PREDICTION OF EROSION CHARACTERISTICS FOR ABLATIVE THROAT INSERT LINERS USING ULTRASONIC VELOCITY MEASUREMENTS

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ABSTRACT

Launch vehicles use ablative nozzle liners to function under very high thermal and erosive environments. In solid motor nozzle throats, graphite or carbon phenolic materials are used because of their high heat of ablation and erosion resistance. Ultrasonic testing is implemented as the primary NDT technique for throat insert liners by almost replacing radiography testing. Though introduced for defect detection, it is found that the ultrasonic velocity measurements can be used in the prediction of erosion characteristics of throat insert liners.

A model is developed for erosion prediction based on solid motor ballistic laws and equations of material density with ultrasonic velocity correlation. Erosion in solid motor throat depends on design, propellant, nozzle and throat material. Assuming other parameters to be constant, the erosion is related to the density of the throat. Also correlation is established between density and ultrasonic velocity in the graphite. Hence, erosion of graphite and carbon phenolic throat insert liner is predicted using ultrasonic velocity measurements. The predicted erosion values are compared with post-flight values.

Keywords: Ablative throat insert liner, Ultrasonic velocity, Erosion.

INTRODUCTION

Ablative nozzle liners are used for functioning under very high thermal and erosive environments because of their thermal, ablative and fire retardant properties. Graphite, carbon phenolic and silica phenolic materials are commonly used. Ultrasonic testing is implemented as the primary NDT technique for throat insert liners. This has almost replaced expensive radiography testing and also provides better coverage and speed at reduced cost of testing. Though it is introduced for defect detection, it is found that the ultrasonic velocity measurements can be used for characterisation i.e., predicting mechanical properties like modulus [1]. Nozzle throat erosion is one of the important inputs for prediction of solid motor ballistic performance. A fairly accurate non-destructive assessment of throat erosion based on ultrasonic testing is presented in this paper. The theoretical model is built based on solid motor ballistic laws and correlation of material density with ultrasonic velocity. Erosion in solid motor throat is correlated to the parameters like specific motor design, propellant, nozzle and throat material [2]. Assuming other parameters to be constant, the erosion is related to the density of throat material. As correlation is established between density and ultrasonic velocity in the graphite [3], erosion of throat graphite is predicted using ultrasonic velocity measurements. Also, it is extended for predicting erosion in carbon phenolic throat insert liner. The predicted erosion values are compared with post-flight values.

THEORY

Ballistic correlation for graphite throat erosion

Graphite, Carbon phenolic and carbon-carbon materials which have excellent thermo-physical properties as well as low densities are widely used as materials for solid motor nozzle throat inserts. During motor operation, the temperature of the nozzle material rises rapidly, due to severe heat transfer from the hot combustion products to the nozzle surface. During combustion, heterogeneous chemical reaction occurs between the nozzle material and oxidising species like H₂O, CO₂ in combustion stream. The ensuing chemical erosion causes the nozzle surface to recede [4]. Hence, erosion in solid motor throat depends on specific motor design, propellant, nozzle and throat material.

Total erosion or recession (R in mm) is given by the empirical relation,

\[ R = [0.5946 (X_{H2O} + X_{CO2})^{1.02} \rho_t 0.75 X_t -0.343 R_t -0.076] \times t \]  

(1)
Where $X_{H_2O}$ is the mole fraction of $H_2O$ during propellant burning, $X_{CO_2}$ is the mole fraction of $CO_2$ during propellant burning, $\rho$ is the density of graphite (g/cc), $P_c$ is the chamber pressure (MPa), $X_t$ is the average entry length from the burning propellant surface to throat (cm), $R_t$ is the radius of nozzle throat (cm), $t$ is the motor operation time (s).

The above equation shows strong relation between throat material density and throat erosion. Conventionally, material density of throat is measured on sample basis. But, composite material is heterogeneous in nature. Material destructive evaluation tests and acceptance methods may not fully capture this variation to the extent that can be used for finer computation activities. Ultrasound is a tool that is being used for non destructive evaluation of materials. The characteristics of sound transmitted through material depend on material properties such as elasticity, density and texture. Thus, monitoring and measuring ultrasonic sound characteristics in material, provide a measure of material properties and its local variations.

**Ultrasonic velocity measurements on graphite throats and their correlation with density**

Ultrasonic testing operates based upon wave-material interaction phenomena and is an established method of non-destructive testing. By propagating a wave in a given medium, information about the medium can be obtained by analyzing the transmitted or reflected signals. Ultrasonic testing can be conducted either by the pulse-echo technique or the through transmission technique. Pulse echo technique uses a single transducer. Through-transmission technique uses two transducers, with the transmitter on one side and the receiver on the other side of the component under test. Through transmission technique needs access on both sides of the component and perfect alignment of two transducers [5]. Velocity measurements in graphite throat are done by adopting ultrasonic testing in dry coupled pulse echo mode. Grids are marked on the graphite throat at cylindrical block level. Ultrasonic probe of 24 or 10 mm diameter & 1 MHz frequency (normal probe) with a suitable ultrasonic flaw detector are used for velocity mapping. Equipment is calibrated by setting the velocity to match the material acoustic properties. Thickness measurements are done at the grids, which are related to the velocity.

The experimental set-up for ultrasonic velocity measurement on graphite throat is shown in Fig. 1. The typical velocity distribution map (development view) made for throat graphite is given below (Fig. 2):

In the similar manner, velocity measurements are carried out on the carbon phenolic throat insert liner. The typical velocity distribution map (development view) for carbon phenolic throat insert liner is given below (Fig. 3):

**Correlation of ultrasonic velocity with density**

Ultrasonic velocity is the parameter that can be used as predictor of material properties of porous materials [6]. In porous material, ultrasonic velocity depends on pore size distribution (a measure of material density). Also, scattering of sound is a function of size of pores (obstacles to sound) and wavelength of sound being used for inspection. At certain ultrasound frequencies (1 to 2 MHz frequency), it is observed that ultrasonic velocity is linearly proportional to pore volume fraction.

Experiments are carried out on the graphite specimens to establish correlation between longitudinal ultrasonic velocity and density. Ultrasonic velocity is measured on the graphite specimens (specimen size: cuboids of 20 mm). Then, density is measured on the same using Archimedes principle. The plot of average ultrasonic velocity versus density of the specimens shows linear relationship between the two with a correlation coefficient of 0.9121 (Fig. 4). Hence, longitudinal ultrasonic velocity is used as a measure of density.
Theoretical model for estimation of throat erosion

The equation for erosion (equation 1) can be rewritten as

\[
\frac{R}{t} = 0.5946 \left( X_{H_2O} + X_{CO_2} \right)^{1.02} \rho^{-1} P_c^{0.876} X_t^{-0.343} R_t^{-0.076}
\]

(2)

The left hand side of the above equation denotes erosion rate. For particular motor design, \( X_{H_2O}, X_{CO_2}, \) and \( X_t \) can be taken as constant. \( R_t \) is measurable parameter and its influence is observed to be very negligible. Thus, erosion rate depend on the density of throat insert and chamber pressure. The quantity \( P_c^{0.876} \) (pressure integral at constant erosion) is nearly constant because of the fact that when the motor pressure \( (P_c) \) increases, correspondingly the motor operation time \( (t) \) reduces or vice versa. So, throat erosion is inversely proportional to the density of throat insert liner. Hence, it is inferred that for a particular design of motor with identified propellant system, erosion depend only on density of throat and also, throat erosion is observed to be linearly related to ultrasonic velocity. Based on the above relations, an empirical model is built to predict the erosion of throat graphite.

EXPERIMENTAL RESULTS

Throat erosion data is generated after flight to experimentally validate the linearity between longitudinal ultrasonic velocity and throat erosion.

The above plot (Fig. 5) shows the linear relationship between longitudinal ultrasonic velocity and throat erosion with the correlation coefficient of 0.854. Hence, empirical model is used for prediction of graphite throat erosion. Comparison between the erosion predicted for graphite throat using the above model and erosion values obtained from post-flight data is given in Table 1.

Table 1: Graphite throat erosion - Predicted and Experimental (post-flight data)

<table>
<thead>
<tr>
<th>Motor No</th>
<th>Ultrasonic velocity range(m/s)</th>
<th>Predicted throat erosion based on ultrasonic velocity (mm)</th>
<th>Erosion based on post-flight estimation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2260 – 2353</td>
<td>19.0 – 21.5</td>
<td>19.3</td>
</tr>
<tr>
<td>2</td>
<td>2270 – 2393</td>
<td>18.5 – 21.0</td>
<td>19.9</td>
</tr>
<tr>
<td>3</td>
<td>2254 – 2403</td>
<td>18.5 – 21.0</td>
<td>20.0</td>
</tr>
<tr>
<td>4</td>
<td>2256 – 2348</td>
<td>19.0 – 21.5</td>
<td>20.2</td>
</tr>
<tr>
<td>5</td>
<td>2334 – 2449</td>
<td>18.0 – 20.5</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Further to above studies, the model is applied for prediction of erosion in ablative throat insert liner made of carbon-phenolic material. Later, the erosion is obtained based on post-flight estimation. The erosion predicted for carbon-phenolic throat insert liner is compared with the one obtained from post-flight data in Table 2.
Table 2: Erosion for carbon phenolic throat insert liner - Predicted and Experimental (post-flight data)

<table>
<thead>
<tr>
<th>Motor No</th>
<th>Ultrasonic velocity range (m/s)</th>
<th>Predicted throat erosion based on ultrasonic velocity (mm)</th>
<th>Erosion based on post-flight estimation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3413 – 3516</td>
<td>12.7 – 19.5</td>
<td>13.7</td>
</tr>
<tr>
<td>2</td>
<td>3394 – 3486</td>
<td>14.6 – 20.6</td>
<td>17.7</td>
</tr>
<tr>
<td>3</td>
<td>3407 – 3560</td>
<td>10.0 – 20.2</td>
<td>14.9</td>
</tr>
<tr>
<td>4</td>
<td>3436 – 3554</td>
<td>10.3 – 18.3</td>
<td>14.9</td>
</tr>
<tr>
<td>5</td>
<td>3419 – 3478</td>
<td>15.1 – 20.1</td>
<td>18.8</td>
</tr>
</tbody>
</table>

From the above comparison, it is seen that there is an excellent match for both graphite throat and carbon phenolic throat insert liner as all the post-flight estimated values are within the predicted range.

CONCLUSION

An empirical relation exists for estimation of throat erosion based on density of throat and other parameters. This has been modified for predicting erosion of graphite and carbon phenolic throat inserts using ultrasonic velocity measurements. Very close matching is observed between the predicted values and post-flight estimates.

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REFERENCES


