

Jet Engine Fuel System Integration in Aircraft Environment - Methodology for Pressure Surge Simulation through Model-Based System Engineering

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ABSTRACT

An Airbus methodology for the assessment of accurate fuel pressure surge at early program stages in the complete aircraft and engine environment based on joint collaboration with LMS Engineering is presented. The aim is to comfort the prediction of the fuel pressure spike generated by an engine shutdown in order to avoid late airframe fuel system redesign and secure the aircraft entry-into-service.

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INTRODUCTION

Fuel pressure surge is an essential topic for modern aircraft and a main driver for airframe fuel system sizing. This phenomenon can occur both during normal and abnormal operations, notably resulting from a sudden change of fluid velocity due to the opening or closure of an engine valve.

During aircraft development phase, Airbus specifies to engine manufacturers a pressure limit at the interface between the engine and airframe based on aircraft fuel system qualification. The verification activities performed by engine manufacturers shall then ensure that the maximum pressure surge will not exceed this requirement.

The purpose of this paper is to present a methodology for accurate prediction of fuel pressure surge on an engine-aircraft integrated environment at early program stage in order to mitigate the risk associated with fuel pressure surge during aircraft development, avoid late airframe fuel system redesign and secure the aircraft entry-into-service.

1. PROJECT OVERVIEW

1.1. Scope

The area of study is the integration of an engine fuel system with its aircraft environment.

The aircraft engine feed fuel system is generally composed of:

- Boost pumps that pressurize fuel up to the engine inlet
- Fuel hydraulic valves (LP SOV, TRV)

The engine fuel system is generally composed of:

- A two stage- pump with a low pressure and a high pressure part
- A Fuel Oil Heat Exchanger (FOHE) that cools the engine oil circuit
- A main fuel filter that prevents fuel contamination
- A fuel metering valve that regulates the flow into the combustion chamber according to the engine thrust power demand
- A High Pressure Shut Off Valve (HPSOV) that shuts down the engine when it stops the flow into the combustion chamber



- Servo valves that support engine performance and power actuators with pressurized fuel.

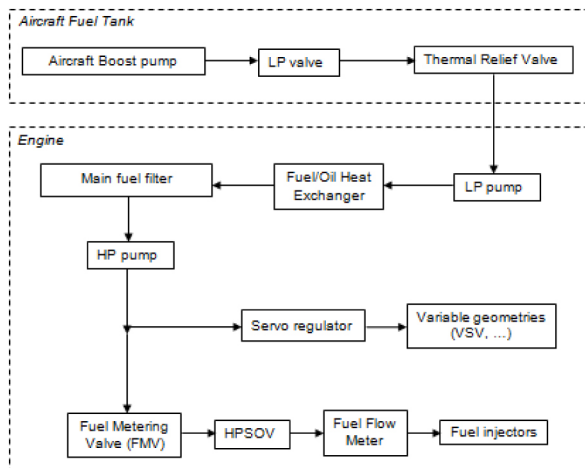


Figure 1. Aircraft-Engine Typical Fuel System Schematic

Water hammer or pressure surge is defined as the change in pressure, either above or below the normal pressure, caused by a variation of the flow rate in a pipe. The flow rate in the pipe can vary due to valve either closure or opening. These pressure surges are propagated along the pipeline from the source (valve) to the constant pressure boundary (tank).

Fuel pressure surge phenomena in the engine feed line are mainly linked to transient phenomena that could occur during normal or abnormal fuel system operation. The main physical phenomenon causing a surge is the closure of a valve such as the engine HPSOV at high engine power conditions.

1.2. Verification and Validation Process

Part of the engine requirements specified by Airbus to the engine manufacturer is the maximum allowable pressure surge level caused by engine valve activation, as measured at the engine fuel system inlet. The engine manufacturer shall ensure through a verification and validation process that in every operating condition the pressure level will be within the requirements specified by Airbus. The worst case condition in terms of pressure surge is defined with maximum engine speed and cold de-aerated fuel (see part 2).

Generally this V&V process is divided in a modelling and a test bench phase that are performed at engine manufacturer facilities followed by an actual aircraft flight test campaign. This engine manufacturer process is performed soon in the aircraft program development. During these phases, the engine fuel system is fully representative, whereas the aircraft part is generally not fully characterized at this stage of the program.

Based on Airbus experience, the engine manufacturer fuel spike predictions run non negligible risk of showing significant discrepancy versus test data from the Airbus test aircraft. These inaccuracies raise an aircraft program risk that can only

be mitigated using requalification or redesign and formerly be closed with test aircraft campaign which is late in the program development.

After a deep analysis of the surge phenomenon, it has been pointed out that the pressure surge risk could be mitigated early in a program development by supporting the engine manufacturer V&V and providing simple airframe fuel system characteristics that impact the fuel surge level behavior.

2. PRESSURE SURGE MODELING

LMS Imagine.Lab Amesim is a graphical software package that enables the modelling, simulation and analysis of multi-physic mechatronic systems; both under steady state and fast dynamic conditions. Such systems are modelled as a collection of C code based components that are connected by the user on a sketch. Component behaviour relies on analytical equations or tabulated models -as chosen by the user- thereby allowing for 0D to 1D system analysis. Each component is specified so as to exchange both flux and effort variables at its ports, which ensures energy conservation at system level (Bond-Graph theory [R 1]). The resulting system model is non-linear space and state function, solved by a solver that automatically chooses the most relevant algorithms as a function of the system numerical stiffness.

Part 2 of this paper summarizes the investigation performed by Airbus and LMS Engineering towards a theoretical analysis of the pressure surge phenomenon. This is based on a simplistic and generic system layout, illustrated with Figure 2, which includes a fuel tank, three fuel pumps, and a valve, all connected by rigid pipes.

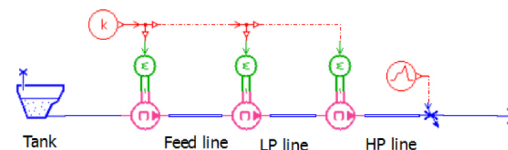


Figure 2. System layout used for generic Pressure surge phenomenon understanding

2.1. Pressure Surge Theoretical Analysis

The velocity of a pressure surge wave is calculated as follows:

$$a = \frac{\sqrt{\frac{1}{\rho}}}{\sqrt{\frac{1}{\beta} + \frac{D}{e \cdot E}}}$$

Equation 1: Sound velocity in a fluid medium

This study has focused on valve closures, which is one of the design cases of an aircraft fuel system. According to the literature, if the valve closure time is less than the wave reflection time, then the maximum pressure rise at the valve happens during the first peak of pressure oscillations, and is given by the Joukowski formula

$$t < \frac{2 \cdot L}{a} \rightarrow \Delta P = \rho \cdot a \cdot U_0$$

Equation 2: Pressure peak (Joukowsky)

In the case where the pressure wave has enough time to propagate upwards to the constant pressure source, through the entire pipework, and come back to the valve before its full closure, then the pressure surge induced at the valve is given by the Michaud formula:

$$t > \frac{2 \cdot L}{a} \rightarrow \Delta P = \frac{2 \cdot \rho \cdot L \cdot U_0}{t}$$

Equation 3: Pressure peak (Michaud)

It is important to mention that these formulas are applicable on very simplistic pipework which are not characteristic of a complex aircraft fuel system.

Note that as opposed to [Equation 2](#) (Joukowsky), [Equation 3](#) (Michaud) neglects the fluid and pipework elasticity (and therefore assumes incompressible fluid and system structure -pipework), and assumes a linear valve closure profile.

2.2. Fluid Properties

Looking at the equations above, fluid properties such as bulk modulus and density are shown to have a direct impact on the pressure spike following a rapid valve closure. Similarly, fluid viscosity, thermal conductivity and specific heat play an important role in characterizing other fluid behaviors (frictions, thermal expansion etc...). Therefore, it is critical that fluid properties are represented appropriately, before a model of the fuel system is built. Fluid properties are pre-defined in LMS Amesim Thermal Hydraulic library for Jet A and Jet A1 (commonly used fuel for aircraft application), and rely on the use of polynomial expressions that can accurately represent fluid properties variation with temperature and pressure. The use of (polynomial) expressions allows for continuously defined fluid properties, which can therefore be derived when needed (as opposed to tabulated properties) as per [Equation 7](#) for example. These properties have been checked and validated against the CRC of aviation fuel reference properties [R 2] as shown with the example of the Bulk modulus, density and viscosity variation with temperature on [Figure 3](#).

The presence of gas in fluids is also taken into account in LMS Amesim, both in its free air/gas form and vapor form (vaporized version of a fluid experiencing pressure levels below its vapour pressure limit). As shown with [Figure 4](#), each fluid is parameterized with three pressure limits, so as to account for the right phases, in the right proportions. Note that the variations of θ (fraction of undissolved air/gas, case 2) and Φ (vapor mass fraction, case 3) are quasi linear with Pressure variation, with added considerations for continuity (hyperbolic tangent profiles).

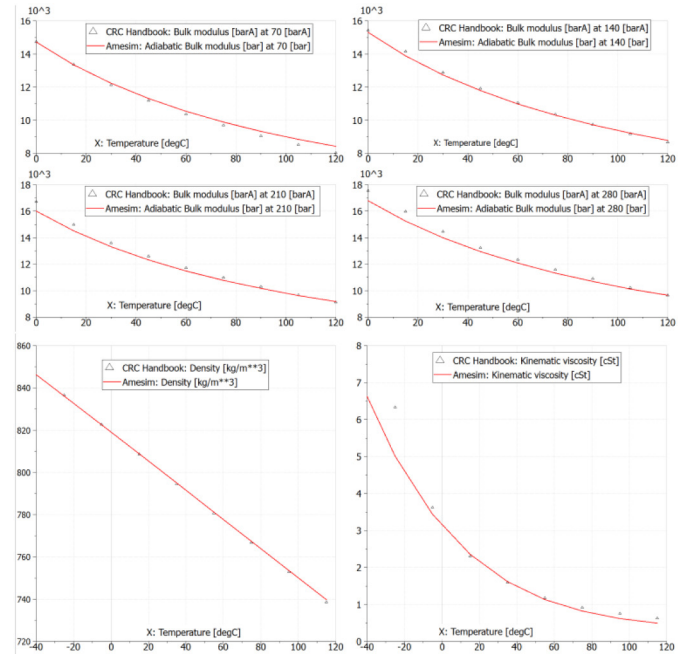


Figure 3. LMS Amesim vs. CRC Handbook Jet-A bulk modulus, density and viscosity

The fluid equivalent density is calculated as the combination of individual densities, as shown with [Equation 20](#), [Equation 21](#), [Equation 22](#) and [Equation 23](#), in line with the zones identified on [Figure 4](#), and relying on the fractions defined with [Equation 4](#), [Equation 5](#) and [Equation 6](#).

$$\text{air gas content} = x = \frac{V_{\text{air/gas}}(P_{\text{atm}}, T_0)}{V_{\text{liq}}(P_{\text{atm}}, T_0) + V_{\text{air/gas}}(P_{\text{atm}}, T_0)}$$

Equation 4: air/gas content fraction

$$\theta = 1 - \frac{P - P_{\text{vap}}^H}{P_{\text{sat}} - P_{\text{vap}}^H}$$

Equation 5: undissolved air/gas fraction (modified Henry's

$$\Phi(P) = \frac{m_{\text{vap}}(P)}{m_{\text{vap}}(P) + m_{\text{liq}}(P)}$$

Equation 6: vapor mass fraction

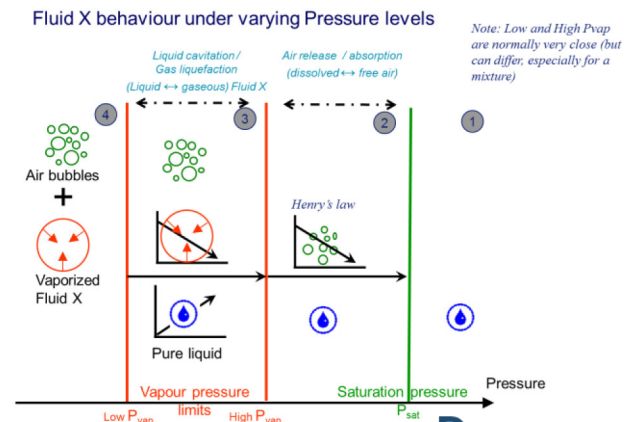


Figure 4. Fluid behavior under varying pressure levels

With fluid density defined as per the above, the fluid equivalent bulk modulus can be derived as follows:

$$\beta_Y = \frac{\rho}{\left(\frac{\partial \rho}{\partial T}\right)_Y} \text{ and } \beta_S = \frac{\rho}{\left(\frac{\partial \rho}{\partial T}\right)_S} = \gamma * \beta_Y$$

Equation 7: Fluid equivalent bulk modulus

Since the worst case condition in terms of overpressure is reached with fully de-aerated fuel (refer to Figure 6), this particular fuel condition is defined as the design case between Airbus and Engine Manufacturers.

2.3. Sensitivity Analysis

Testing Conditions

The aim of this part is to validate LMS Amesim pressure surge predictions with theoretical behavior expectations. An analysis of the influent parameters has been performed in order to define the best modelling technique to be used and to highlight any potential hard points that would require further investigation.

First, the valve closure rate (or flow rate evolution during its closure) has been analysed. As suggested by theory, it appeared that in the Joukowski conditions (fast closure) the valve closure profile does not influence the value of the first pressure peak: both linear and exponential profiles have yielded the same pressure peak at the valve. However when the Michaud condition is met (slow closure), the closure time is not the only influencing parameter (see Equation 3), the closure profile also has an impact on the peak pressure observed at the valve inlet, as shown with Figure 5. Again, the Michaud equation is only valid for a linear valve closure.

The impact of the fluid air/gas content and temperature on the overpressure induced by a valve closure has also been quantified, as shown with Figure 6 and Figure 7. This is the direct result of their impact on the sound velocity and bulk modulus, as per Equation 1 and Equation 2.

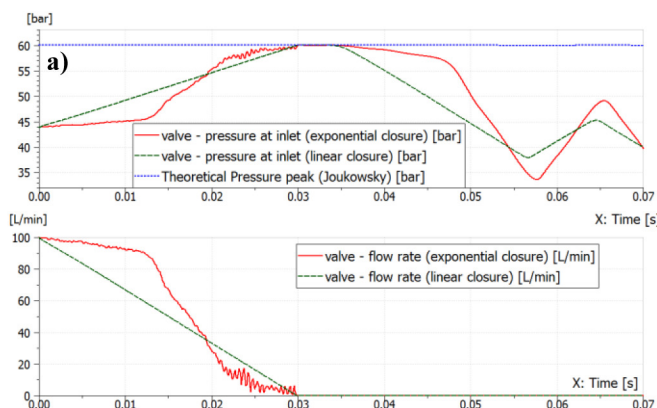


Figure 5.

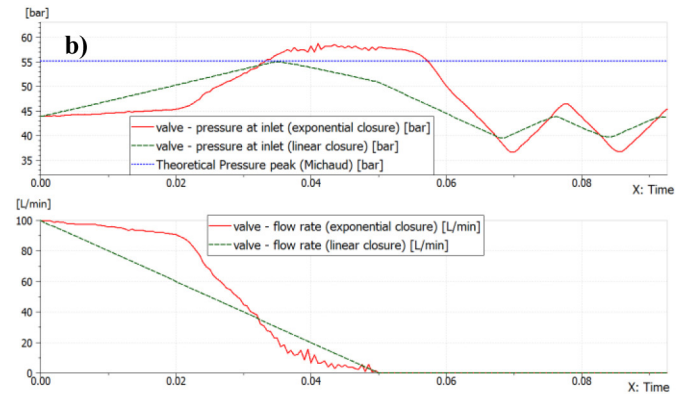


Figure 5. (cont.) Influence of the valve closure rate on the overpressure in bar and flow rate in L/min behavior measured at the valve (a: Joukowsky Scenario; b: Michaud Scenario), Red curve: exponential closure; Green curve: Linear Closure; Blue Curve: Theoretical Results

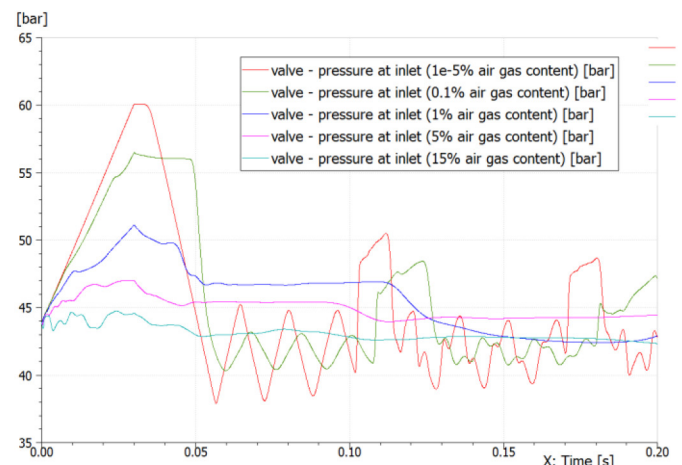


Figure 6. Influence of the fluid air/gas content on the overpressure in barA (Joukowski scenario)

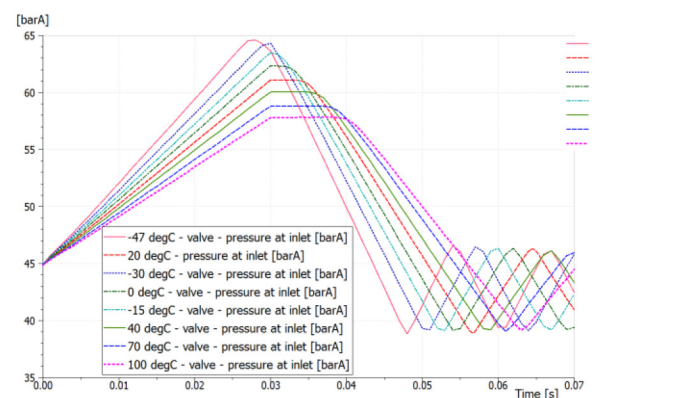


Figure 7. Influence of the fluid temperature on the overpressure in barA (Joukowski scenario)

Testing System Layout

The aircraft industry commonly relies on the use of flexible pipes for integration purposes. In terms of pressure surge particularly, a flexible pipe has the ability to significantly dampen the overpressure ([R 8]) due to its viscoelastic characteristics. This has been investigated with the system

layout shown with [Figure 8](#). The watchful reader will notice that the flexible pipe does not need to be connected directly to the valve where pressure is measured in order to have an impact.

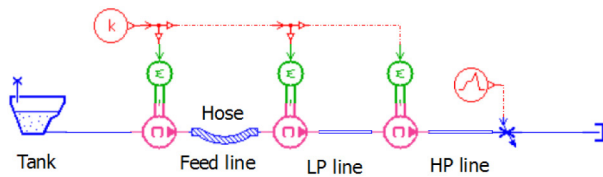


Figure 8. Modified system layout (flexible hose addition)

When a flexible hose is added to a rigid system pipework, it generates a modification of the system hydraulic stiffness. This is modeled in LMS Amesim through a further correction of the fluid bulk modulus β_s (already accounting for the presence of air / gas in the liquid), yielding an effective bulk β_{eff} , as shown with [Equation 8](#).

$$\beta_{eff} = \frac{1}{\frac{1}{\beta_s} + \frac{w_{comp}}{1 + w_{comp} * (P - P_0)}}$$

Equation 8: System effective bulk modulus

This bulk modulus modification enables a large reduction of the first pressure peak at the valve inlet, as shown with [Figure 9](#), and as suggested by [Equation 2](#) (in which the speed of sound depends on the system effective bulk). In addition and as a result of the bulk modification as well, the presence of hoses also impacts the system natural modes through a modification of its hydraulic stiffness $K_{eq} = \beta * A^2/V$.

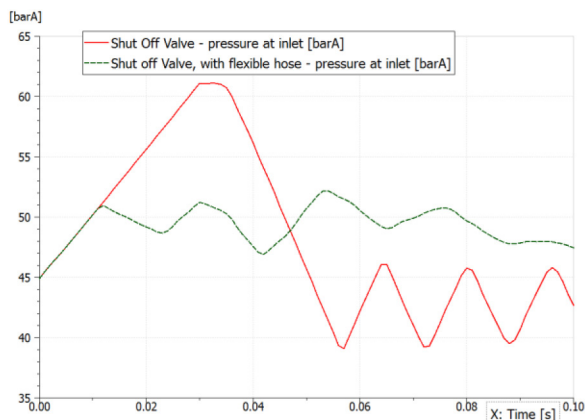


Figure 9. Impact of a hose on the pressure peak in barA measured at the valve (Joukowsky); Red Curve: Baseline Pipework; Green Curve: Addition of Flexible Hose

Another way to interpret this reduction in the first pressure peak at the valve is to consider that the hose flexibility generates an under-pressure wave that is reflected backwards, towards the valve. This reflected wave is the result of a sudden change in the acoustic impedance of the pipework as mentioned in [\[R 9\]](#). This pressure wave attenuation due to a modification in the pipework acoustic impedance has been also observed by Wylie & AI in [\[R 10\]](#). A detailed theoretical analysis of pressure wave reflection is provided in [appendix](#). It is

important to mention that these reflected waves will have a tremendous impact on the surge value at a specified measurement location. Notably these reflections are not taken into account in the theoretical formula given with [Equation 3](#) and will lead to large modification in the maximum pressure value measured.

In the present test case, the time at which pressure at the valve stops rising is exactly the one needed by a wave to travel from the hose to the valve, as a result of the valve shut off, which supports the theory that the pressure peak is dampened by an under-pressure wave.

Additional investigations have been performed to better understand the impact of the system layout on the overpressure generated by a valve closure, for which the reader is referred to the [appendix](#).

From this part 2, it can be concluded that the theoretical formula for pressure surge calculation are applicable in very particular cases that are not relevant in aircraft/engine integrated environment. The use of a dedicated model is then needed to ensure that the pressure surge phenomenon is accurately quantified at early program stage.

3. AIRCRAFT FUEL SYSTEM MODEL

The Airbus / LMS Engineering collaboration has been continued with an actual aircraft and engine fuel system, with a view to be able to mitigate with simulation the risk linked to pressure surge, very early in a program development.

3.1. Airframe Network

The architecture of a typical airframe fuel system is depicted with [Figure 1](#), which highlights the presence of two types of components: centrifugal feed pumps, and hydraulic valves.

Centrifugal Pump

Centrifugal pumps are modeled in LMS Amesim based on nominal performance. Pressure rise is calculated from similarity laws, allowing for the pump performance to be deduced from known performance in reference operating conditions. Temperature rise through the pump is based on the theoretical hydraulic power $Pow = Q * \Delta P$ and overall efficiencies: the amount of power that is not used for fluid pressure rise is converted into temperature rise.

Hose/Pipe

The pipe models for rigid or flexible in LMS Amesim are based on pressure and flow rate differential equations, as per [Equation 9](#) and [Equation 10](#). This allows for their capacitive behavior to be taken into account ([Equation 9](#)) as well as the fluid inertia and friction ([Equation 10](#)). Note that an analogy of the pressure force term of [Equation 10](#) to its mechanical form allows for a hydraulic equivalent inertia to be derived such that $I_{hyd} = \rho * L/A$.