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USING DIFFERENTIAL PRESSURE SENSOR TO MEASURE NITROUS OXIDE LEVEL IN A TANK

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Abstract

A method for measuring the level of liquid nitrous oxide oxidizer in a hybrid rocket motor oxidizer tank is proposed. Presented approach is more accurate than the most commonly used method of this measurement, which employs weighting of the whole sounding rocket or an oxidizer tank. In our solution we use a differential pressure sensor to measure the change of pressure at the bottom of an oxidizer tank in comparison to the pressure of the gas phase above the liquid. Due to usage of a relatively short oxidizer tank, with height of 900 mm, and density of nitrous oxide being smaller than water, at 786.6 $\frac{kg}{m3}$, measured pressure differences are small, which requires high resolution of the sensor.

Our system was prepared to work in a hybrid rocket motor of SimLE student organisation from Gdansk University of Technology (Gdansk, Poland). Developed propulsion system is designed to allow a sounding rocket with 4 kg of payload to accurately reach a flight altitude of 3000 m. The reason for accurate calculation of oxidizer amount in a tank is precise altitude planning for a sounding rocket launch which does not employ any active aerobraking system. For this flight strategy, accurate measurement of engine parameters is crucial.

The described system is theoretically able to measure liquid level with a 5 mm resolution, which corresponds to roughly 50 g of nitrous oxide in the tank. Other approach, using a load cell, showed measurement resolution of 100 g of weight difference. This method was susceptible to hysteresis due to friction and other external conditions on a launch rail. Preliminary results from hybrid rocket engine tests are presented along with perspective for further method improvement.

Nomenclature

F	force
g	standard gravity
h	height
m	mass
n	number
P	pressure
RC	Rated Capacity
RO	Rated Output
S	Surface
V	voltage
ρ	density

Subscripts

e	excitation
G	gaseous
h	hydrostatic
L	liquid

max	maximal
o	output
p	power
ref	reference
s	static
TR	total rocket

Acronyms/Abbreviations

ADC	Analog-Digital Converter
DPS	Differential pressure sensor
EuRoC	European Rocketry Challenge
NIST	National Institute of Standards and Technology
OIML	International Organization of Legal Metrology
SAC	Spaceport America Cup
SRAD	Student Research and Development

1 Introduction

Background for this work was laid during hybrid rocket engine development project in SimLE student organisation. Experiments with rocket propulsion begun in 2019, when the team decided to participate in Spaceport America Cup (SAC) 2020. Before this decision, our team's rocket could be propelled with commercial rocket motors, which are available in Poland in very limited supply.

In an attempt to prepare bigger rocket, more powerful engine must have been developed, this time by the team itself. Due to Polish law environment, student research and development (SRAD) of solid rocket motors is strictly prohibited, which leaves student rocketry teams or rocketry enthusiasts with two choices: hybrid or liquid propulsion. High complexity of the later made the team focus on hybrid propulsion.

1.1 R6 rocket

R6 rocket is the sixth rocket developed by SimBa - rocketry division of SimLE student organisation. R6 employs hybrid rocket engine which burns polypropylene and polyamide as fuel, and nitrous oxide as oxidizer. It is developed by the team to participate in international rocketry competitions, such as SAC or European Rocketry Challenge (EuRoC). In both cases, the main goal is to deliver ca. 4 kg of scientific payload to a flight altitude of ca. 3 km [1], [2]. Most important information about R6 rocket is summarised in the Table 1.

Table 1: Rocket dimensions and weights summary

Rocket length	4470 mm
Rocket diameter	153 mm
Vehicle weight	27.45 kg
Payload weight	4.00 kg
Propellant weight	11.27 kg
Lift-off weight	42.73 kg

Nitrous oxide filling system described in this paper was conceived as a part of R6 rocket propulsion system, therefore many weight and dimensional constraints are derived from the rocket capabilities.

1.2 Differential pressure sensor

The Differential Pressure Sensor (DPS) proposed in this paper is a component of oxidizer filling system. The reason for its usage is testing of a new method of nitrous oxide level measurement in a tank. Prior to experiments with DPS, our team's approach was based on a load cell and aimed to measure the weight of a rocket mounted on a launch rail during oxidizer filling procedure. The weight method, with various approaches, is often used among other student rocketry teams using hybrid rocket motors [3], yet it comes with drawbacks, which will be discussed later in this paper.

Usage of DPS aims to mitigate the drawbacks of weighting method and increase level measurement precision, which is crucial to properly predicting rockets flight altitude. In this approach we measure the difference between static pressure of an gaseous phase of an oxidizer in the top of the tank and hydrostatic pressure of an liquid phase exerted on the bottom of it. This method is used commercially, for example to measure level of cryogenic liquids [4], [5]. Additionally, our sensor of choice is equipped with thermometer on its pressure sensing membrane, which allows us to determine the density of an oxidizer. Combination of these two variables allows us to measure the liquid level.

1.3 Work objectives

This paper provides description of developed system used to measure nitrous oxide level in a tank described subsection 3.1. Main goals of our project are:

- Theoretical background of a method
- Preparation of working system
- Determination of systems parameters

- Comparison of our novel system with previous approaches

2 Theory and calculation

This section aims to provide background for comparison of the two approaches to nitrous oxide level measurement our team decided to use in the project. Firstly, necessary calculations for both methods will be presented, then methods will be discussed along with their perceived benefits and drawbacks.

2.1 Weight measurement

Weighting method utilises some kind of force sensor, mounted usually under the rocket on a launch rail [3] or inside the rocket to measure only the nitrous oxide tank. Different placements are also possible, that is to measure the oxidizer mother bottle, but this approach presents even more difficult to predict inaccuracies. Those inaccuracies come from possible leaks in the filling system or complexity of determination of nitrous amount in fittings between the mother bottle and the rocket's tank.

Author's sensor of choice when measuring the weight of a rocket was a load cell. Load cells come in many shapes, but in general rely on measuring strain of the known material to determine the load placed on it. This measurement is based on strain gauges in quarter-, half- or full-bridge circuitry, most often already compensated for temperature [6].

2.1.1 Constraints

- Allowed load of the sensor must be higher than total weight of a rocket
- Sensor must fit in desired mounting position

2.1.2 Calculations

Equations provided below will consider two main cases: measuring load cell output using ADC or relying on accuracy class if used load cell was certified by International Organization of Legal Metrology (OIML).

The first method relies on rated capacity (RC), rated output (RO) and excitation voltage (V_e) of a load cell and number n of ADC bits based on its V_{ref}. The lowest voltage change possible to measure using ADC is:

$$\Delta V = \frac{V_{ref}}{2^n} \tag{1}$$

When the load cell is loaded to its RC, its output after [6] will be:

$$V_{max} = V_e * RO \tag{2}$$

Force measured with an load cell with known V_{max} is:

$$F = \frac{V_o}{V_{max}} * RC \tag{3}$$

Therefore, combining information from equations 1 and 3, minimal force difference measured in this setup will be:

$$\Delta F = \frac{\Delta V}{V_max} * RC \tag{4}$$

The second method, based on OIML recommendation [7], uses Cx class of a load cell, where x is the number of thousandfold divisions of a RC. In this method, lowest load change possible to measure is:

$$\Delta F = \frac{RC}{x * 1000} \tag{5}$$

2.2 Differential pressure measurement

Differential pressure measurement method is based on assumption, that pressure in gaseous phase of an oxidizer (later referred to as the static pressure) is uniform. With this assumption, we can identify the two pressures in the system: static pressure of gaseous phase in the top of the tank, and the static pressure with an addition of hydrostatic pressure of a column of liquid oxidizer in the bottom of it. By using the DPS, we can obtain the difference between the two pressures, which in result will be only the hydrostatic pressure of the liquid [8].

DPS must be placed inside of an rocket and be tightly connected to the oxidizer tank, which is more challenging than engineering associated with weighting method. Authors DPS of choice is a membrane type digital sensor, further described in subsection 3.2, which mitigates the need to prepare data acquisition system for it and provides already calibrated measurements.

2.2.1 Constraints

- Allowed static pressure of the DPS must be more than 120 bar
- DPS must fit inside the flight vehicle
- Hydraulic connections to both ends of oxidizer tank must be possible

2.2.2 Calculations

Hydrostatic pressure (P_h) of the liquid column of known height (h_L) depends on the static pressure (P_s) above it, the gravitational acceleration (g) and the liquid density (ρ_L):

$$P_h = P_s + \rho_L * g * h_L \tag{6}$$

Since we measure only the difference between static pressure and hydrostatic pressure from equation 6, equation for column height can be stated as:

$$h_L = \frac{P_o}{g * \rho_L} \tag{7}$$

Output pressure P_o will be provided by an DPS, so the last variable to determine is the density of used liquid. By measuring the oxidizer temperature, its density could be obtained using one of the publicly available databases (*REFPROP* by NIST [9]) or papers such as [10].

Example pressure and density vs. temperature curves are shown on Figure 1. This data can be used to determine nitrous oxide density using the temperature readout from the DPS.

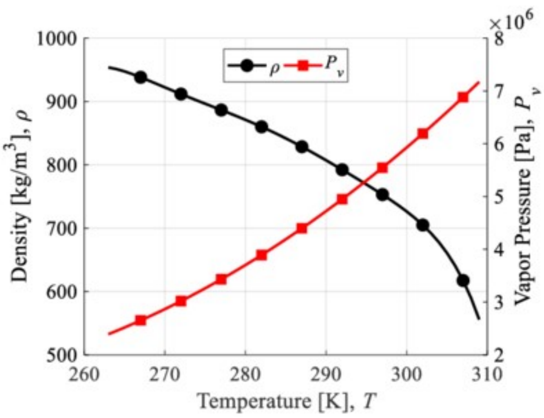

Figure 1: Pressure and density properties of liquid nitrous oxide [10]

To process this density data in a measuring system, a curve will be fitted to existing numerical data, and coded in the information processing system.

3 Materials and methods

This section describes hardware used by the authors in their experimental setup. Used oxidizer tank will be described along with DPS, load cell and measuring electronics. Methods for data acquisition and processing will be provided.

3.1 Oxidizer tank

The tank for the H-15 hybrid rocket engine from a R-6 rocket is used as and container for nitrous oxide during our experiments. It was designed and manufactured by members of SimLE scientific society. Its dimensions are summarized in the Table 2.

Table 2: Oxidizer tank main parameters

Dimension	Value
Length	900 mm
Diameter	135 mm
Volume	10 l
Material	Aluminum AW2007

Tank is equipped with a safety relief valve, absolute pressure sensor and (-) side connection to DPS on the upper ending. The lower ending has connections for (+) side of DPS and the main oxidizer outlet. On both tank ends additional thermocouples are mounted. For operation during winter months, tank could also be wrapped in a heating mat and additional layer of insulation, to maintain proper temperature of nitrous oxide.

3.2 DPS

In this setup PD-33X differential pressure transmitter manufactured by KELLER Druckmesstechnik AG is used. This sensor's most important properties are shown in the Table 3.

Table 3: PD-33X specification [11]

Differential pressure	300 mbar
Accuracy	0.05 % Full Scale
Total error	0.1 % Full Scale
Line pressure	200 bar
Interfaces	RS485, 4-20 mA
Application	Wet/Wet

Additionally, when using this sensor in digital communication mode (via RS485), one can access more values than only differential pressure output, such as measuring diaphragm temperature. This allows authors to more precisely determine the density of measured liquid using density tables from NIST.

3.3 Load Cell

NA151 Load cell manufactured by MAVIN was used in the experiment. During initial system development this relatively inexpensive model was chosen, due to one-time usage of this sensor, which was destroyed by motor exhaust after every rocket launch. Load cell's parameters are summarised in the Table 4.

Table 4: NA151-100 specification [12]

Rated Capacity	1000 N
Rated Output	2.0 mV/V
OIML Class	C2
Recommended Excitation	5-12 V

4 Results

Sample calculations of resolution will be presented in this section. This information will provide basis for further discussion of both researched methods of measurement of liquid nitrous oxide amount in the tank.

4.1 Sample calculation

Firstly, minimal liquid column height difference measurable by PD-33X DPS will be calculated. Taking its specification, from Table 3, we can read that its *Total error* is *0.1% Full Scale*, which refers to its *Differential pressure* measurement. This allows us to calculate minimal pressure difference:

$$\Delta P = 0.1\% * 300\,mbar = 0.3\,mbar = 30\,Pa \qquad (8)$$

For this calculation we will assume density of liquid nitrous oxide at 25 °C to be $\rho_{L@25°C} = 780\,\frac{kg}{m^3}$ [13]. Taking above values, and putting them into Equation 7 gives:

$$\Delta h_L = \frac{\Delta P}{g * \rho_{L@25°C}} = 3.92\,mm \qquad (9)$$

In a tank described in section 3.1 this Δh_L would be equivalent to:

$$\Delta m_L = \Delta h_L * S * \rho_L = 43.7\,g \qquad (10)$$

where S is the surface of oxidizer tank of circular cross-section.

Secondly, using Equation 5 and parameters from Table 4 about NA151 load cell, we can calculate the best possible resolution of this method of nitrous oxide level measurement. As NA151 load cell is a *C2* class instrument with $RC = 600\,N$, we can calculate the ΔF as:

$$\Delta F = \frac{1000\,N}{2 * 1000} = 0.5\,N \qquad (11)$$

To calculate the weight-resolution, we need to use Newton's Second Law:

$$\Delta m_L = \frac{\Delta F}{g} = 50\,g \qquad (12)$$

4.2 Experimental data

Unfortunately, due to logistics problems which authors encountered after their participation in SAC 2022, proper experimental data could not be obtained for this paper and acquiring it is the first goal for further work in this topic.

5 Discussion

Sample calculation presented above present only a slight advantage of DPS measurement in comparison with weight measurement system. However authors' previous experience shows, that the lack of directness of the later method presents many problems not occurring in the first one.

Errors occurring when employing the rocket weighting method are:

- Hysteresis in the measurement, due to friction between the rocket and a launch rail
- High susceptibility to environmental factors, especially wind

With this factors included, authors were unable to measure rocket weight with greater accuracy than $\pm 200\,g$, which introduces significant error to the flight altitude prediction. In extreme cases, rocket movements, amplified by the existence of friction, changed weight read-outs by a factor of kilogram, which is nearly 20% of total oxidizer capacity of a tank.

In the vicinity of nominal oxidizer amount in our tank, which is $\sim 6000g$, at standard operating temperature of $\sim 20°C$, each $100g$ of oxidizer correspond to roughly 3% of the flight altitude. While it does not seem to be a significant difference, in highly competitive environment of student rocketry competition it could result in different position in overall classification of a team.

Method based on differential pressure measurement seems to be more accurate, and less susceptible to outside errors, when compared to weighting method, however it comes with its own drawbacks, such as complicated placement of the sensor in a limited space available inside a flight vehicle and a high cost of needed DPS.

Further investigation into this method will follow this paper, mainly focused on gaining experimental data to reliably compare both approaches, developing more convenient methods of DPS mounting and automatising density measurements, to lessen the uncertainty arising from usage of previously developed density-temperature plots.

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