Modeling and Fault Simulation of Propellant Filling System

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Abstract. Propellant filling system is one of the key ground plants in launching site of rocket that use liquid propellant. There is an urgent demand for ensuring and improving its reliability and safety, and there is no doubt that Failure Mode Effect Analysis (FMEA) is a good approach to meet it. Driven by the request to get more fault information for FMEA, and because of the high expense of propellant filling, in this paper, the working process of the propellant filling system in fault condition was studied by simulating based on AMESim. Firstly, based on analyzing its structure and function, the filling system was modular decomposed, and the mathematical models of every module were given, based on which the whole filling system was modeled in AMESim. Secondly, a general method of fault injecting into dynamic system was proposed, and as an example, two typical faults — leakage and blockage — were injected into the model of filling system, based on which one can get two fault models in AMESim. After that, fault simulation was processed and the dynamic characteristics of several key parameters were analyzed under fault conditions. The results show that the model can simulate effectively the two faults, and can be used to provide guidance for the filling system maintain and amelioration.

1. Introduction
Propellant filling system is one of the key ground plants in launching site of rocket that use liquid propellant. There is an urgent demand for ensuring and improving its reliability and safety, and there is no doubt that Failure Mode Effect Analysis (FMEA) is a good approach to meet it. Whereas the high test expense and the danger of fault experiments lead to the shortage of the fault data used for FMEA, it is indispensable and of great importance to model and simulate the working process of the filling system in fault condition.

In recent years there are many researches on fault simulation of the filling system. Starting from the transient pipe flow equation of one dimensional compressible fluid and using finite control volume method, F. Gao did a simulation of the working process of the fluid piping system for liquid-propellant rocket engine test-bed [1]. Using the finite element state-variable model for one-dimensional ideal gas flow, Y. hen established the modularized simulation model of the tank pressurization system of LRE test-bed, obtained detailed distribution curves of state parameters for the pipe net [2]. Q-S. Zhang analyzed the LRE test-bed, established the static mathematic model of the fluid system and the tank pressurization system and carried out the fault simulation with the method of quasi-typical line and finite element [3]. M. Gao did modeling and fault simulation of LRE test-bed propellant filling system based on Modelica/Dymola [4].

Aiming at the propellant filling system of an inland launching site, fault modeling and simulation analysis were did in this paper. Based on analyzing its structure and function, the filling system was modular decomposed. A simulation model was established in AMESim, which is a modeling and
simulation software based on Bond Graph. A general method of fault injecting was proposed, based on which two typical faults were injected into the simulation model. At last, based on the fault models, simulation analysis on typical faults is studied.

2. Introduction of AMEsim
AMESim (Advanced Modeling Environment for performing Simulations of engineering systems) is a popularly modeling, simulating and dynamics analysis software for mechanical/hydraulic system and fluid, transmission agent [5]. It supplies an integrity platform for system engineering designing, modifying and optimizing, so as to study the stable and dynamic state performances of any component in the system. Liking Bond Graph, AMESim describes the relation of each component in the system with graphic manner, which can reflect the variation of load in components and the power fluid in the system. The components in AMESim can do two-way data transmission and the variables in components are true physical variables, obeying causal relation. Preceding Bond Graph, AMESim can visualized reflect the working fundamental of system. The model in AMESim is nearly identical with schematic diagram of system [6].

AMESim has many merits, as below:
- Backup of modeling for many subject;
- Graphic physical modeling manner;
- Having intellectual resolver which is
- Having strong function of quadric development;
- Having integrity diagnostic tool;
- Having smart interface technique.

3. Modular Modeling of the filling system
Propellant filling system is the aggregation of all the equipments and devices utilized to store, transport, fill or discharge propellants, with the main purpose of feeding the propellants to the engine with the required flow rate and pressure. It is mainly composed of storage (tank), filling pump, flow sensor, valve, pipe and control equipment, etc. When modeled, the system is first divided into many different modules, which are open and flexible, and according to its characters, each module is modeled using one or more basic graph components in AMESim. For the sake of clarity and concision, the schematic diagram of a ground propellant filling system is given in figure 1. In the following of the paper, without extra specification, what the filling system refers to is just the system shown in figure 1.

3.1. Module Compartmentalization and Definition
According to the theory and the method of modular modeling, the filling system is divided into four main modules by physical structure: module of pipeline, module of valve, module of capacity and module of pump, all of which have the characteristic of typification, independence, and easy connectivity.
- Module of pipeline: In the filling system, as an important carrier of propellant, pipeline ensures propellant flow smoothly to engine. Because of friction, there is flow resistance in pipe, which makes the loss of energy and flow rate in pipeline. There is also compressibility in pipelines, which makes the fluid compress. We assume that fluid in pipeline is in the state of laminar current, ignore the fluctuation effect.
- Module of valve: As to filter, compensator, fluid sensor and various valves, slenderness ratio is less and the flow area in the direction of propellant flow is changed. They can be considered as lumped parameter model, where the pressure and the flow rate can be calculated as below:
\[ \frac{dP_1}{dt} = \frac{a_1^2}{V_1} \left( \frac{dm_1}{dt} - q_m \right) \] (1)
\[ \frac{dP_2}{dt} = \frac{a_2^2}{V_2} \left( \frac{dm_2}{dt} - q_m \right) \] (2)
\[ q_m = C_q A \sqrt{2 \rho (P_1 - P_2)} \] (3)

where \( V_1, V_2 \) is the capacity of inlet, outlet capacity unit; \( \frac{dm_1}{dt}, \frac{dm_2}{dt} \) and \( q_m \) are the mass flow rate of inlet, outlet and valve respectively; \( \rho \) is the density of propellant, \( C_q \) is the coefficient of flow, \( A \) is the flow area of valve and can be calculated as below:
\[ A = f(\theta) \cdot A_{\text{max}} \] (4)

where \( A_{\text{max}} \) denotes the max flow area of valve, \( \theta \) is the opening angle of valve.

- Module of capacity: There are two modules of capacity in real filling system: the propellant storage and the propellant tank. The propellant storage is the source of propellant. The propellant tank is on the engine of liquid rocket, and stores propellant which is filled into it. We assume that the volumes of the two modules are fixed, and the temperature is stationary.
- Module of pump: filling pump is the main working plant in the process of filling. It is a plunger pump, driven by electric machine. The input of pump is mechanical energy and the outputs are pressure and flow rate. When modeled, we only consider the loss of energy caused by friction.

3.2. Modeling of the modules in AMESim

In AMESim, the above four modules can be modeled using the abundant graph component in basic and special libraries.

1) Module of pipeline: Two components in AMESim library are used to model pipeline: “round-straight tube” and “bend tube”, as shown in figure 4. The first component is considered as distributed parameter and handled with-finite element method. The properties of each part of component are defined according to the actual distribution of pipeline, including length of pipe, diameter of pipe, wall thickness, etc. The second component is considered as lumped parameter model, which is modeled the elbow pipe. Also, some properties are needed to be defined according to the practical situation.
2) Module of valve: According to the dissimilar operation mode, the module of valve is modeled by three assemblies of components, as shown in figure 2.

- Figure 2a is modeled the filter, compensator and fluid sensor, the flow area of which is fixed and cannot be changed.
- Figure 2b is modeled the hand-operated valve, the electromagnetic valve, and the pneumatic valve, which include return-air valve, discharge valve, valve front of pump, valve back of pump, valve front of fluid sensor, outlet valve, inflow valve and outflow valve, etc. though the control mechanics is different, for the simplicity and convenience, the three valves are modeled as two-port valve controlled by input signal. \( f(\theta) \) is linear function of control signal, which is generated by signal generator, as shown in figure 2.
- Figure 3c is modeled the pressure relief valve, which is controlled by the technology gas supplied by special devices and used on the filling system to prevent overpressurization. In view of the whole dynamic process of relief valve, there are three states including total closed, half open and total open. Without regard to leakage, the mass flow rate of valve can be calculated precisely using equation (5) instead of equation (3):

\[
q_m = \begin{cases} 
0 & \text{if } dp \leq p_{\text{closed}} \\
\frac{[(dp - p_{\text{closed}})^2 \times \rho \times G]}{p_{\text{open}} - p_{\text{closed}}} & \text{if } p_{\text{closed}} < dp < p_{\text{open}} \\
\frac{(dp - p_{\text{closed}}) \times \rho \times G}{p_{\text{open}}} & \text{if } dp \geq p_{\text{open}}
\end{cases}
\]  

(5)

where \( dp \) is the pressure differential between the inlet and outlet, \( p_{\text{closed}} \) and \( p_{\text{open}} \) are respectively the maximum closed pressure and minimum opening pressure, and \( G \) denotes the conductance of the valve when open.

3) Module of capacity: Two components are used to model the module of capacity: “hydraulic volume” and “hydraulic accumulator”, as shown in figure 4. The first component is modeled the propellant storage, which is filled with fluid at initial, and the pressure of which is stationary. The second component is modeled the propellant tank, which is filled with air at initial, and the pressure of which is changed with the fluid’s filling.

4) Module of pump: the model of pump in AMESim is shown in figure 3. Driven by cam follower, which is controlled by electrical motor, the piston did reciprocally motion, with which the volume is changed and fluid is inflow/outflow. The two poppet are modeled the cylinder body. The mechanical components supply resistance of friction, which cause the loss of energy.
Other than the four modules, the properties of liquid medium are also needed to be defined, including kinematic viscosity, mass density, pressure of atmosphere, etc.

3.3. Modeling of the whole system in AMESim

Based on the modules of the components we defined, the model of the filling system in AMESim is assembled as shown in figure 4. The type of all signal generators can be changed as we need in simulation, though they are constant source in figure 4.

4. Fault Injection

Fault injecting is an important procedure in fault simulation. As to the process simulation of dynamic system, all faults can be injected into simulation model by changing the input signal in various manners (such as add a module), as shown in figure 5. $U_i$ is the input value, $\Delta U_i$ is the fault of sensor at input end, $U_c$ is the control input, $\Delta U_c$ is the fault of operation agent, $\Delta U_o$ is the fault needed to simulate, $y$ is the output value, $\Delta y$ is the fault of sensor at output end, $U_{o^0}, U_{o^0}^i, y^o$ are corresponding real values.
Given \( U = [u, u_c, u_d]^T \) and \( \Delta U = [\Delta u, \Delta u_c, \Delta u_d]^T \), the fault simulation model can be described by equation (6):

\[
\begin{align*}
\dot{X} &= A(t)X + B(t)U + F(t)\Delta U \\
Y &= C(t)X + D(t)U + \Delta Y
\end{align*}
\]

According to the fault mode static analysis of the filling system, the most frequent and dangerous faults are leakage and blockage. The fault simulation of them will be discussed in the following.

4.1. Leakage
Because of tiredness or oscillation, leakage will occur at the joints or welding seams of the pipeline. In addition, it would also cause leakage if the valve of the let pipeline or blowing line is not totally closed. Leakage fault can be injected into model by add a by-pass channel in a pipeline. The pressure at the output end of the by-pass channel is atmospheric pressure invariably, as shown in figure 7a

4.2. Blockage
The valve and filter can be jammed by the impurities mixed in the propellant, leading to the reduction of the flow area and the augment of resistance. In order to model filter blockage, the model of filter shown in figure 2a is changed with a similar one but is variable, and an actuating signal is added to control its flow area, as shown in figure 6b.

According to the schematic shown in figure 6, the fault modules can be modeled in AMESim as shown in figure 7. Actuating signal adjust diameter of leakage orifice and flow area of filter.
5. Fault Simulation
The fault model is shown as figure 8, in which there are two modules of fault. We simulate and discuss the two faults separately. When one fault is present, the other isn’t. The actuating signal can be any form, though they are constant in figure 8.

\[ d = 0.01D \]

5.1. leakage
Set simulation time as 100s, and the leakage fault occurred at 40s. The diameter of leakage orifice \( d = 0.01D \), where \( D \) is the diameter of pipeline. The simulation result of the flow rate at the inlet of tank and the pressure at outlet of pump is shown in figure 9.

\[ A_{\text{max}} = 0.5A_{\text{max}} \]

5.2. Blockage
Also set simulation time as 100s, and the blockage fault occurred at 40s. The flow area of filter \( A = 0.5A_{\text{max}} \), where \( A_{\text{max}} \) is the flow area when the filter health. The simulation results of the flow rate at inlet of tank and the pressure at outlet of pump is shown in figure 10.
6. Conclusion

Based on the modular decomposed of the filling system, a simulation model is developed using modeling and simulation software AMESim, and the characteristics of the flow rate and pressure of the real system can be well shown. It is proved that AMESim is an effective tool modeling and simulation for complex mechanical system.

Fault Injecting can be easily done through adding fault module and changing the input signal, without modifying their mathematic model. Based on the method, two typical faults (leakage and blockage) are injected into the model and be simulated in AMESim. The effect of the faults is analyzed based on the simulation result, which can provide guidance for inspecting, diagnosing, maintaining and ameliorating the filling system.

However, we made some hypothesis in order to make modeling easily. Therefore, more studies are needed in future to update the fidelity of simulating the dynamic response of the filling system.

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