UNIVERSITY OF COLORADO BOULDER

ASEN 2004 - VEHICLE DESIGN & PERFORMANCE

Static Test Stand Report

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GROUP 10

Lab Section 303 (12:30pm - 2:20pm)

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Contents

Nomenclature

CI	=	Confidence Interval
$\bar{X}$	=	mean of data
SEM	=	Standard Error of the Mean
s	=	standard deviation of the sample data
N	=	Number of Samples
I_{sp}	=	Specific Impulse [s]

Introduction and Theory

A static test stand is an important tool that is used to collect important data that is used for further analysis and determination of important variables. Typically a static test stand is used to collect data from the thrust of the rocket over time. This metric is important in determining the specific impulse of the rocket on the test stand. Specific impulse, I_{sp}, is a measure of how efficiently a rocket uses it's propellant and mathematically, that equates to the thrust divided by the propellant mass flow rate. Throughout this lab, specific impulse will be in units of seconds. With the thrust curve found from the static test stand, the specific impulse was found by taking the area under the thrust curve, the impulse, and dividing it by the mass of the propellant and the acceleration due to gravity. This specific impulse value calculated is important as it allows for a quick way to determine the thrust for the rocket, provides a quick way to determine engine efficiency, it greatly simplifies mathematical analysis of the rocket's thermodynamics, and it gives a way to determine engine requirements and specifications. It is expected that a water bottle rocket will have a specific impulse within the range of 1 to 2 seconds. Of course, there is uncertainty with this value. In order to be certain about this uncertainty, multiple simulation tests must be completed and it must be observed how accurate the uncertainty is. To determine the amount of tests needed, the confidence interval can be used. First, the standard error of the mean must be considered as it describes the accuracy of the resulting averages and sample values for any given test. With this found, using the confidence interval, a confidence level can be set and the number of tests required can be found. The confidence interval is equal to the mean of the data set plus the z-value times the standard error of the mean. The z-value represents a value that directly relates the standard deviation of the sample mean to the real mean. It is found statistically and corresponds to a desired confidence interval. With the aid of the confidence interval, the number of tests needed can be determined. If the specific impulse data was required to be ± 0.1 seconds at a given confidence, then the value of the z-value times the standard error of the mean, must be, less than 0.1 seconds. From this the number of tests required to complete for a certain confidence level can be determined

Materials and Methods

An integral part of the test setup, the static test stand was a custom build using industrial grade materials. It has two piezo crystal load cells on each end of the top plate with four clamps designed to secure a center plate which is placed in the square hole in the middle of the top plate. Below the top plate, two aluminum blocks are placed on a larger bottom plate with a circular hole in the center for the release of the pressurized water and air. The center plate is a square plate with threads designed for a coke bottle and a red sticker at one of the four corners that must line up with the red sticker on the top plate. The air pressurization system has two components, the airline that connects to the bottle and the air tank. The bottle airline has a quick connector to attach to the tank, a black rubber stop to be placed in the bottle and a white check valve to prevent water from leaking into the line. The air tank has two valves, a red one on the end of its line near the sensors and a yellow one on the tank, with both being closed when perpendicular to the line. The end of the tank line has two sensors, a accurate pressure gauge and a pressure regulator with a knob to control flow. The pressure in the tank must be checked as if it is any less than 40 psi the bottle will be inaccurately pressurized. The final piece of the setup is the launch plate which is a smaller metal plate that fits around the rubber stopper and has a string attached to it. These pieces of the setup can be seen in Figure 1.

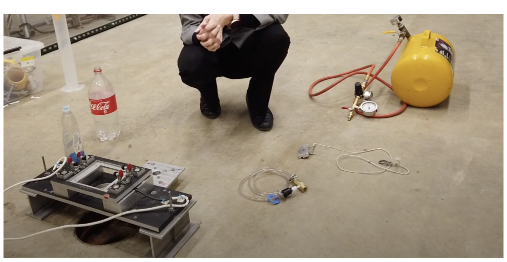


Fig. 1 Physical aspects of the test apparatus

To set up the test apparatus the bottle must first be filled with 1000 mL of water. Once filled and checked the bottle can be threaded into the center plate and the stopper can be pushed into the bottle after being coated in soap. The launch plate can then be installed to the stopper on the opposite side as the red dot. Checking that all connections are secure the bottle air line and the launch chord can be routed through the top of the test stand with the launch chord only going through the square hole and the tubing going through both the square and circle hole. Flipping the bottle, the center plate can be fitted into the square hole, ensuring that the red dot is on the correct side. Once this is completed the four clamps can be securely fastened and pressure can be applied to the bottle. To set the pressure the yellow valve should be opened while keeping the red valve closed and using the regulator knob to get 40 psi. At this point ensure all team members have safety glasses on and connect the tank and bottle air line using the quick connect. Opening the red valve slowly, hold it open for a few seconds before closing it, disconnecting the air tank and moving the air tank to a safe location. Wait for the VI team to zero the load cells and within five seconds perform the launch after a three second audible countdown.

To set up the VI a couple physical connections must first be double checked. First check that two white cords labeled channel 0 and channel 1 come from the test stand to the signal conditioner. Looking at the back of the conditioner ensure both switches are switched downward and that the conditioner is properly hooked up to the data acquisition box. Additionally, ensure strong connection to the sensor by checking the indicator on the front of the conditioner. Finally, ensure all of the hardware is correctly plugged in and turned on. Opening the VI from the lab computer, it will appear as seen in Figure 2, go through the reminders listed. Running the VI will prompt the user for test parameters and after entering these values continue and enter the test frequency as 1.652 kHz. Coordinating with the launch crew, use the knobs on the front of the conditioners to zero the sensors to at least one zero after the decimal. Once the countdown to launch reaches two, run the data capture and save the resulting file with the appropriate file name.

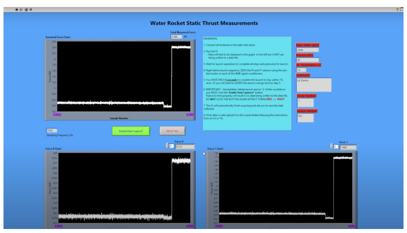
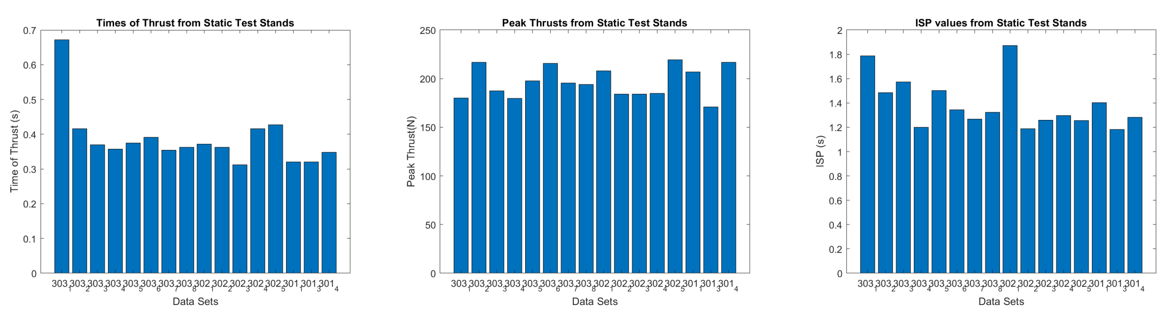


Fig. 2 Static test VI

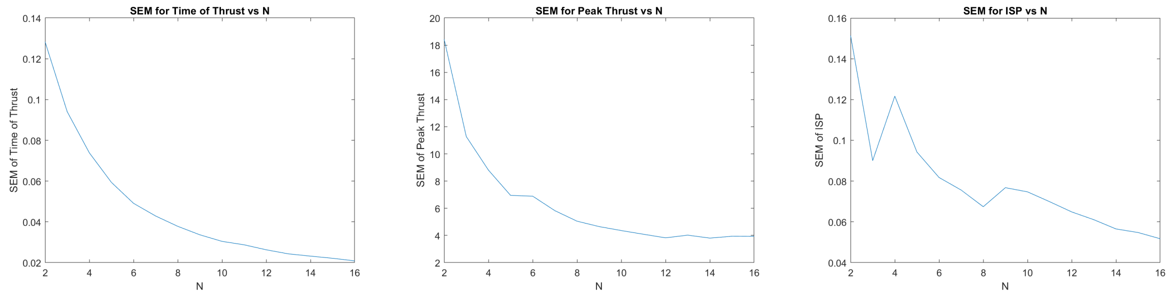
To analyze data from static tests a MATLAB script was developed that could calculate I_{sp} from a given test data set. The script reads in a file using predetermined naming conventions and divides data based on section. A function is called that loads file data and pulls the summation of load cell values into one vector, converting to Newtons, and creating a corresponding time vector using the frequency. Due to the data files containing excess data, it must be truncated before the integral of the force curve can be taken. This is done by calculating an average value of data points before and after thrusting and comparing data points to this average. Once the data points leave a predetermined tolerance range from the first average the rocket is assumed to be thrusting and once the data has reentered the tolerance of the second average for a certain number of consecutive points the rocket is assumed to have stopped thrusting. The first tolerance is larger than expected so that the script can discriminate when the force reading is caused by pulling the stopper non-horizontally. Using the newly determined range, a trapezoid approximation is done and the I_{sp} is calculated by dividing the force integral by propellant mass multiplied by the acceleration of gravity. The reason that a separate average value had to be calculated for before and after the thrust occurred was due to the zeroing of the sensors. Initially, the bottle contained water and pressurized air, resulting in a larger weight. Zeroing the sensor at this point results in an offset in the thrust diagrams once the contents of the bottle is expelled. This offset is mitigated by assuming a linear expulsion of mass and simply adjusting the thrust values for the added weight of the water and air before integrating the diagram.

Results



(a) Time of Thrust **(b) Peak Thrust** **(c) ISP Values**

Fig. 3 Comparisons Across all Data Sets



(a) Time of Thrust **(b) Peak Thrust** **(c) ISP**

Fig. 4 Standard Error of the Mean vs Number of Samples

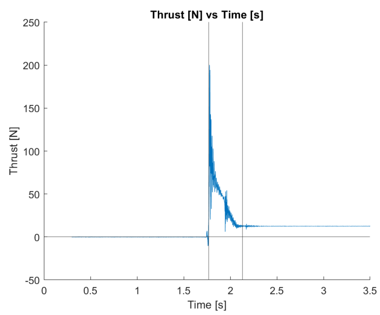


Fig. 5 Representative Force Curve From 303-1

The Average Peak Thrust and Time of Thrust were found to be 196 ± 16 N and 0.386 ± 0.08 s. SEM (Standard Error of the Mean) is used to indicate how well the mean from sample data represents the true mean. This value is found by dividing the standard deviation of the sample data by the number of samples. It is useful to use this when you have a large data set. SEM allows you to use a smaller sample size to represent the large data. This saves both time and processing power. Figure 4 shows the SEM values vs. the number of samples. the SEM is expected to decrease As more tests are added to the data set, because as more samples are added, the closer the calculation is getting to the true mean. The SEM of the full data set for ISP, Time of Thrust, and Peak Thrust is 0.05, 0.02, and 3.9.

Using the standard deviation of the specific impulse, 0.2069 seconds, and the z-value, the number of tests required to be within a certain confidence level can be determined as outlined in the theory section. It was found that to have a 95% confidence interval and a specific impulse within 0.1 seconds of the real mean, that 17 tests would need to be completed. If the difference from the real mean is changed to 0.01 seconds, there would need to be 165 tests completed to achieve a 95% confidence interval. Further percent confidence intervals and the amount of tests required to achieve that percent, can be viewed in Table 1.

Real Mean Difference / Percent Confidence	95%	97.5%	99%
0.1 [s]	17	22	29
0.01 [s]	165	215	285

Table 1 Number of Tests Required for Percent Confidence and Difference From Real Mean

Conclusion

Through calculating the SEM with an uncertainty of .1 seconds, it was determined that 17 tests are needed to establish a 95% confidence interval in the thrust data. This demonstrates that the mean of the values for the specific impulse becomes more accurate when there are more tests conducted. This is due to the fact that if a smaller uncertainty is desired, more tests are needed to fulfil a 95% confidence interval. In other words, as more tests are conducted, the 95% confidence interval describes an increasingly smaller uncertainty. This relates to uncertainty in the rocket flight performance in that 95% of the collected data points for the specific impulse will be within .1 of the mean specific impulse. This is true for all uncertainties as long as the required number of tests are run.

References

[1] ASEN 2004 Vehicle Design and Performance Textbook

Sellers, Jerry, Astore, William, Giffen, Robert, and Larson, Wiley. *Understanding Space*, Chapter 14. 3rd ed., The McGraw-Hill Companies, Inc., 2005.

[2] Water Bottle Rocket Lab Assignment Trudy Schwartz and Aaron Johnson. “Water Bottle Rocket Lab” Spring 2020, University of Colorado Boulder

[3] Error Lecture Torin Clark. “Review of Rocket Equation, Propulsion, Launch, Orbits+ Error Ellipses” Spring 2020, University of Colorado Boulder

[4] ASEN 2012 Textbook

Taylor, J. R., *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*, Chapters 1, 2, 3, 4. Mill Valley Ca.: University Science Books, 1997.

[5] Ann and H.J. Smead AES Laboratory and Shops Videos. "Static Test Stand VI Operation". *Youtube*. Available: https://www.youtube.com/watch?v=QnjWaGqrFBg&feature=youtu.be. Accessed April 13 2020

[6] Ann and H.J. Smead AES Laboratory and Shops Videos. "Static Test Stand Launching". *Youtube*. Available: https://www.youtube.com/watch?v=7YZ4B-DINqA&feature=youtu.be. Accessed April 13 2020

Appendix

Appendix A: Member Contributions

Name	Score	Tasks
MacPherson, Cole	100	Worked on introduction and theory. Computed and wrote about the data in Table 1
Taylor, Trey	100	Worked on the Methods and Materials, and helped develop the pseudo-code for the script
Uprety, Ankrit	100	Worked on Results, and set up report
Loewito, Daniel	100	Primary author of the script used to analyze and clean the data
Sechrist, Cole	85	Wrote the conclusion section and helped with proof reading and editing.
Schumacher, Bradley	74.7	proofread and edited report and contributed to appendix

Appendix B: MATLAB Code

Listing 1 Main Script

```
%No variables in 301-4

%housekeeping
clear;
clc;
close all;

name = [];

data_303 = [];
for k = 1:8
    filename = sprintf('LA_Demo_303_%d',k);
    str = sprintf('303_%d',k);
    [t_thrust, I_sp, max_thrust] = datacleaner(filename);

    data_303 = [t_thrust I_sp max_thrust; data_303];
    name = [name; convertCharsToStrings(str)];
end

data_302 = [];
for k = 1:5
    filename = sprintf('LA_Demo_302_%d',k);
    str = sprintf('302_%d',k);
    [t_thrust, I_sp, max_thrust] = datacleaner(filename);

    data_302 = [t_thrust I_sp max_thrust; data_302];
    name = [name; convertCharsToStrings(str)];
end

data_301 = [];
for k = 1:4
    if k ~= 2
        filename = sprintf('LA_Demo_301_%d',k);
        str = sprintf('301_%d',k);
        [t_thrust, I_sp, max_thrust] = datacleaner(filename);
```

```
        data_301 = [t_thrust I_sp max_thrust; data_301];
        name = [name; convertCharsToStrings(str)];
    end
end

data = [data_303; data_302; data_301];
t_thrust = data(:, 1);
ISP = data(:, 2);
max_thrust = data(:, 3);

avg_t = mean(t_thrust);
avg_ISP = mean(ISP);
avg_max = mean(max_thrust);

std_t = std(t_thrust);
std_max = std(max_thrust);
std_isp = std(ISP);

% number of tests of 95% accuracy of 0.1 [s]
z = 1.96;
N_95_01 = ((z*std_isp)/(0.1))^2;

% number of tests of 97.5% accuracy of 0.1 [s]
z = 2.24;
N_975_01 = ((z*std_isp)/(0.1))^2;

% number of tests of 99% accuracy of 0.1 [s]
z = 2.58;
N_99_01 = ((z*std_isp)/(0.1))^2;

% number of tests of 95% accuracy of 0.01 [s]
z = 1.96;
N_95_001 = ((z*std_isp)/(0.01))^2;

% number of tests of 97.5% accuracy of 0.01 [s]
z = 2.24;
N_975_001 = ((z*std_isp)/(0.01))^2;

% number of tests of 99% accuracy of 0.01 [s]
z = 2.58;
N_99_001 = ((z*std_isp)/(0.01))^2;

%SEM STuff
N = [];
std_stuff = [];

for k = 2:numel(data(:,1))
   N = [N; k];
   std_stuff = [std_stuff; std(t_thrust(1:k)) std(ISP(1:k)) std(max_thrust(1:k))]; %t, isp
end

SEM_t = [];
SEM_ISP = [];
SEM_max = [];
```

```
for k = 1:numel(std_stuff(:,1))
    SEM_t = [SEM_t; std_stuff(k, 1)/sqrt(N(k))];
    SEM_ISP = [SEM_ISP; std_stuff(k, 2)/sqrt(N(k))];
    SEM_max = [SEM_max; std_stuff(k, 3)/sqrt(N(k))];
end

figure
plot(N, SEM_t)
title('SEM for Time of Thrust vs N')
xlabel('N')
ylabel('SEM of Time of Thrust')

figure
plot(N, SEM_ISP)
title('SEM for ISP vs N')
xlabel('N')
ylabel('SEM of ISP')

figure
plot(N, SEM_max)
title('SEM for Peak Thrust vs N')
xlabel('N')
ylabel('SEM of Peak Thrust')

figure
bar(ISP)
set(gca, 'XTick', 1:numel(ISP), 'XTickLabel', name);
title('ISP values from Static Test Stands')

figure
bar(t_thrust)
set(gca, 'XTick', 1:numel(t_thrust), 'XTickLabel', name);
title('Times of Thrust from Static Test Stands')

figure
bar(max_thrust)
set(gca, 'XTick', 1:numel(max_thrust), 'XTickLabel', name);
title('peak Thrusts from Static Test Stands')
```

Listing 2 Cleaning the Data

```
function [t_thrust, I_sp, max_thrust] = datacleaner(filename)
    %Does not work for files: 303_9, 301_2
    %Weird diagrams in: 303_8, 301_4

    %setup
    data = load(filename);
    data = data * 4.44822;          %N
    summ = data(:, 3);
    %Sampling rate 1625 Hz
    f = 1625;
    t = linspace(0, numel(summ)/f, numel(summ));

    %index of t = 0.3s and t = 3.5s
    i1 = numel(t) - numel(t(t>0.3));
```

```
i2 = numel(t(t<3.5));

%Truncate data
summt = summ(i1:i2);
t = t(i1:i2);

%tolerance of 1N
tol = 25;

%avg from phase 1 and 2
avg1 = mean(summ(1:i1));
avg2 = mean(summ(i2:end));

tolmet = true;
index1 = 1;
while tolmet
    index1 = index1 + 1;
    if abs(summt(index1) - avg1) > tol
        tolmet = false;
    end
end

tol = 1;
index2 = index1;
tolnotmet = true;
count = 0;
while tolnotmet
    index2 = index2 + 1;

    %it prefires otherwise
    if abs(summt(index2)-avg2) < tol
        count = count + 1;
    else
        count = 0;
    end

    if abs(summt(index2)-avg2) < tol && count > 20
        tolnotmet = false;
    end
end

t_thrust = t(index1:index2);
sum = summt(index1:index2);

figure
hold on
plot(t, summt)
yline(0);
xline(t(index1));
xline(t(index2));
xlabel('Time [s]')
ylabel('Thrust [N]')
title('Thrust [N] vs Time [s]')
```

```
    %mass from the data file
    m = 1;          %kg
    g_0 = 9.81;          %m/s^2
    avg_offset = avg2/2;     %N
    sum = sum - avg_offset;    %adjusted
    I_sp = trapz(t_thrust, sum)/(m*g_0);
    max_thrust = max(sum);
    t_thrust = t_thrust(end) - t_thrust(1);
    %{
        figure
    hold on
    plot(t, summt-avg_offset)
    yline(0);
    xline(t(index1));
    xline(t(index2));
    xlabel('Time [s]')
    ylabel('Thrust [N]')
    title('Thrust [N] vs Time [s]')
    %}
end
```

Appendix C: MATLAB Figures

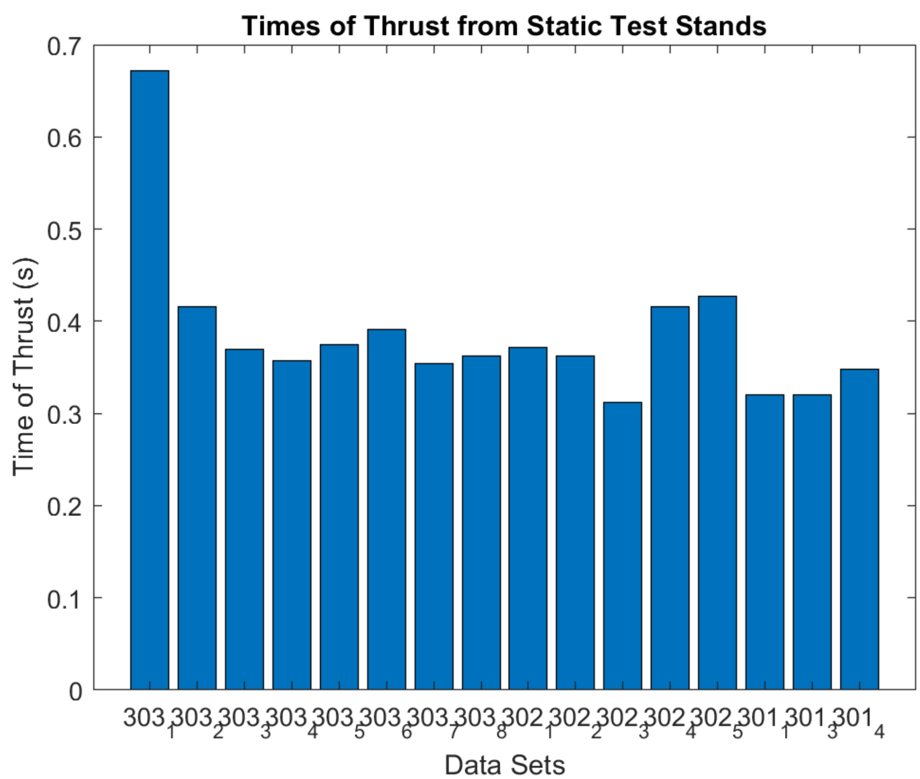


Fig. 6 Time of Thrust

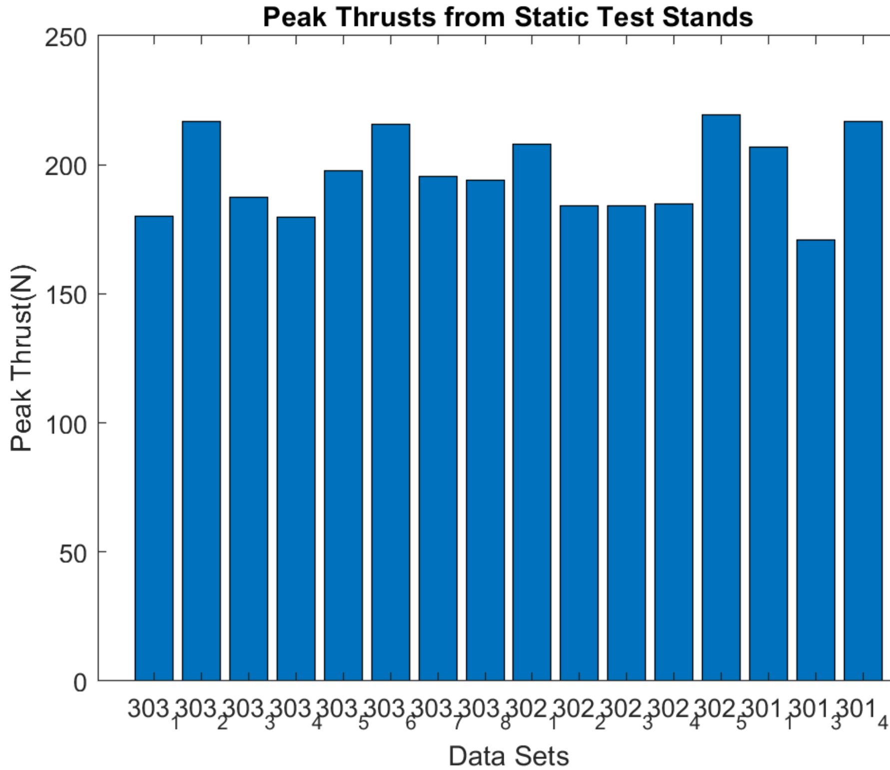


Fig. 7 Peak Thrust

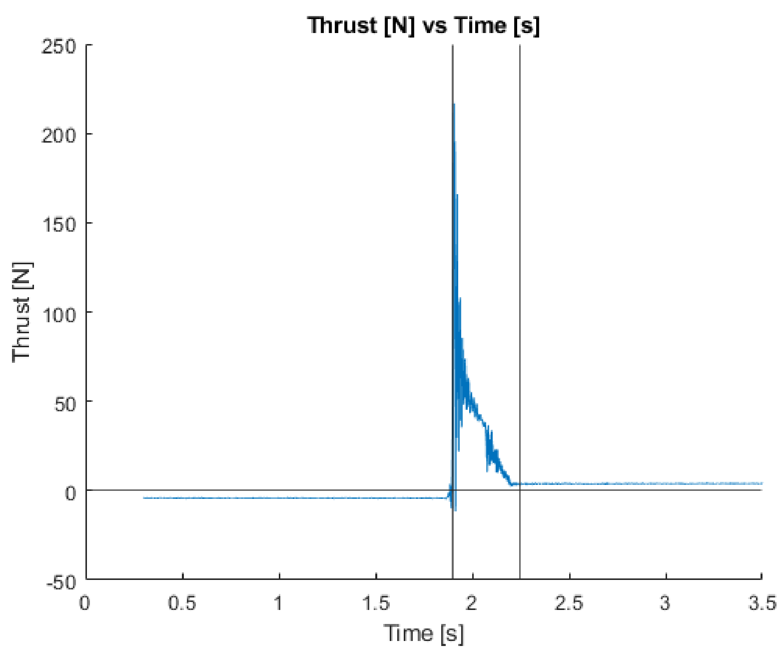


Fig. 8 Thrust Diagram from Test 301-1

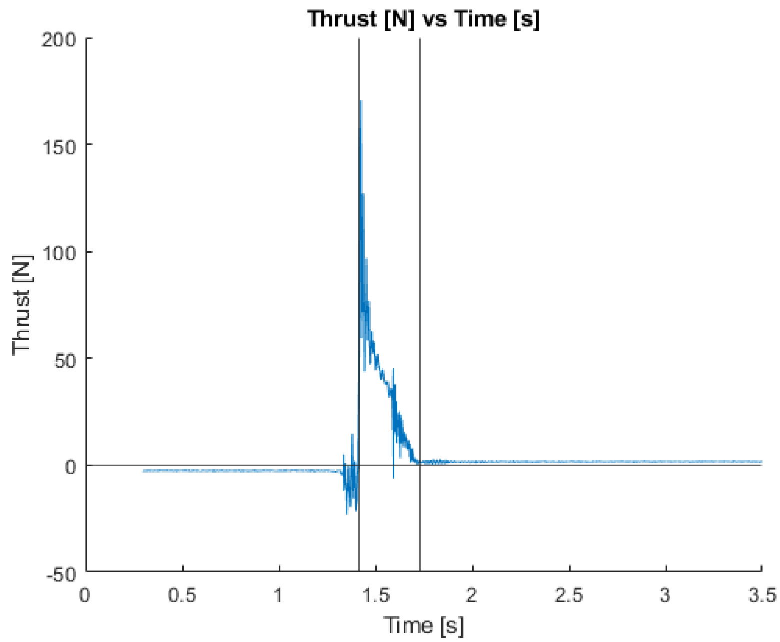


Fig. 9 Thrust Diagram from Test 301-3

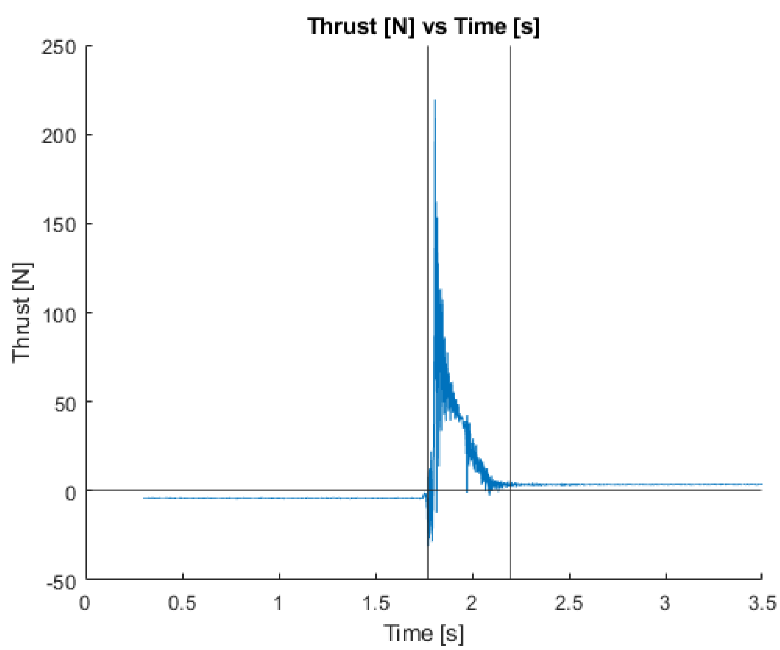


Fig. 10 Thrust Diagram from Test 302-1

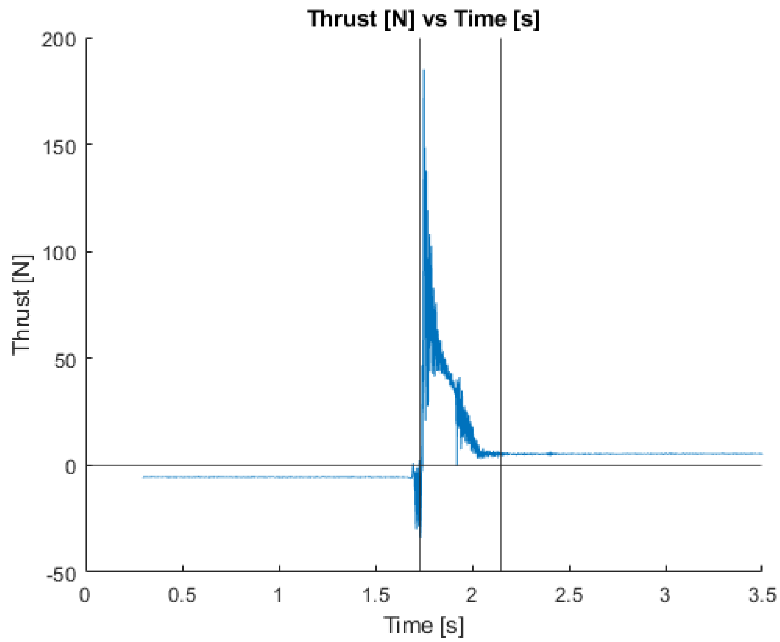


Fig. 11 Thrust Diagram from Test 302-2

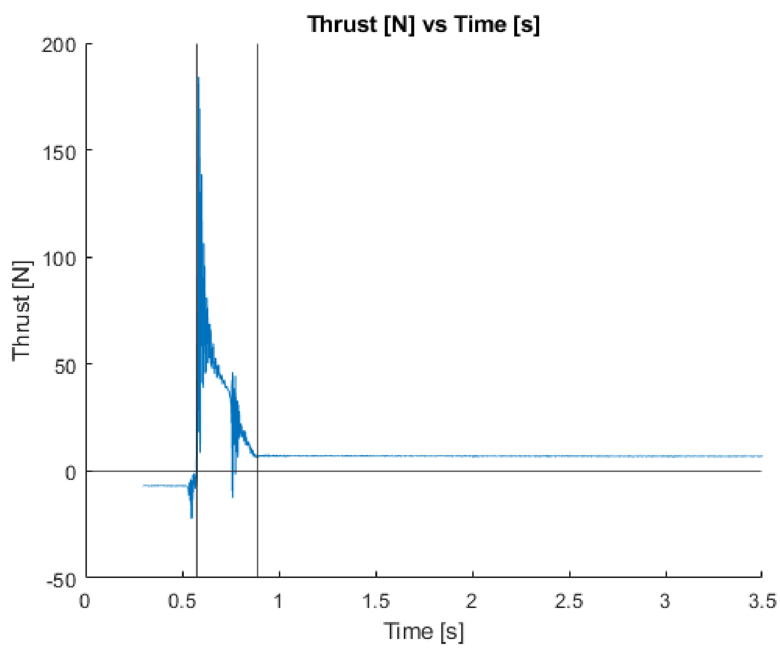


Fig. 12 Thrust Diagram from Test 302-3

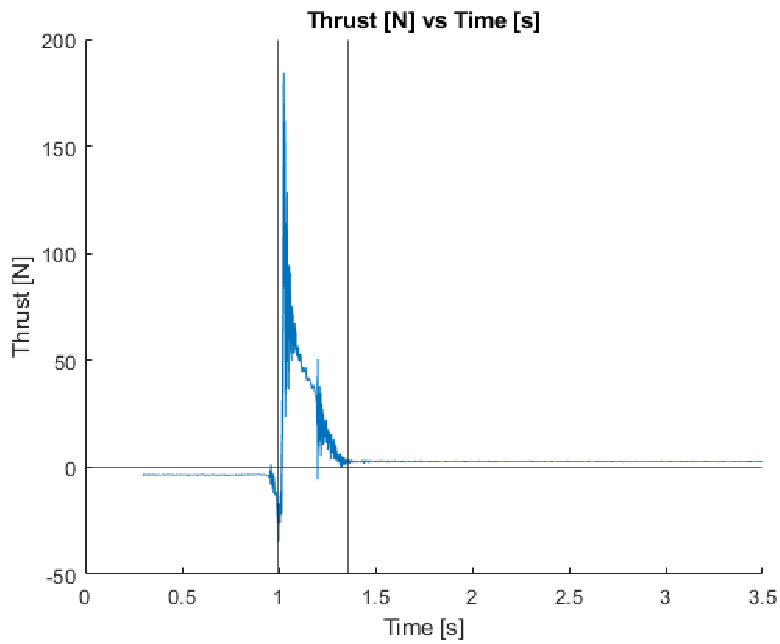


Fig. 13 Thrust Diagram from Test 302-4

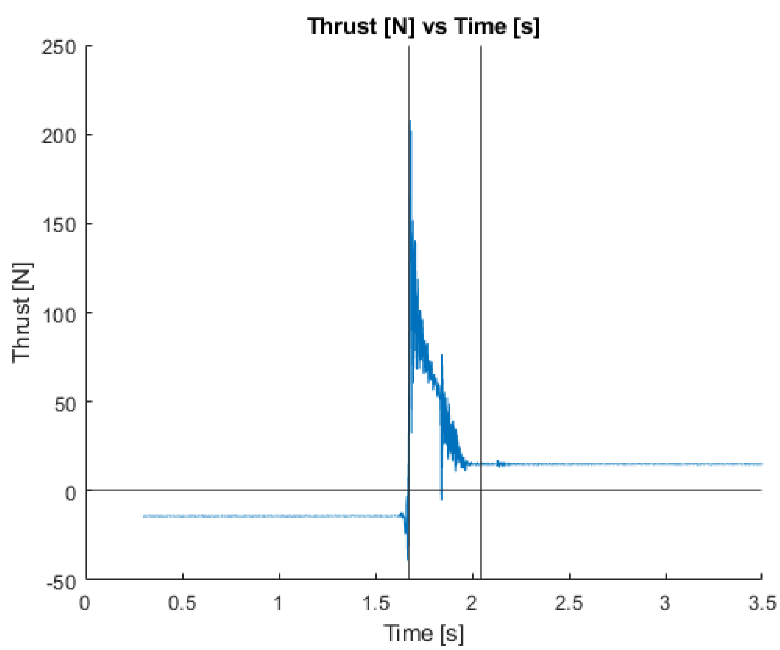


Fig. 14 Thrust Diagram from Test 302-5

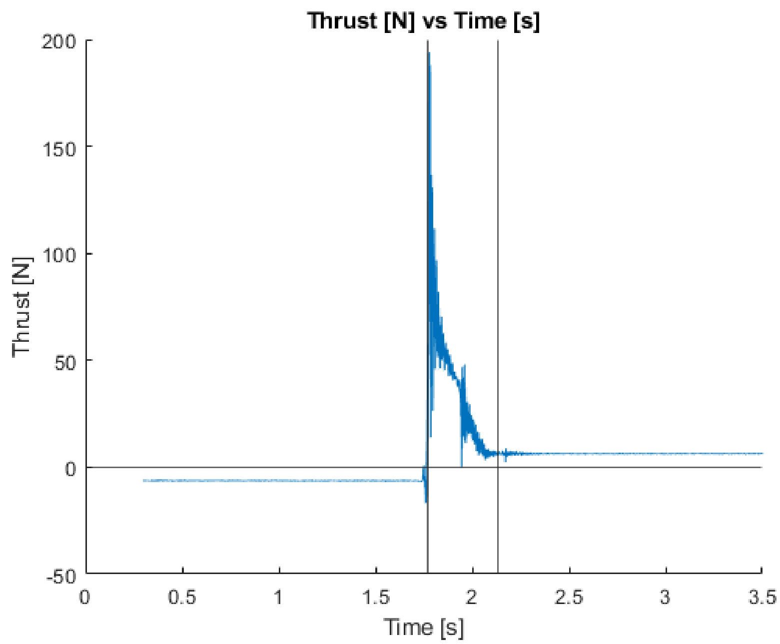


Fig. 15 Thrust Diagram from Test 303-1

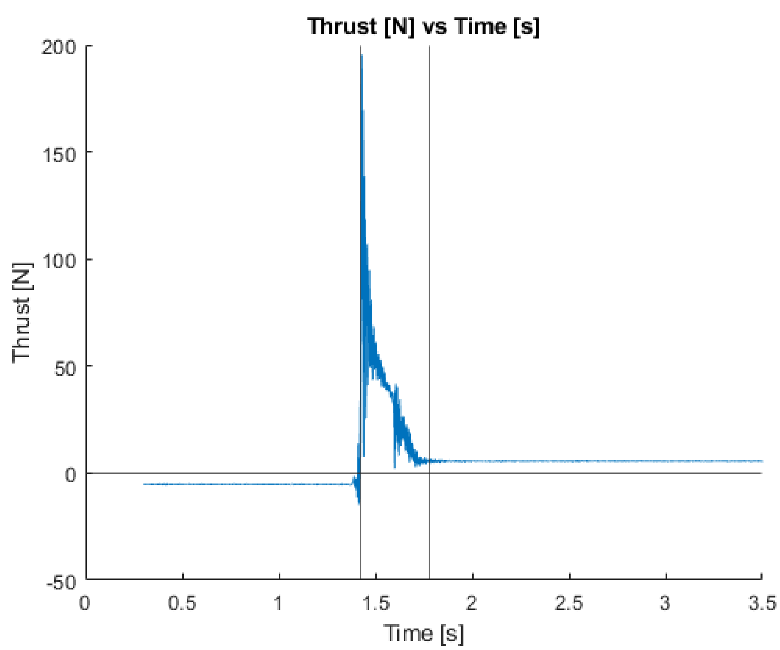


Fig. 16 Thrust Diagram from Test 303-2

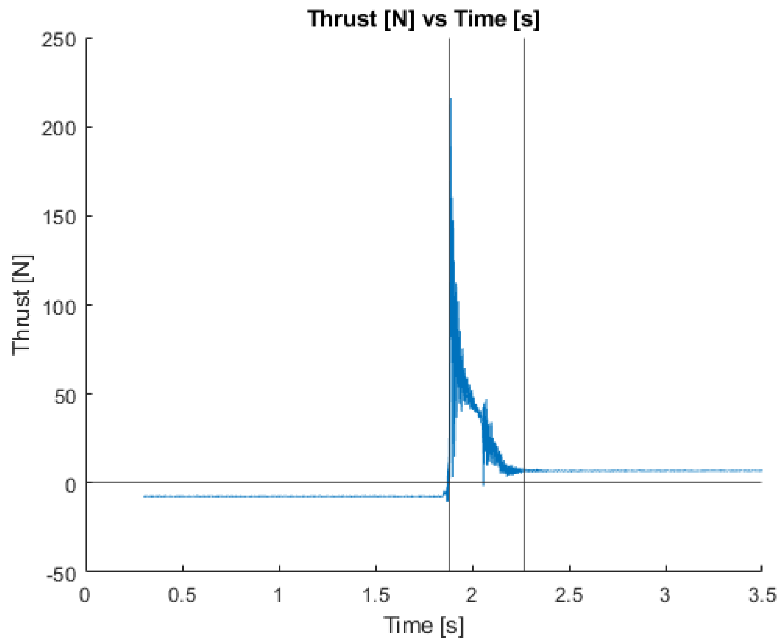


Fig. 17 Thrust Diagram from Test 303-3

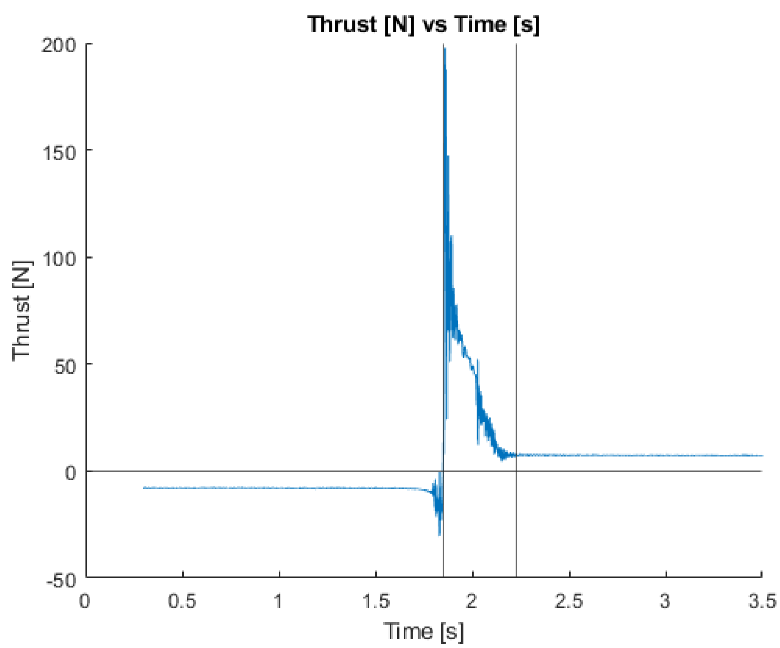


Fig. 18 Thrust Diagram from Test 303-4

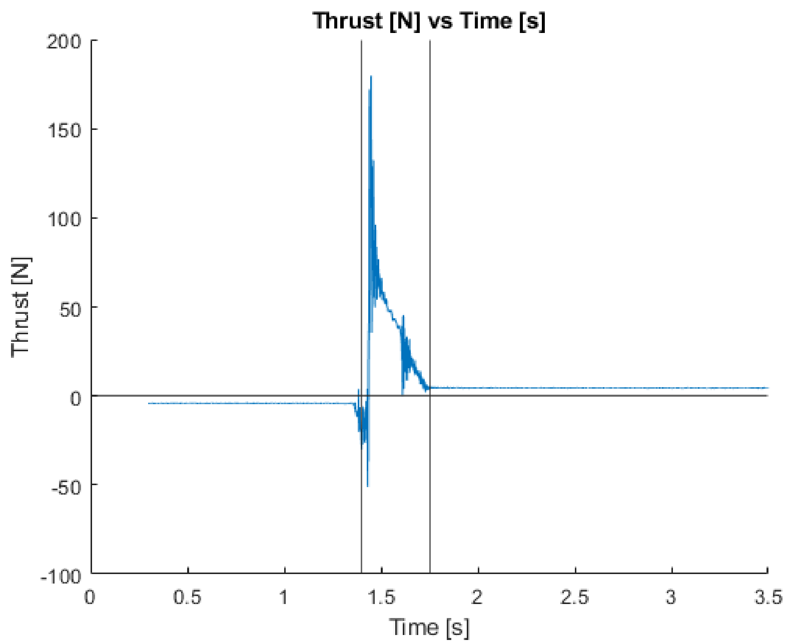


Fig. 19 Thrust Diagram from Test 303-5

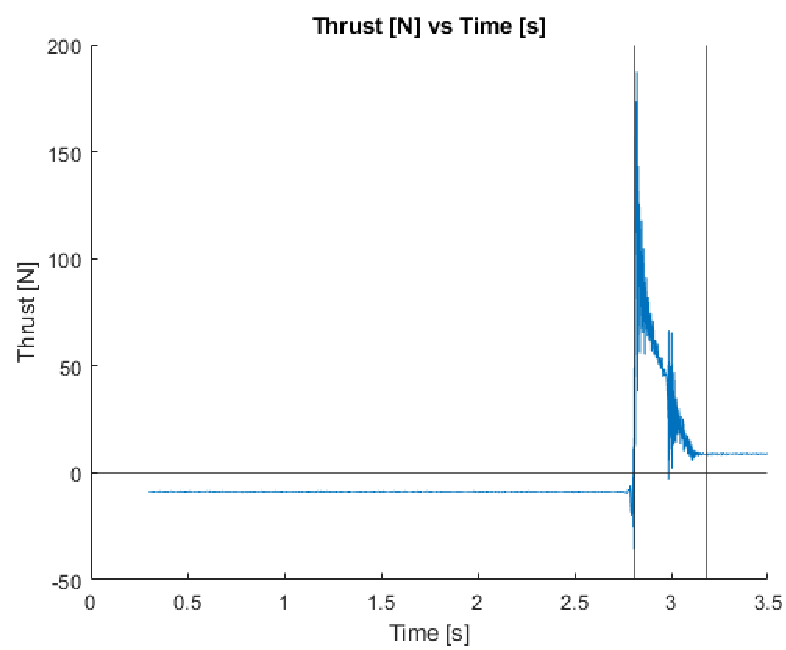


Fig. 20 Thrust Diagram from Test 303-6

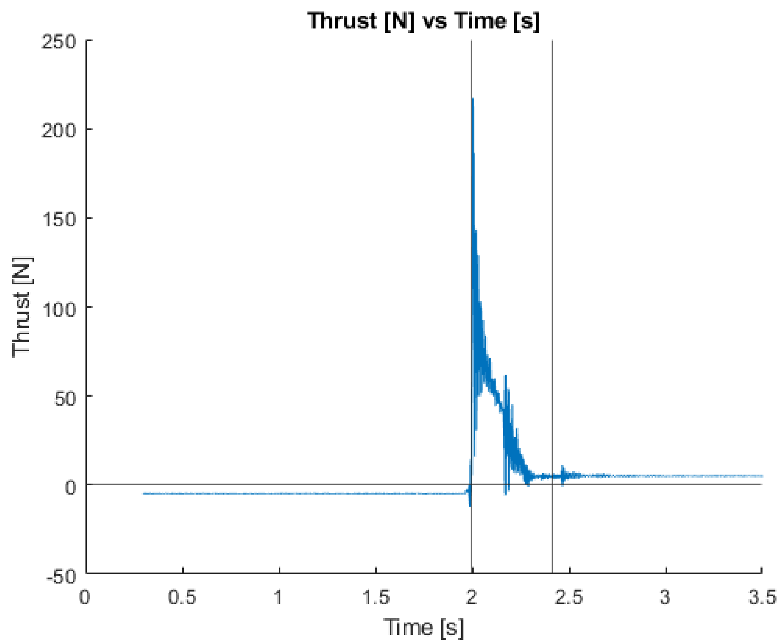


Fig. 21   Thrust Diagram from Test 303-7

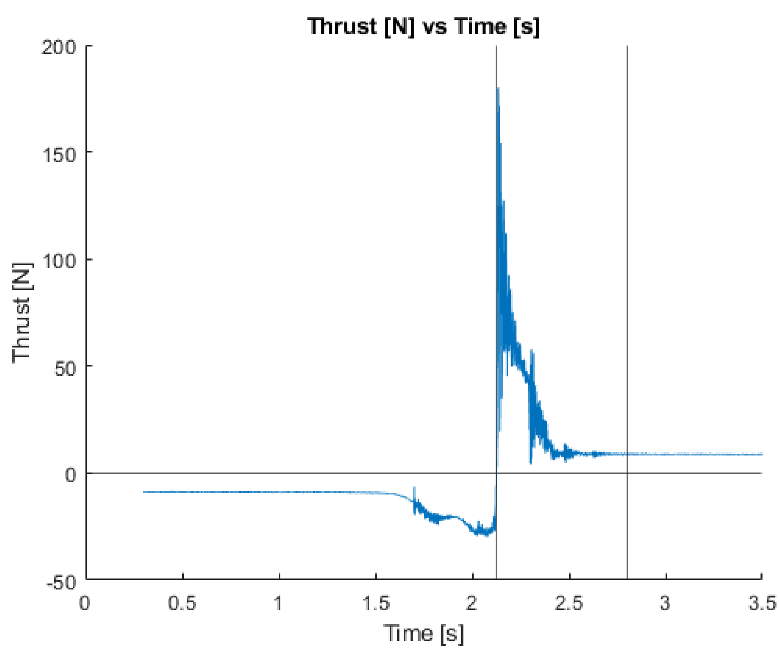


Fig. 22   Thrust Diagram from Test 303-8