Application of Anova to Pulse Detonation Engine Dynamic Performance Measurements

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***Abstract*—Application of Anova to Pulse detonation engine dynamic performance measurement resulted in quantifying engine functionality during various operations. After evaluating the performance, techniques of improving it, were applied in multiple areas of relevant interest. This produced encouraging results and helped in upscaling efforts in a significant manner. The current paper deals in the details of anova implementation and systematic identification of key areas of improvements. The improvements were carried out after careful selection of plans in the engine, ground rig and instrumentation setup etc. It also yielded better reproducibility of performance and optimization of main subsystems of PDE. Further, this will also contribute to reduce the development cycle and trial complexity also, if researchers continue to extract concern areas to be addressed.**

Keywords— Pulse Detonation Engine, Thrust, Anova, Thrust measurement, Engine ground rig, Defalgration to Detonation (DDT)

A. Abbreviations and Acronyms

Abbreviation	Nomenclature	Units
PDE	Pulse Detonation Engine	-
PDRE	Pulse Detonation Rocket Engine	-
P_1	Chamber pressure at station 1	bar
PFR	pressure flow regulator	-
CFD	Computational Fluid Mechanics	-
FCS	fire control system	-
ECCU	Electronic command and control unit	-
SCR	Silicon - Controlled Rectifier	-
AC	Alternating Current	-
NI	National Instruments Inc.	-
tdms	NI Diadem File storage format	-
ANOVA	Analysis of Variance	-
$PS_1, PS_2, PS_3, PS_4, \dots\dots PS_n$	Pressures Samples	bar

I. INTRODUCTION

Pulse detonation engines (PDE) offer a lightweight, low-cost & high thrust alternative for aerospace applications up to hypersonic velocities. PDE is an aerospace engine, which works on detonation principles. It has got few components of simple geometry and have no complex moving parts. Currently, PDE technology is being developed for upper stages that boost satellites to higher orbits. The advanced propulsion technology could also be used for lunar and planetary landers and excursion vehicles that require throttle control for gentle landings. It is also a competitive contender for missile systems application due many other advantages also. It would allow rockets to carry heavier load, reduce costs of launch into orbit too. Even though, PDE is key engine option from last 5 decades for aerospace applications, but a very limited progress has happened in development of fly worthy engine based on these principles.

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In a breakthrough move, Russian scientists have become the first ever to successfully test a pulse-detonation rocket engine (PDRE) in July and August, 2016, on clean fuel (**oxygen-kerosene pairing**), claiming this will be the future of space travel. Americans, Japanese, French and Chinese teams are busy in making PDE powered missions a reality.

TBRL is also engaged in PDE design and is in mature stage to development and testing of ground demonstrator. Getting the desired thrust at all intervals is a key concern of designers and TBRL has put great concentration into this. Detonation achievement phenomenon by using Schelkin spiral blockage ratio optimization was carried out in CFD and experiments to enhance the thrust [1]. During PDE development, designers have faced frequent thrust fluctuations of significant range and emerged as key area to be addressed in addition to integration challenges [2], [3] and [4]. Researchers have earlier developed gaseous PDE ground demonstrator [5] and presently working on liquid fuel based PDE on detonation principles [6]. The power fluctuations will result due random variation of chamber pressure P_1. Calibrated and careful selection of various parameters in PDE cycle will help to handle these issues to a large extent. The coming paras is dwelling on our approach to handle this issue too.

II. Research Methodology - The Analysis of Variance (ANOVA)

Since, PDE engine is known to have problems of producing consistent thrust without fluctuations, so some techniques are to be applied to identify the phenomenon and address it through carefully drafted strategies [7]. TBRL has applied research methodology of statistical techniques to understand the problem and address it through focused approach [8].

The “analysis of variance” (ANOVA) is used, when comparing three or more groups of numbers [9]. The ANOVA technique is an established practice to understand and isolate the pattern of chamber pressure / thrust variations, so it is explained as under:

A. Purpose

The reason for doing an ANOVA is to see if there is any difference between groups on some variable [9].

ANOVA is available for both parametric (pressure data) and non-parametric (classification/ordering – firing frequency) data.

B. Non-parametric and Parametric

ANOVA is available for score or interval data as parametric ANOVA. This is the type of ANOVA you do from the standard menu options in a statistical package.

The non-parametric version is usually found under the heading "Nonparametric test". It is used when specimen have rank or ordered data.

You cannot use parametric ANOVA, when the data is below interval measurement. Where data is categorical, ANOVA method is not suitable. It would be useful to apply Chi-square technique, which is about interaction rather than about differences between groups.

C. Types of ANOVA

- One-way between groups
- One-way repeated measures
- Two-way between groups
- Two-way repeated measures

TBRL has applied one-way ANOVA to Chamber pressure measured (P_1) to analyze the data and provide inferences on the spread of data to reduce the spread of time history of data.

III. PDE Trial Setup

Experimental PDE trial setup planned by TBRL (refer fig.1) for getting the measurement of various parameters to assess the performance of the PDE [2]. The fuel and air are injected into PDE tube at certain pressure and interval using a unique injection schemes at typical pressures and equivalence ratio established after series of calculations and perfected in experiments. A test rig consisting of purified compressed air cylinder bank, Dome regulator, pressurized flow regulator (PFR) and its allied instrumentation of dial gauges and pressure gauges instrumented through recorders for data storage. This rig also supports to meter and force fuel to be pumped in PDE tube through injector. The current setup helps the PDE input parameter control and regulation.

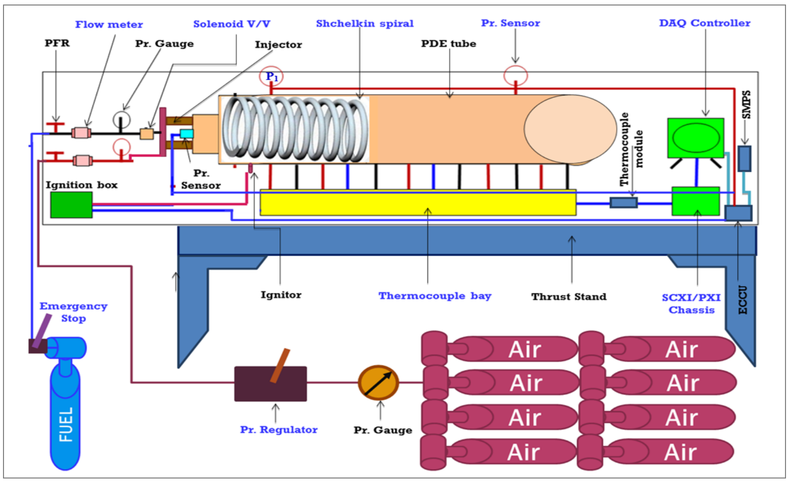

Fig. 1 Trial Setup of PDE experimental plan

The various operations of PDE cycle are carried out in a particular sequence and timing plan, which are altered and fine-tuned to meet our practical requirements. Generally, with a small shift in parameters require retuning of all parameters to get proper output, which is still having performance parameters variations of the order of 20-30% due various reasons. The paper deals with the handling of this issue using complex statistical pattern study and plan to pin point the cause and strategy to address it.

A dedicated fire control system (FCS) is designed to create significant ignition flame spark [5] using SCR based high voltage setup, which is commanded for deflagration / detonation at specific intervals through complex electronic command and control unit (ECCU), inputted remotely through serial link. In present configuration, all these systems are AC powered.

A powerful NI data acquisition system is used to acquire the data from multiple sources at separate sampling rates and being analyzed online and stored in tdms format for detailed offline analysis also. The current paper uses this stored data for doing statistical data analysis.

NI Diadem, Mathworks Matlab & MS Excel is used to carry out data processing, analysis and graphical visualization. This is covered in para V in details.

IV. Trial Data Analysis using Conventional Statistical Methods

In the current application, peak of tube pressure at stage 1 (P_1) in the tube is a key parameter to assess the performance of the PDE. We have used 3 sets of PDE firings at various frequencies are used. These are at 8 Hz, 10 Hz & 12 Hz frequencies. Firstly, 8 Hz frequency data is analyzed and subsequently, the analysis is carried out on all other available frequencies data also.

A. *Statistical Analysis of 8 Hz P_1 data*

The data set used for analysis is 160+ peaks of P_1. First to carry out preliminary analysis of data, standard statistical techniques are used. Following assumptions are made to study the pattern:

- Input pressure of fuel and air are uniform throughout the run
- Temperature of tube is constant in the tube
- Ignition pulse spark is of same strength & duration in each shot
- Reflecting shock from the rear end of the Schelkin is not considered
- Pressure sensor sensing element is not in contact with Schelkin
- Effect of vibrations is uniform in all shots

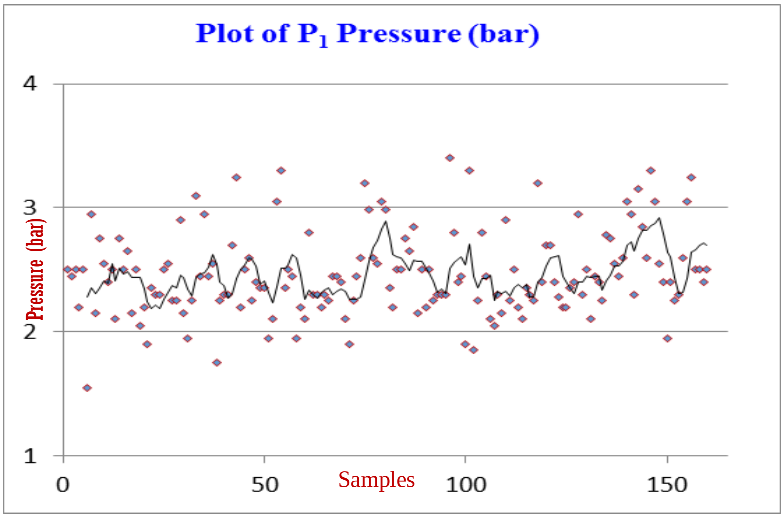

Fig. 2 P1 scatter plot and trend pattern for 8 Hz firing

1) Sample Spread Analysis

First, peak values scatter is plotted for 8 Hz firing (figure 2). 4 point moving average based trend line is also inserted for better pattern analysis. The conclusions drawn are shown in table 1.

<table>
<tr><td colspan="5">Pressure analysis</td><td colspan="2">Shot analysis</td></tr>
<tr><td>variation of pr (Bar)</td><td>1.5 to 3.5 (2)</td><td>mid value</td><td colspan="2">2.5</td><td>missed shots</td><td>0</td></tr>
<tr><td>20% (>3 bar)</td><td rowspan="2">points</td><td>15</td><td rowspan="2">%</td><td rowspan="2">15.5</td><td>higher pr shots</td><td>2</td></tr>
<tr><td>-20% (<2 bar)</td><td>10</td><td>low pr shots</td><td>4</td></tr>
<tr><td>10% (>2.75 bar)</td><td rowspan="2">points</td><td>23</td><td rowspan="2">%</td><td rowspan="2">18.6</td><td>% miss</td><td>0</td></tr>
<tr><td>-10% (<2.25 bar)</td><td>17</td><td>cases consi-dered %</td><td>100</td></tr>
</table>

Table 1 Pattern analysis of 8 Hz data spread

From the present data analysis, it is established that 18.6 % data is having more than 10% variation spread of pressure. This is one pattern, which is established from current analysis. From trend lines, it is established that trend variation is only from 2.25 to 2.75 (variation band of 0.5 bar only) bar with most of its parameters falling near 2.4 bar.

2) Average Spread Analysis

To analyze it further, averaging technique is used [8]. The data is averaged at every one second interval and results are plotted in fig. 3. the formulae used are as per equation, data point, d is

$$d = average\ of\ PS_1, PS_2, PS_3, PS_4, \dots \dots PS_n \qquad \dots\dots (1)$$

Additionally, 4 point moving average based trend line is also inserted for better pattern analysis. Ignoring three peaks, most of the data is very close to 2.4 bar. It means that average values of data follow a significant pattern and is reproducing the repeatability.

From the above analysis, following inferences are drawn:
- The average spread is between 2.3-2.7 bar
- There are 4 insistentent jumps in data
- highest jump is about 0.4 bar
- If ignored, this jump, all other jumps are less than 0.2 bar

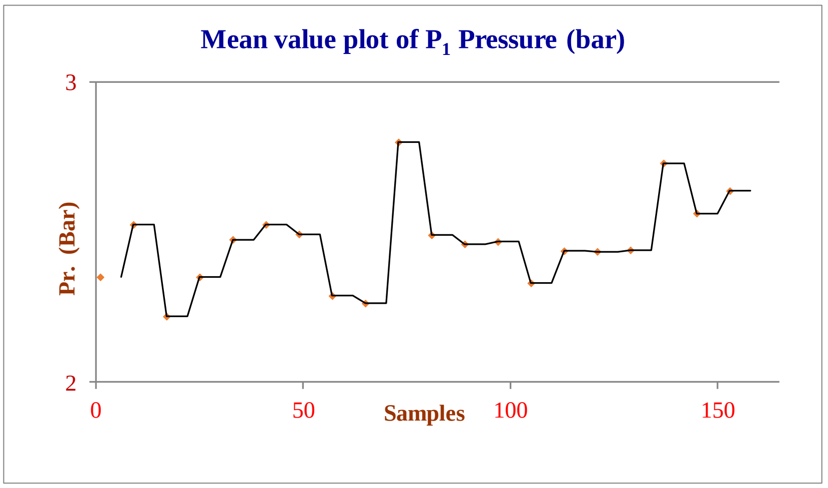

Fig. 3 Avearage P1 plot and trend pattern for 8 Hz firing

From the above analysis, following inferences are drawn:
- The average spread is between -0.3 to 0.3 bar
- There are 3 insistentent jumps in data
- highest jump is about 0.4 bar
- If ignored, this jump, all other jumps are < 0.2 bar
- eventhough data appears to have large spread, but trendline gives more sensible interpetations of the spread of data

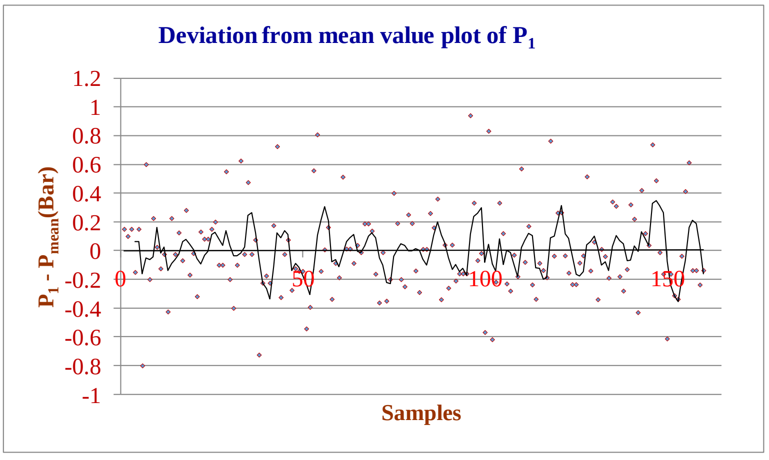

Fig. 4 Devaition of P1 plot and trend pattern for 8 Hz firing

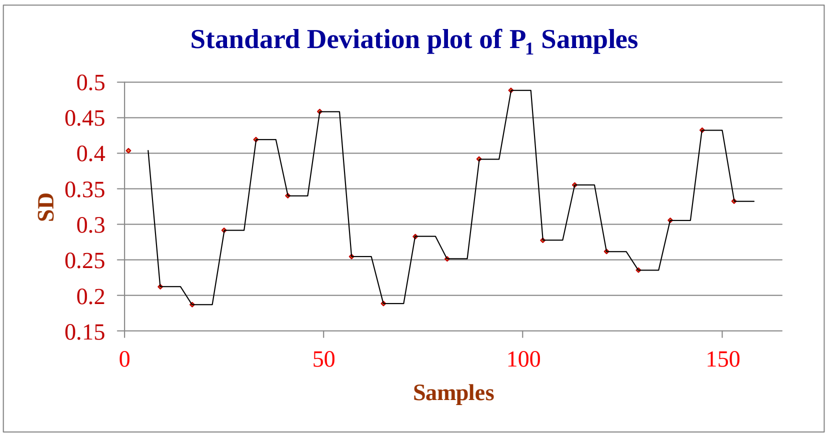

Fig. 5 Standard deviation of error signal (P1) plot and trend pattern for 8 Hz firing

3) Standard Deviation Spread Analysis

Standard deviation is established practice to analyze large spread of random data to provide pattern analysis. So, Standard deviation (SD) from mean is calculated from per second mean is calculated and the spread is examined [8]. The SD data spread is plotted in fig. 5. Additionally, 4 point moving average based trend line is also inserted for better pattern analysis of derived data.

From the above analysis, following inferences are drawn:

- The SD spread is between -0.2 to 0.48
- There are 4 insistentent jumps in data
- highest jump is about 0.38
- Eventhough data appears to have large spread, but trendline gives similar interpetations

4) Histogram Spread Analysis

Histogram is another method to analyze large spread of random data to provide pattern analysis. So, P_1 value histogram is plotted and the spread is examined. The Histogram spread is plotted in fig. 6. It is established that max no. of 46 samples are having values ranging from 2.21-2.43 bar and 44 samples are having values ranging from 2.43-2.63 bar.

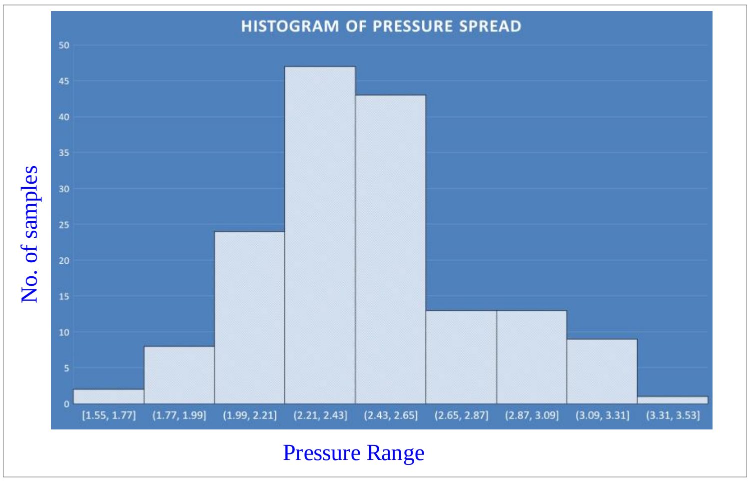

Fig. 6 Histogram depicting P1 spread pattern for 8 Hz firing

B. Spread Analysis of 8/10/12 Hz P_1 data:

The data set used for analysis is 160+ peaks of P_1 deviation from their per second mean. First to carry out preliminary analysis of data, standard statistical techniques of local spread analysis are used. The spread is plotted to highlight the frequency effect in fig. 7. Following observations are made on the data analysis:

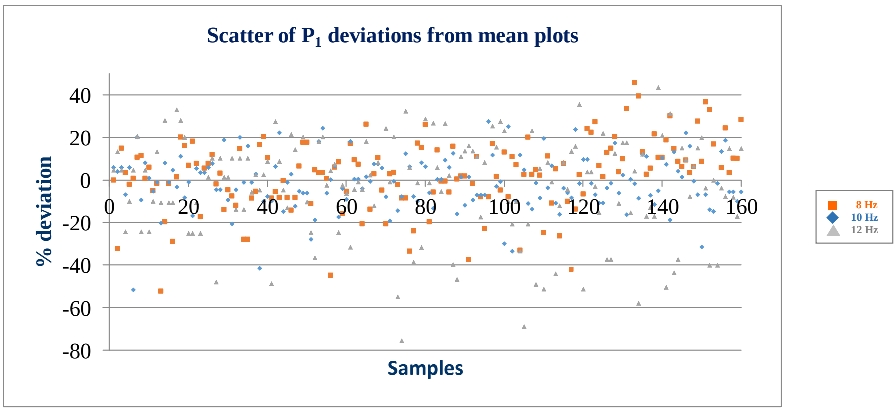

Fig. 7 Scatter plot of 8/10/12 Hz firing

- Spread of data is more significant at higher frequncies
- Missed firing/high pressure shots are more frequent in higher frequencies
- Pressure build-up is also depleted as upscaling of frequencies is planned
- Net impulse is improved with frequncies upscale

Subsequently, the plot % of points falling in various error deviations from per second mean are plotted as under shown in figure 8.

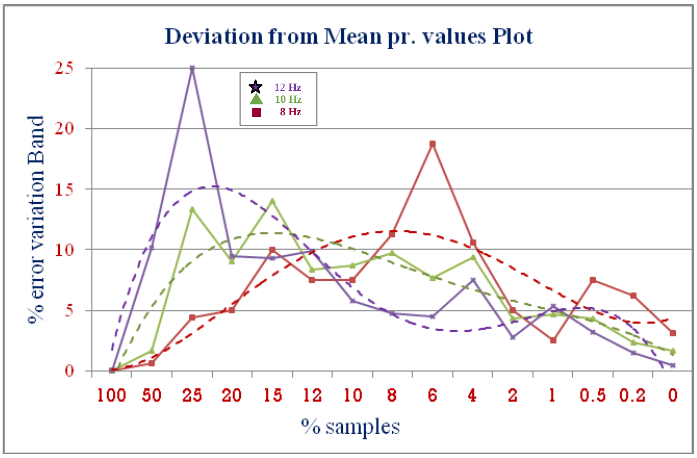

Fig. 8 deviation of P_1 from P_1 (per second mean) plot with trend pattern for 8Hz / 10 Hz / 12 Hz firing

From this analysis, the interperation are:

1. for 8 Hz, 8 % samples have for than 11 % variation
2. for 10 Hz, 20 % samples have for than 11.5 % variation
3. for 12 Hz, 25 % samples have for than 15 % variation

From this analysis, it is interpreted that as frequency is upscaled, the error magnitude and sample spread falling in higher magnitude is increasing. It is due to the fact that optimization exercises for higher frequencies need to be carried out. Further, the error margins also higher and reasons for this will be dealt with in succeeding paras anlong with anova.

V. ANOVA APPLICATION TO PDE PROBLEM

One-way ANOVA compares three or more unmatched groups, based on the assumption that the populations are Gaussian [9]. In the current problem, 8 Hz, 10 Hz and 12 Hz datasets are three unmatched groups. The assumptions are:

- Each sample is an independent random sample
- The distribution of the response variable follows a normal distribution
- The population variances are equal across responses for the group levels. This can be evaluated by using the following rule of thumb: if the largest sample standard deviation divided by the smallest sample standard deviation is not greater than two, then assume that the population variances are equal.

The key parameters are:

count, ….(2)

….(3)

….(4)

….(5)

Groups	Count	Sum	Average	Variance
8Hz_dev%	160	-234.659	-1.46662	158.2412
10Hz_Dev%	299	4326.285	14.46918	189.5913
12hz_DEV%	465	-3905.69	-8.39934	1037.233

Table 2 Summary table of 8 Hz / 10 Hz / 12 Hz data

Variability can also be defined in terms of how close the scores in the distribution are to the middle of the distribution. Using the mean as the measure of the middle of the distribution, the variance is defined as the average squared difference of the scores from the mean. Based on the test data and following above assumptions, data is fed to single factor Anova in two steps, and results are tabulated in table 2 for step I (using equation (2) to (5)), subsequently in table 3 for step II as below:

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	95709.79	2	47854.89	78.29388	3.95E-32	3.005498
Within Groups	562934.9	921	611.2214			
Total	658644.7	923				

Table 3 Anova table of 8 Hz / 10 Hz / 12 Hz data

A. P value

The P value tests the null hypothesis that data from all groups are drawn from populations with identical means. Therefore, the P value answers this question:

If all the populations really have the same mean (the treatments are ineffective), what is the chance that random sampling would result in means as far apart (or more so) as observed in this experiment.
If the overall P value is large, the data do not give you any reason to conclude that the means differ. Even if the population means were equal, you would not be surprised to find sample means this far apart just by chance. This is not the same as saying that the true means are the same. You just don't have compelling evidence that they differ.

If the overall P value is small, then it is unlikely that the differences you observed are due to random sampling. You can reject the idea that all the populations have identical means. This doesn't mean that every mean differs from every other mean, only that at least one differs from the rest. Look at the results of post tests to identify where the differences are.

In PDE experiments, p value is observed to be 3.95E-32, which is very small, so random sampling differences are observed.

B. F Ratio and ANOVA table

The P value is computed from the F ratio which is computed from the ANOVA table.

ANOVA partitions the variability among all the values into one component that is due to variability among group means (due to the treatment) and another component that is due to variability within the groups (also called residual variation). Variability within groups (within the columns) is quantified as the sum of squares of the differences between each value and its group mean. This is the residual sum-of-squares. Variation among groups (due to treatment) is quantified as the sum of the squares of the differences between the group means and the grand mean (the mean of all values in all groups). Adjusted for the size of each group, this becomes the treatment sum-of-squares.
Each sum-of-squares is associated with a certain number of degrees of freedom (df, computed from number of subjects and number of groups), and the mean square (MS) is computed by dividing the sum-of-squares by the appropriate number of degrees of freedom. These can be thought of as variances. The square root of the mean square residual can be thought of as the pooled standard deviation.

The F ratio is the ratio of two mean square values. If the null hypothesis is true, you expect F to have a value close to 1.0 most of the time. A large F ratio means that the variation among group means is more than you'd expect to see by chance. You'll see a large F ratio both when the null hypothesis is wrong (the data are not sampled from populations with the same mean) and when random sampling happened to end up with large values in some groups and small values in others.

The P value is determined from the F ratio and the two values for degrees of freedom shown in the ANOVA table.

F Ratio in PDE experiments is observed to be 78.29388, which shows that value is on higher side, but still in significant region.

C. Tests for equal variances

ANOVA is based on the assumption that the data are sampled from populations that all have the same standard deviations. Prism tests this assumption with two tests. It computes the Brown-Forsythe test and also (if every group has at least five values) computes Bartlett's test. Both these tests compute a P value designed to answer this question:

If the populations really have the same standard deviations, what is the chance that you'd randomly select samples whose standard deviations are as different from one another.

The same observations are also observed in PDE experimental data analysis.

More so, f_{crit} is 3.055, which is also stating that samples are wide spread, but however in the acceptable limits.

VI. DISCUSSION

From the above analysis, it is proved that reproducibility of pressure variations in PDE tube at pressure port 1 is significant, random and repetitive, but within limits. Team has carefully studied the causes of these variations. The main causes are listed below [2]:

- Variation of source line pressures due long pressure lines
- Higher pressure range gauges at rig

- Erratic behaviour of PFR & Dome loaded pressure regulator
- Purity and homogeneity of fuel and air
- Injector issues:
  - design and fabrication issues
  - non homogenous mixing
- Schelkin spiral issues:
  - Mounting mechanism not restrained from vibrations
  - Long length giving shock reflections
  - Random pressure sensor/transmitter touches
- Ignition Command Issues:
  - relay getting stuck or improper contacts
  - Mechanical lags in command following
  - ECCU fire pulse design & time resolution problems
- Ignitor Issues:
  - Body cracking due vibration or ceramic damage
  - Carbon formation at tip
- Misc. Issues
  - heating of tube
  - online variation of pressure
  - contamination
  - sediments in lines and filters
  - leakage and age related problems

All these problems are being addressed simultaneously. The variations in pressures have reduced significantly after addressing key issues of gauges, mounting mechanism of Schlekin spiral, new ignition system design etc. The process of design of injector, ECCU and Fire control system will take one year plus and remaining issues also will get resolved. If these problems are addressed properly, then PDE can be easily to an engine for future aerospace applications [10].

VII. Conclusions

After this analysis, the team is able to identify the pattern of fluctuation of parameters, which is inherent across globe in PDE technologies. Due which, the focus has moved to correct the various shortcomings in design and trial management to help team to execute time bound assignment of give the system with less than 10 % variation in pressure in 95 % of samples of trial data in operable zone of trial, leaving first one second and last one second. This involves development of new systems and technologies as covered in para VI. By incorporating few of the modifications, the results are encouraging. The system will work within the specified band by improving the identified issues within a span of one year.

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References

[1] Sanjay Kumar Soni , Amarjit Singh, Manmohan Sandhu, Aashish Goel, Ram Kumar Sharma, **"Numerical simulation to investigate the effect of obstacle on detonation wave propagation in a pulse detonation engine combustor",** International Journal of Emerging Technology and Advanced Engineering Volume 3, Special Issue 3: ICERTSD-2013, ISSN 2250-2459, pp 458-464, 2013.

[2] Subhash Chander, TK Jindal, "**Integration Challenges in Design and Development of Pulse Detonation Test Rig**" International Journal of Advance Research in Electrical, Electronics and Instrumentation Engineering, Volume 1, Issue 4, ISSN: 2278-8875, DOI : 10.15662/ijareeie, pp 291-304, 2012.

[3] Frank K. Lu, **"Progress and Challenges in the Development of Detonation Engines for Propulsion and Power Production",** Applied Mechanics and Materials, ISSN: 1662-7482, Vol. 819, pp 3-10, 2016.

[4] Subhash Chander, Tejinder Kumar Jindal, "**Performance Enhancement of Surface to Air Missile by Application of Pulse Detonation Engine based Secondary Propulsion System**", International Journal of Mechanical Engg. (IJME), Recent Science Publications, 2014.

[5] Subhash Chander, Dr. TK Jindal, "**Design of Automated Fire Control System for C_2H_2/O_2 Pulse Detonation Rig**", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 2, Issue 2, ISSN: 2278-8875, DOI : 10.15662/ijareeie, pp 924-932, 2013.

[6] Ramamurti, K, **"Explosions and Explosion Safety",** Tata Mcgraw Hills Publishing Co. Ltd., ISBN 9780070704473, 2010

[7] Kothari, CR, Garg, G., **"Research Methodology: Methods and Techniques",** ISBN-13: 978-8122436235, New Age Publishers, 2014.

[8] Montgomery, D.C., Runger, G.C**., "Applied Statistics and Probability for Engineers",** John Wiley & Sons, 2003.

[9] Eva Ostertagová, Oskar Ostertag,**"Methodology and Application of Oneway ANOVA",** American Journal of Mechanical Engineering, Vol. I issue 7, ISSN (Print): 2328-4102, ISSN (Online): 2328-4110, DOI : 10.12691, pp 256—261, 2013.

[10] Subhash Chander, Tejinder Kumar Jindal, "**A study of possible technical aspects needed to be addressed in respect of system engineering of surface to air missile by application of pulse detonation engine**", International Journerl of Mechanical Engineering (IJME), Volume 1, Spl. Issue 1, ISSN: 1694-2302, pp 40-43 (2014).