General Pressurization Model in Simscape

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Abstract

System integration is an essential part of the engineering design process. The Ares I Upper Stage (US) is a complex system which is made up of thousands of components assembled into subsystems including a J2-X engine, liquid hydrogen (LH2) and liquid oxygen (LO2) tanks, avionics, thrust vector control, motors, etc. System integration is the task of connecting together all of the subsystems into one large system. To ensure that all the components will “fit together” as well as safety and, quality, integration analysis is required. Integration analysis verifies that, as an integrated system, the system will behave as designed. Models that represent the actual subsystems are built for more comprehensive analysis. Matlab has been an instrument widely use by engineers to construct mathematical models of systems. Simulink, one of the tools offered by Matlab, provides multi-domain graphical environment to simulate and design time-varying systems. Simulink is a powerful tool to analyze the dynamic behavior of systems over time. Furthermore, Simscape, a tool provided by Simulink, allows users to model physical (such as mechanical, thermal and hydraulic) systems using physical networks. Using Simscape, a model representing an inflow of gas to a pressurized tank was created where the temperature and pressure of the tank are measured over time to show the behavior of the gas. By further incorporation of Simscape into model building, the full potential of this software can be discovered and it hopefully can become a more utilized tool.

System Integration Analysis and Modeling

Complex systems are built in sections. These sections form subsystem where each subsystem performs a different task of the overall performance of the whole system. Not only does each subsystem have to work flawlessly individually but also these subsystems have to work together as a whole. Integration of all the subsystems is a challenging task since components developed separately do not always fit together. System integration analysis is required to verify that the system will complete its desired function once all the components are put together.

A major portion of system integration analysis is dealing with models and model building. Creating models allows engineers to understand the potential problems that might arise when putting a system together. A model that can accurately represent an object or process while being simple is a good model. In search of new modeling tools, Simscape software was explored. Simscape was used to build a model that represents a gas inflow into a pressurized tank.

Background Information

The Upper Stage of the Ares I vehicle is an extensive and complex system. The Ares I can be divided into three main elements: First Stage (solid rocket boosters), the Upper Stage and the Orion CEV (Crew Exploration Vehicle). The Upper Stage is located in between the Orion and the First Stage, providing the second boost to take the CEV into lower earth orbit (LEO). It is made of major subsystems such as a J2-X engine, main propulsion system, avionics, thrust vector control, and motors. Currently these subsystems are in the process of being integrated through high fidelity models. Figure 1 demonstrates an exploded view of the Ares I vehicle.

As the Upper Stage is analyzed new methods to model, simulate and analyze all the subsystems of the stage are sought upon. One tool that that will be explored for this project is Simscape, a tool provided by Simulink.

Simulink, which is a tool, provided by Matlab, is used to design, simulate and analyze dynamic systems. Simulink is a powerful tool when the mathematical model of a dynamic system has been acquired.

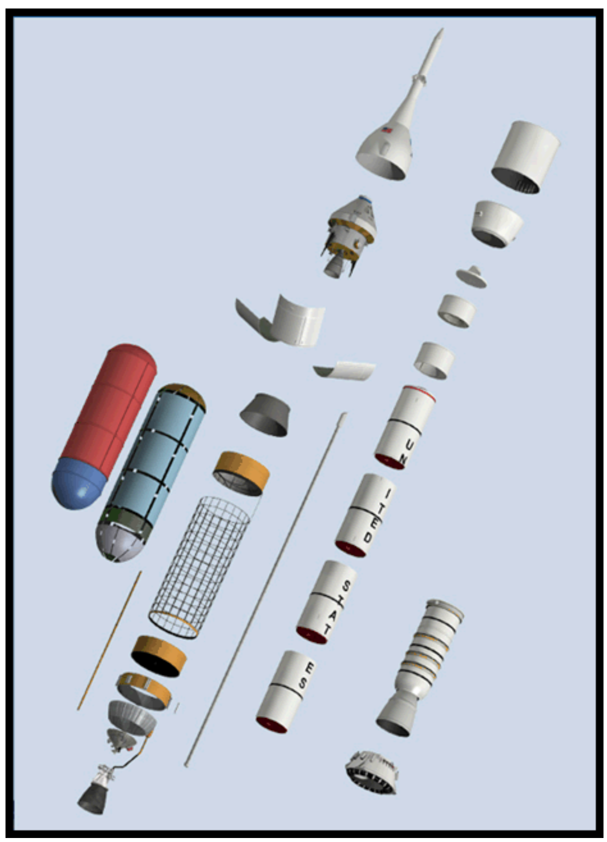

Figure 1-Ares I Elements

But to derive a mathematical model of a system that accurately predicts the time behavior of particular parameters can be cumbersome and difficult. This is due to the fact that the mathematical models involve differential equations and manipulating these differential equations can be quite the task. But Simulink provides another helpful method of modeling physical systems, Simscape. Simscape provides a multi-domain environment that allows users to model physical (such as mechanical, thermal and hydraulic) systems using physical networks approach.

Purpose

The purpose of the project has two objectives; one is to explore Simscape software and understand its capabilities and the other objective is to create a model of a gas inflow into a pressurized tank using this software. The model must be designed to meet certain specifications where the dynamic behavior of the gas inside the tank must be shown. The model will be developed in Simscape but a graphical user interface will be created via Matlab for the model so that initial conditions of the system can be specified. After developing the gas flow model, the pros and cons of modeling through Simscape will be compiled. The pros and cons of modeling with Simscape will show if this software can be utilize as an alternative tool for modeling.

Methods

Model

A model in Simscape that simulates a gas flowing into a pressurized tank was created. The model had to meet certain requirements:

- *Inputs*: Gas and tank initial conditions (temp, pressure, volume)
- *Outputs*: Know the conditions of the temp, mass, pressure and density of the gas inside the tank as a function of time

A GUI (graphical user interface) was created where all the information relating to the initial conditions of the gas and tank will be contained and also the outputs of the simulation will be displayed. Flow rate control of the gas will also be given to the user through the GUI. The GUI will demonstrate six plots: Mass Flow Rate, Heat Flow Rate, Total Mass, Density, Tank Pressure and Tank Temp all vs. Time.

The dynamics of the system are shown in Figure 2. First the gas, with specified initial conditions, will flow through a compressor, which controls the mass flow rate of the gas. The user will choose a particular flow rate that the gas will flow into the tank. The flowing gas as it enters the pressurized tank will then go through a series of sensors to determine its temperature, pressure and mass and heat flow rate.

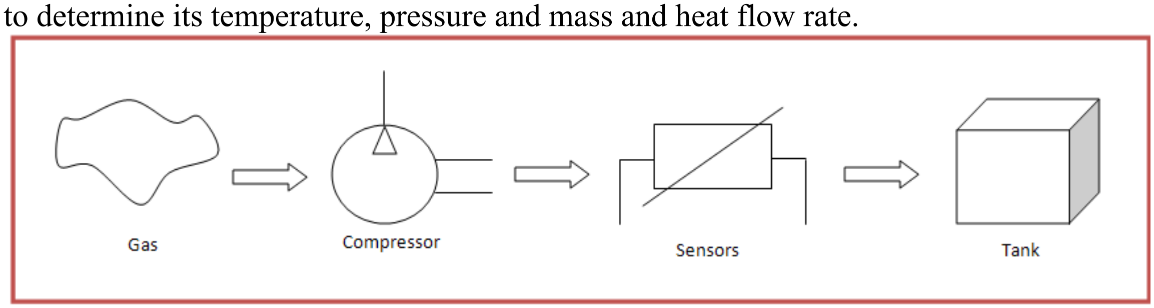

Figure 2-The model dynamics

Software: Simulink, Simscape & Matlab

Simulink: As explained in the MathWorks website, “Simulink software models, simulates and analyzes dynamic models”. Simulink provides multi-domain graphical environment to simulate and design time-varying systems. Simulink is a powerful tool to analyze the behavior of systems over time.

Simscape: Simscape exist as a block library provided by Simulink that uses the Simulink environment to model and design physical systems using the Physical Networks approach. In the Physical Networks approach, each system is represented as consisting of functional elements that interact with each other by exchanging energy through their ports. The connecting ports mimic physical connections between elements, where each connection represents an energy flow. Simscape provides a Library with blocks for different types of physical components for physical systems such as mechanical, electrical and hydraulic. This allows for easy interchangeability for any Simscape model. Figure 3 shows an electrohydraulic servo-valve.

Simscape makes modeling physical systems easier. This is due to the fact that if components can be connected in the real world, they can be connected in the software. For example, if you wanted to model a mass-spring-damper system that is rotating, in Simscape you would connect a rotational mass, spring and damper with a sensor and then the motion of the system is ready to be simulated. If you wanted to include the inertia, all you would need to incorporate into your model is an inertia block and now you model takes account for the inertia of the mass. For comparison, if the same model was created in Simulink, the equations of motion would have to be obtained. Once all the mathematics is taken care of, then the simplified equations will have to be incorporated manually into Simulink. To add the effects of inertia to this model you would have to refer back to your math equations and modify them. This would take your design back to the beginning. As shown with this example, the complexity of your model can be easily adjusted just by adding or removing blocks from your code.

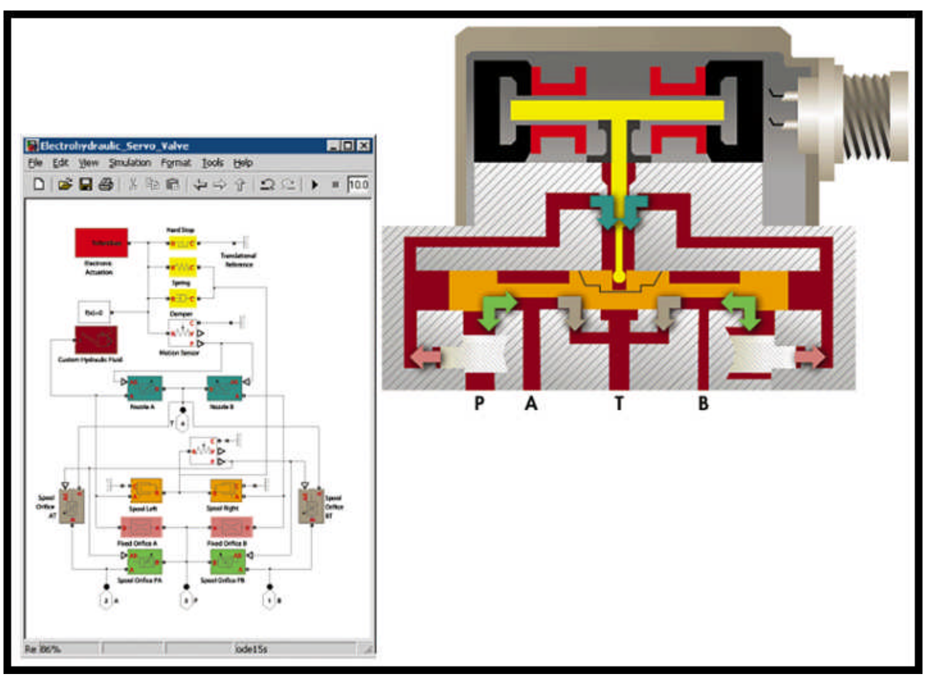

Figure 3-A schematic of an electrohydraulic servo-valve (top right) and its corresponding Simscape code (bottom left). Picture is courtesy of the MathWorks website.

Simscape will construct these

differential algebraic equations for your system. The equations characterize the behavior of your system.

<u>Matlab:</u> A widely used high-level language, Matlab provides engineers for an environment for computing intensive tasks faster. Matlab has many applications. For this project, the *guide command* was used. This initiates an environment and a set of tools to create a simple graphical user interface.

Results

The Simscape code of the *Pressurized Tank* model is shown in Figure 4. The model consists of a compressor, a mass and heat flow sensor, a pressure and temperature sensor and a gas tank. Inside the model a Gas Properties block has been added where the specific heat at constant pressure and at constant volume and the viscosity of the model can be modified. This allows you to simulate the time behavior of different gases.

NOTE: The only place where the tank's orifice can be modified is in the code, since this parameter was omitted from the GUI for simplicity. However, if needed, the orifice size could be included in the GUI.

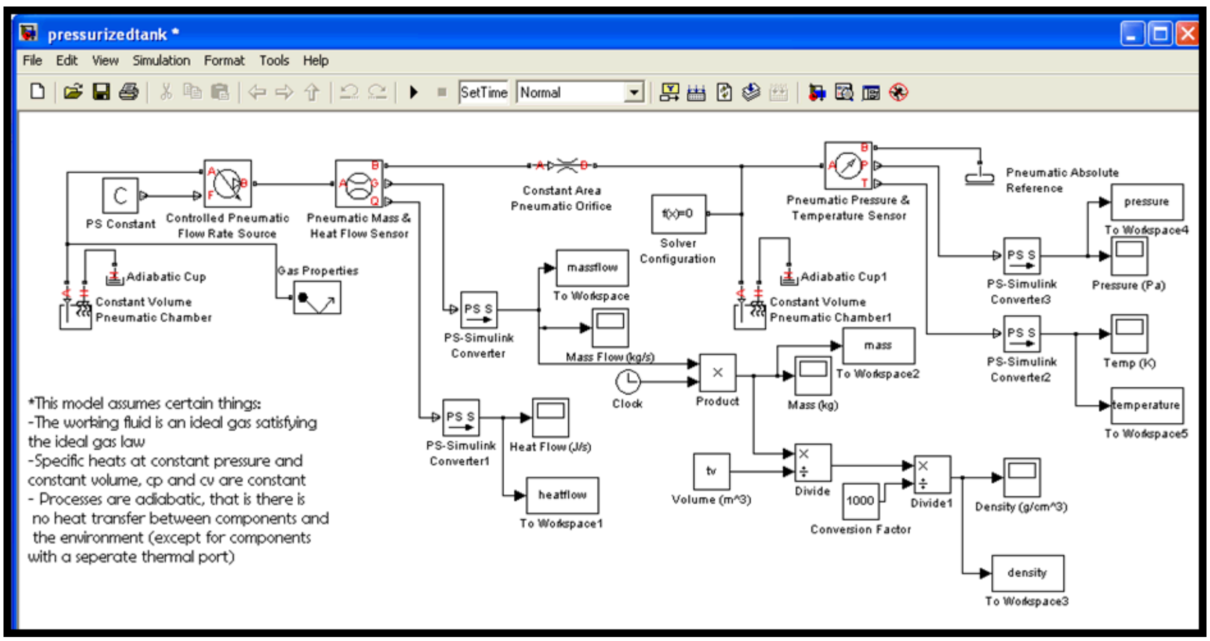

Figure 4-The Simscape code of the Pressurized Tank Model

The model for this project was created using the Pneumatic Block Library from Simscape, where the software makes certain assumptions:

1. The working fluid is an ideal gas satisfying the ideal gas law
2. Specific heats at constant pressure and constant volume, cp and cv are constant
3. Processes are adiabatic, that is there is no heat transfer between components and the environment (except for components with a separate thermal port)

In the next page, Figure 5, the graphical user interface for the model is shown. To simulate the model certain parameters need to be specified by the user.

- For the gas and the tank their initial conditions must be specified which are:

- *Volume* (m^3)
- *Pressure* (Pa)
- *Temperature* (K)

- Because of the compressor, the GUI gives the user control over the *Flow Rate* (kg/s) of the gas into the tank.
- An added feature to the GUI is control over the *Simulation Time* (s), which determines for how long the time behavior of the gas is going to be analyzed. **Depending on the Initial Conditions of the tank and gas and the Flow Rate, the time range of possible analysis of the model will change.*

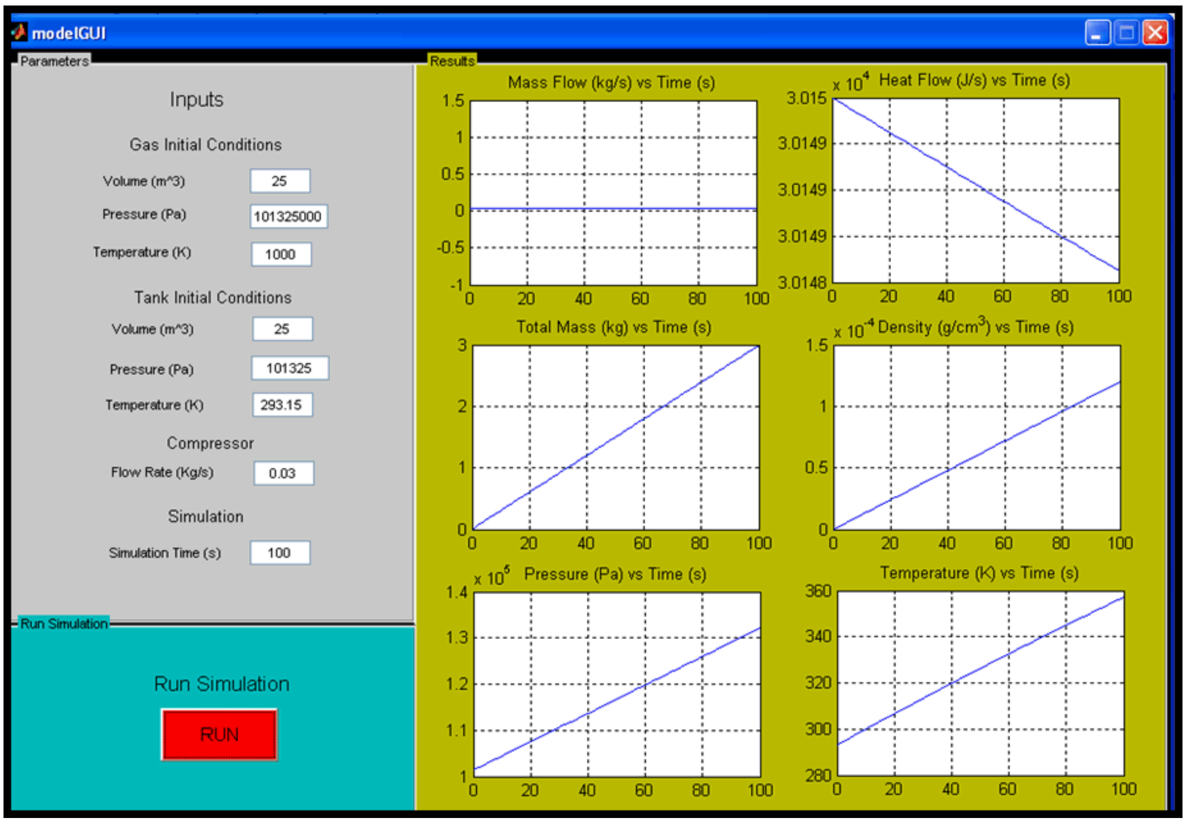

Figure 5-The GUI for the model

Once all the desired information has been inserted and the run button on the GUI has been clicked, six different graphs are generated:

- Mass Flow Rate (kg/s) vs. Time (s)
  - This graph will plot a constant value throughout its simulation because of the compressor. The compressor stabilizes the flow rate of the model. If the compressor was to be removed, and the gas is allowed to flow into the tank without any regulation, the Mass Flow Rate (kg/s) vs. Time plot will demonstrate transient, unstable behavior of the gas as it stabilizes at the beginning of the simulation. For the purposes of this model, the gas flow is maintained stable throughout the simulation.
- Heat Flow Rate (J/s) vs. Time (s)

    - This plot represents energy flow from the outer gas to the gas inside the tank. As time progresses, the energy flow per time decreases due to the fact that the inner and outer gas conditions begin to become similar reducing the differential needed for energy flow to happen.
- Total Mass (kg) vs. Time (s)
    - The total mass of the gas that has entered into the tank is shown in this graph. It is simply calculated from the Mass Flow Rate (kg/s) multiplied by the Time (s).
- Density (g/cm^3) vs. Time (s)
    - The increase in density is shown in this plot. Compression effects of the gas have been omitted since the model assumes that the working fluid is an ideal gas. To calculate the density of the gas inside the tank the following calculation is performed:
        - $Density\left(\frac{g}{cm^3}\right) = \frac{total\ mass\ (kg)}{tank\ volume\ (m^3)} * \frac{1}{1000}(conversion\ factor)$
- Pressure (Pa) vs. Time (s)
    - As more gas enters the tank, the pressure inside of the tank also increases. Because of the assumptions made in the model, a linear pressure pattern is demonstrated in the plot where the gas does not change phase at any moment.
- Temperature (K) vs. Time (s)
    - The temperature increase inside the tank is shown in this graph. It is assumed that the whole process is adiabatic; no energy is lost through heat.

Conclusion

Simscape serves as an alternative option for modeling, simulating and analyzing dynamic systems. It is focused on modeling physical systems only. This includes modeling for multi-domain physical systems. The block libraries provided by Simscape contain fundamental blocks that can be integrated together to create custom components. Some key features include:

- Object-orientated modeling language
- Models can be converted into C code
    - Run your model in Real Time, allowing you to do HIL (hard-ware-in-the-loop) testing
- Provides environment to model, simulate and analyze physical systems
- User can specify parameters and variables, all unit conversations are taken care of
- Simscape builds the differential algebraic equations which characterize the behavior of your system

There are some limitations when modeling with Simscape. Some of the limitations have been highlighted:

- Some Restricted and Unsupported Simulink Tools
- Simulink Tools not compatible with Simscape Blocks
    - Cannot set break points on Simscape blocks

    - Execution order tags do not appear on Simscape blocks
- Code Generation and Fixed-Step Solvers
    - C++ code generation is not supported
    - Block diagnostics not supported

Early in the design process, Simscape can be utilized to determine the requisites of a subsystem to meet certain criteria. For example, if an engineer was interested in controlling the pressure inside of a tank that has a flowing gas into it, he can develop a model with Simscape that represents this situation. The engineer can then specify the conditions of the tank and its environment in his model, where then the system dynamics can be simulated. The information needed to develop an appropriate control scheme can then be obtained. Simscape is a beneficial tool to have when designing physical systems.

Overall, Simscape facilitates modeling physical systems. Models created in Simscape can be adapted into different simulation environments, can simulate interactions of multi-domain systems, and adjusting the complexity of the model is simple. Simscape is a great program for top-level modeling.

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