
<tr>
<td>IOP 6 – Kulite (37m)</td>
<td>0.33</td>
<td>81</td>
<td>69</td>
</tr>
<tr>
<td>IOP 7 – Kulite (76m)</td>
<td>0.43</td>
<td>153</td>
<td>38</td>
</tr>
</tbody>
</table>
In order to evaluate the IOP wave propagation velocity, three sensors (IOP 2, IOP 3 and IOP 1) are kept in line at various distances from the nozzle exit. Fig. 6.21 shows the IOP levels at IOP 2, IOP 3 and IOP 1 locations. The Sensors IOP 2, IOP 3 and IOP 1 are located at a radial distance of 56.2m, 66.2m and 76.2m respectively. Time of travel for the Overpressure wave between IOP 2 and IOP 3 is 0.02387s and between IOP 3 and IOP 1 is 0.02387sec. IOP wave travelled with a constant velocity of Mach 1.23. Table 6.5 shows the location and velocity details for the three locations.

![Graph showing IOP levels comparison between IOP 1, 2 & 3 in ST-03](image)

**Fig.6.21 Comparison of IOP levels between IOP 1, 2 & 3 in -ST-03**

<table>
<thead>
<tr>
<th>Location</th>
<th>Radial Distance from nozzle exit (m)</th>
<th>Time at peak (s)</th>
<th>IOP levels (mbar)</th>
<th>Mach No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOP 2</td>
<td>56.2</td>
<td>0.38161</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>IOP 3</td>
<td>66.2</td>
<td>0.40605</td>
<td>160</td>
<td>1.23</td>
</tr>
<tr>
<td>IOP 8</td>
<td>76.2</td>
<td>0.43048</td>
<td>120</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Ignition Overpressure decay rate with respect to distance from nozzle exit is plotted for ST-03 case (Fig.6.22). Theoretical estimate of Decay is made according to $1/X^2$ law. A good match is seen between the recorded decay rate and the theoretical estimate.
Overpressure Decay Characteristics ST-03

- Experimental Decay
- Theoretical Decay

Distance (m)

Comparison between Druck and Kulite Data

Fig. 6.22 Ignition Overpressure Decay with respect to Distance

Fig. 6.23 Comparison of IOP levels between IOP 1 & 1a in ST-03
Motor Chamber Pressure rise rate in ST-03 static test was 19.8MPa/s. Amplitude of the Overpressure wave recorded using the Druck sensor is higher compared to Kulite sensor. At Location IOP 1, Kulite sensor has read 120mbar while Druck sensor has read 181mbar. This time of Overpressure peak recorded is same for both Druck and Kulite. Similar observation is made at location IOP 2.

**6.3.5 Comparison of IOP levels between ST-01, ST-02 & ST-03**

To analyze the effect of chamber pressure rise rate and the effect of acquisition rate on the IOP levels, similar location IOP data is compared between ST-01, ST-02 and ST-03. Two Kulite sensors i.e., IOP 2 and IOP 3, were mounted at similar locations in all the three tests. Fig.6.25 and Fig.6.26 shows the comparison of IOP levels. Total raw data is plotted first and then followed by the constructed data to analyze the IOP signature.
Fig. 6.25 Comparison of IOP levels between ST-01, ST-02 & ST-03 at IOP 2
Fig. 6.26 Comparison of IOP levels between ST-01, ST-02 & ST-03 at IOP 3
6.3.6 SUMMARY OF IOP CHARACTERISTICS FOR FREE FIELD HORIZONTAL TESTING OF SOLID ROCKET MOTORS

In the small scale solid rocket motor Ignition Overpressure analysis, spatial characterization of Ignition Overpressure environment is carried out. Decay characteristics of Ignition Overpressure propagation velocity and amplitude with respect to distance and propagation angle are studied. Ignition Overpressure amplitude decay characteristics have indicated the decay of the energy front of the wave, showing that the energy front is highly directional and concentrated more towards the center axis of the motor. Further, Ignition overpressure velocity decay characteristics were studied in detail, which emphasized on the spherical nature of the IOP wave showing uniform velocity with various IOP propagation angles.

Considering the results from the small scale solid rocket motor tests, further in the medium or large solid rocket motors IOP sensors are located more along the center axis, since the energy front directionality is high and the highest IOP amplitude is most likely to be observed in the IOP propagation angle closer to the motor center axis.

From the medium scale rocket motor IOP data analysis it was found that the IOP amplitude levels decay with respect to the distance from the nozzle exit plane and the frequency content of the Overpressure wave was in line with the frequency content obtained from the scaling criteria using the Strauhol number.

Further, to analyze the IOP levels in full scale an effort was made to capture the IOP signatures produced during the Static testing of 3nos. of large scale solid rocket motors (ST-01, ST-02 & ST-03) using unsteady pressure sensors (Kulite). During the Ignition pressure transients regime of ST-01, ST-02 & ST-03, it was observed that the average chamber pressure rise rates were 15.6MPa/s, 17.2MPa/s and 19.8MPa/s respectively during the initial T+0.2 to T+0.3s. From the literature it is well known that the Motor chamber Pressure rise rate is the most dominant factor determining the signature of the IOP wave, so this factor was deeply studied and the effect of this change in the large scale solid rocket motor is analyzed.

During all the static tests the IOP signature shapes were found to be similar to the one reported in literature (Positive triangular pulse followed by a negative half
sine wave). During S200-ST-01 test peak IOP value was recorded to be 43mbar at IOP 1 location (31m from nozzle exit plane) with a frequency of 39Hz. In S200-ST-02 at the same location, it was recorded as 30mbar with a frequency of 38Hz. As far as the IOP 2 location (56m from nozzle exit plane) is concerned, the IOP values recorded were 12mbar (49Hz), 33mbar (35Hz) and 202mbar (67Hz) for S200-ST-01, ST-02 and ST-03 respectively. The reason for higher IOP amplitude for ST-03 may be attributed to the higher motor chamber pressure rise rate.

From the tests it was found that in general, IOP signal is found to propagate at supersonic speed and decay rapidly with distance and time. Considering the IOP decay characteristics for S200-ST-01, it is seen that the amplitude decay pattern seems to follow 1/x² rule, where x is the radial distance between the two successive IOP locations. Similar trend was more or less observed for S200-ST-03 also.

The current chapter has detailed the IOP characterization for a free field case, where the solid rocket motor is kept in horizontal condition and there are no deflections for the IOP wave. In the launch pad, the vehicle is in vertical condition on the MLP and Jet Deflector Duct. The effect of these structures on the IOP needs to be characterized.