SIMULATION OF FLUID MECHANICAL AIRCRAFT SYSTEMS FROM CONCEPT EVALUATION TO QUALIFICATION TESTS

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Abstract

This paper gives an overview of the modelling and simulation work for the military aircraft JAS 39 Gripen´s fuel system.
Fuel systems have several modelling challenges such as both compressible air and less compressible fuel that give stiff differential equations, g-forces effects, nonlinear cavitation and saturation. It is also a complex system that requires a model with integrated system software. Dynamic models based on physical differential equations have generally been used. The modelling work has been done in Easy5.
Simulations have been done during the whole development cycle of the aircraft from concept evaluation to qualification tests. The paper gives some examples from the simulations where system performance and the internal states of the system are calculated.
Finally, the paper focuses on numerical instability of fuel systems.

1 Introduction

Saab has the ability to develop and integrate complete aircraft systems. The Gripen, the world's first fourth-generation fighter aircraft in active service, is the most powerful and advanced aircraft Saab has ever built as well as the most flexible and cost effective. Saab has capability and know-how to take the overall responsibility as a tier one supplier, through an overall approach, for managing the comprehensive sub-tier supply chain, from design through development, systems integration, validation and production to life cycle support. Saab's expertise is within safe, reliable, compact and light, low power consuming and care-free systems solutions.

Some of the vehicle systems that are designed and integrated in military and civil aircrafts by Saab are:

- Electric power system
- Thermal management system
- Anti-ice and de-ice
- Flight system and hydraulic and electric actuators
- Fuel systems with in-flight refuelling
- Auxiliary power unit and system
- Hydraulic system
- Landing gear and brake system
- Engine system
- Integrated modular avionics for control units
- Control and monitoring software for systems

Complete systems, subsystems, equipment, control unit's hardware and software are integrated with 60 years of experience, currently from the military fighter Gripen, the civil aircrafts Saab 340 and 2000, the trainer Saab 105 and UAVs.

In order to achieve cost-effectiveness, modelling and simulation are used since 1968 to develop the most complex vehicle systems. Generally, modelling and simulation within vehicle systems are used today for

- Total system specification and design, e.g. functionality on ground and in air

- Equipment specification and design
- Software specification and design
- Various simulators
- Test rig design

Vehicle aircraft systems are complex systems. Complex systems require complex test rigs and complex installation of the equipment in test aircrafts. During the Gripen project it was soon found that if only one major redesign of the fuel system in a test aircraft could be spared, not only all modelling and simulation work for the fuel system but also the environmental control system could be paid.

Simulation reduces the risk of detecting late design faults in the development work. Research has shown that early detection and correction of design faults cost 200-1000 times less than late design faults, [1] and [2]. See Figure 1.

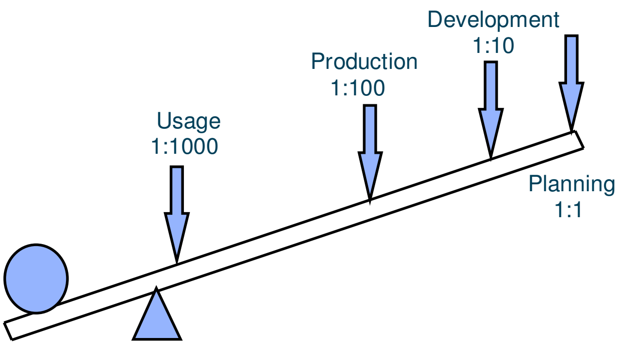

Figure 1 Cost to correct design faults during the planning, development, production and customer usage phases.

2 The Four Fluid Mechanical System Models of JAS 39 Gripen

Within fluid mechanical systems, Saab AB has developed four major total system models for Gripen in the commercial tool Easy5:

- Environmental control system (ECS)
- Hydraulic supply system
- Fuel system (FS)
- Auxiliary power system

The models are complex aircraft system models which include equipment as well as the software controlling and monitoring each system. Aircraft systems have several modelling challenges such as modelling g-forces effects, mixing fuel and air in fuel systems and flight envelop and environmental dependency of the ECS. The modelling work has been done in Easy5.

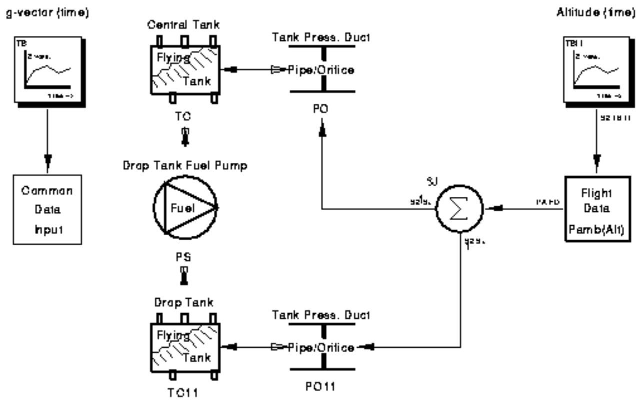

Figure 2 The Saab fuel system library. From [3].

Depending on the system type, the modelling work has been various. Within hydraulics and ECS, Easy5 subroutines of the equipment have been used and modified, while a new unique library, Figure 2, had to be designed by Saab AB, [3], in order to model the fuel system in Easy5.

3 Fuel System Model

The fuel system model of JAS39 Gripen in Figure 3 has 300 components and a control unit with 270 input signals and 80 output signals.

All components in the systems have been physically modelled, such as valves, pipes, tanks, sensors, heat exchangers. Each box represents a component in the system. Each solid line in the model represents a power port, e.g. two fluid states (total pressure, mass flow) or electric states (current, voltage).

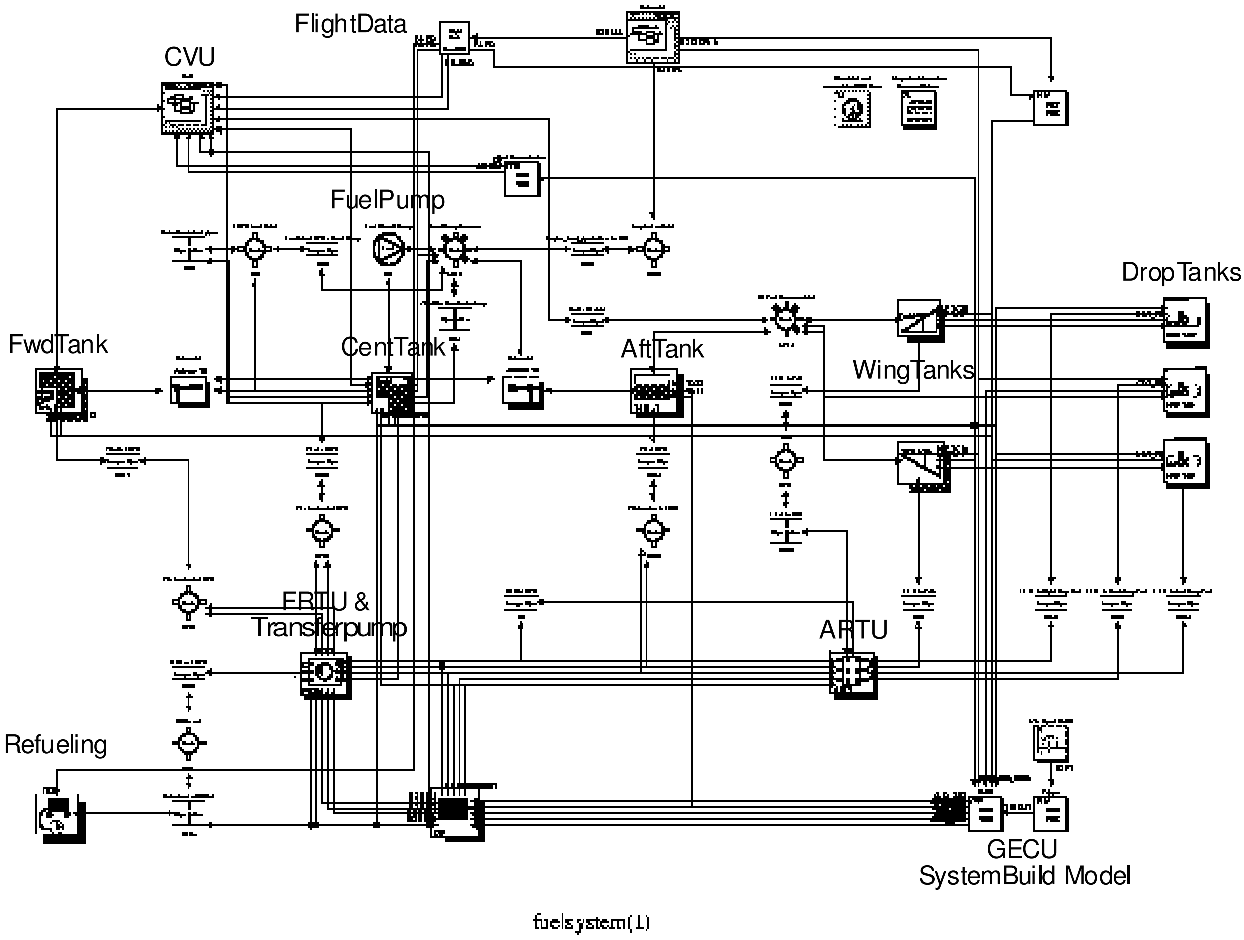

Figure 3 The fuel system model of Gripen

Since the lines represent pipes and wires and boxes components, the model looks like the system schematics on the screen.

The environmental conditions such as flight conditions (g-forces, altitude) are inputs to the model. So are the interfaces to other systems where energy is transferred into the system (fuel consumption of engine).

Dynamic models based on physical differential equations have generally been used. Black-box models have been used for some equipment of minor interest such as sensors. Tables have been used for highly nonlinear phenomena such as cavitation. The control unit is represented by the system software model in MatrixX/Systembuild.

The system software is incorporated as a subroutine which is automatically generated from the software specification in MatrixX/Systembuild, Figure 4. To integrate new code takes 4h after a minor software redesign. The hardware of the control unit has not been modelled in these models.

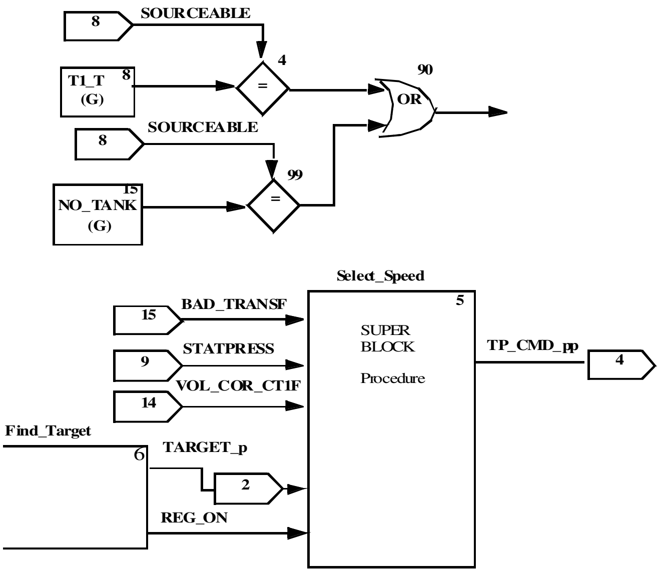

Figure 4 System software in Systembuild

4 Fuel System Simulations

The objectives of the fuel system's simulations at Saab are to verify and validate system function and performance during

- Conceptual design and development of new systems for aircrafts, ground supply equipment. Also test rigs are simulated.
- Integration of new equipment, such as pumps, valves, etc in the system.
- Development of new software for control and monitoring of the fuel system.
- Tactical validation; to check FS performance.
- Flight and rig testing; to complete tests that cannot be tested (e.g. qualification).

Both system performance and internal states can be simulated for

- Different operation conditions (engine or APU supply, etc)
- Different operation states (height, Mach no, temperatures, humidity)

Fuel system states and variables that are simulated are:

- Flow to and from components
- Pressure before, inside and after components
- Speed of engines, motors, pumps and cylinders
- Sensor signals, control signals
- Internal signals in control units
- Others

4.1 Simulation of System Performance

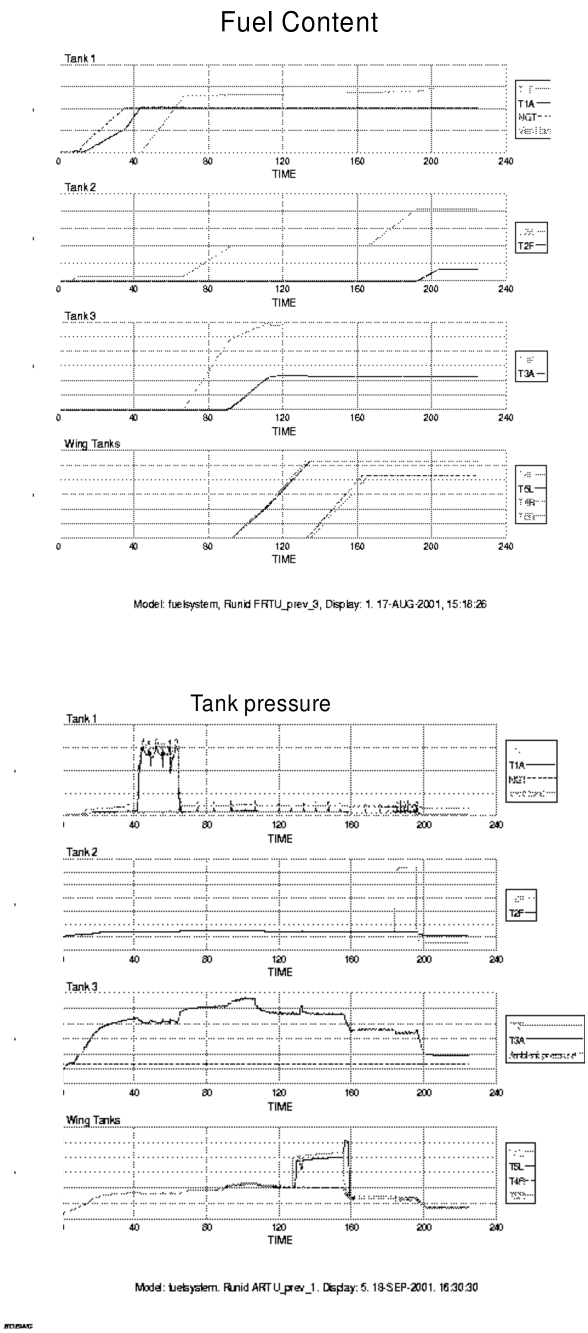

Figure 5 Refuelling – simulation results

In Figure 5, the simulation results when refuelling the seven tanks in JAS39 Gripen are shown. The diagram shows the fuel content level according to the sensors in the tanks as a function of time. The pressure levels in the tanks are also shown.

4.2 Simulation of System Software

One simulation area which is particularly interesting today is verification and validation (V&V) of the software controlling and monitoring the fuel system. In JAS 39 Gripen, it has been shown that simulation with physical models enhances the quality of the software while reducing the time.

Today such software is often modelled in tools such as MatLab/Simulink, MatrixX/Systembuild and SysUML in the aircraft industry. V&V with simulation is therefore easily done within fluid mechanical and electric power systems by integrating auto-generated code into physical models such as Saab has done in the Easy5 models.

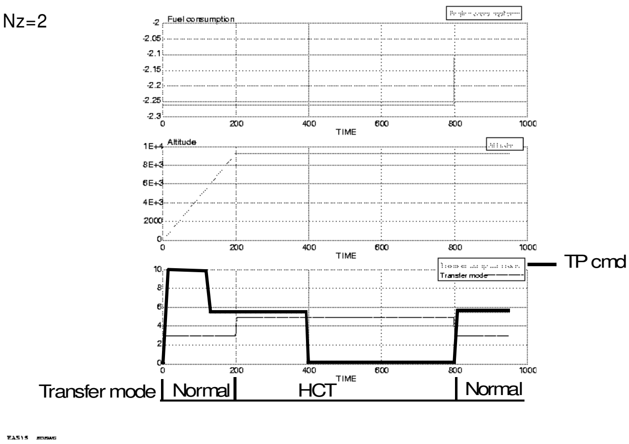

Figure 6 Simulation of system software

Figure 6 shows a simulation example where the transfer modes in the fuel system control software has been simulated.

Especially the quality of monitoring software for fault detection and isolation can be enhanced if simulated with such accurate models. According to [5], the literature shows that about 50% of the line replaceable units removed from aircraft are classified as no fault found (NFF). NFF both increases the unscheduled maintenance cost and the spare cost while reducing the availability of the aircraft. To enhance the quality of monitoring software is therefore a highly interesting area to focus on.

Monitoring software is not simple to verify and validate in test rigs and aircrafts since faults should be introduced in the system. To introduce faults in a test rig increases the risk to damage the test rig. That can be severe for the time schedule in a development project. Introducing faults in an aircraft may lead to a situation where air worthiness is not achieved. Simulation is therefore a powerful tool.

5 Fuel Systems and Numerical Instability

5.1 Numerical Instability

Modelling nonlinear complex systems such as a fuel system require handling of stiff differential equations. Stiff differential equations may result in numerical problems such as numerical instability when the differential equations are integrated.

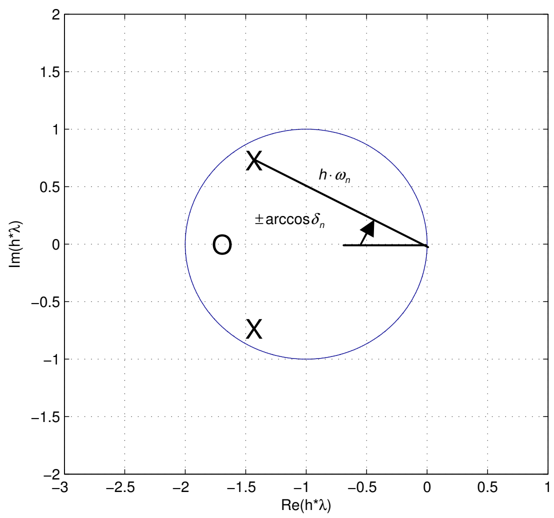

Figure 7 Stability area for Eqn. (1) integrated with Euler's method.

Stiff differential equations are generally achieved when the differential equations that model the system have large differences in each equation's bandwidth. Also discontinuous nonlinearities may result in stiff differential equations. Here, methods to improve continuous stiff differential equations will be discussed.

Basically, there are three different strategies to stabilize stiff differential equations. These strategies are illustrated in Figure 7, based on [3]. The stability area of the system in Eqn. (1) has been plotted there when integrated with Euler's method.

$$\dot{x} = \lambda x \quad where \quad x(0) = 1 \tag{1}$$

In the figure, the two poles to the second order differential equation, Eqn. (2), are shown with X. If the poles of a differential equation of a stable system are within the stability area of the integration method used, numerical stability will be achieved. Otherwise, numerical instability is achieved.

$$\ddot{y} + 2\delta_n \omega_n \dot{y} + \omega_n^2 y = \omega_n^2 bu \tag{2}$$

The two poles are found on a radius of $h \cdot \omega_n$ at the angles $\pm \arccos \delta_n$ for damping ratios $\delta_n < 1$, see also Figure 7. If $\delta_n > 1$, the system becomes two first orders systems with poles in $(-h\omega_n(\delta_n + \sqrt{\delta_n^2 + 1}), \quad 0 \cdot j)$ and in $(-h\omega_n \frac{1}{\delta_n + \sqrt{\delta_n^2 + 1}}, \quad 0 \cdot j)$.

For the first order system in Eqn. (3), one pole is found at $(-h\omega_n, \quad 0 \cdot j)$. See the O in Figure 7.

$$\dot{y} + \omega_n y = \omega_n bu \tag{3}$$

The first strategy to stabilize the integration of a differential equation is to replace the integration method. It should be replaced with an integration method with a stability area that covers the poles of the modelled differential equations.

Secondly, the time step of the integration method can be reduced until the poles are within the stability area.

Thirdly, the model of the system can be altered, e.g. the natural frequency can be decreased until the poles are within the stability area. For the inexperienced simulation engineer, this method may seem inexact since the model will not exactly represent the real system then. However, if the model's frequency range has been specified, as described in [5], with a model bandwidth ω_m, there is no point in modelling dynamics higher than ω_m. Therefore, the dynamics can either be removed from the differential equation in (1) and (2) so the equations become algebraic equations (numerically stable) such as in Eqn. (3)

$$y = bu \tag{3}$$

When dynamics are required in the model, ω_n can instead be approximately reduced to

$$\omega_n > 0.7 \cdot \omega_m \tag{4}$$

5.2 Example: Fuel tank with pressurized air

Fuel systems with its two different media, fuel and air, have by default stiff differential equations. Fuel is approximately 10 times less compressible than air. Therefore, a tank filled with only fuel has a natural frequency that is app. 10 times higher than a tank filled with air.

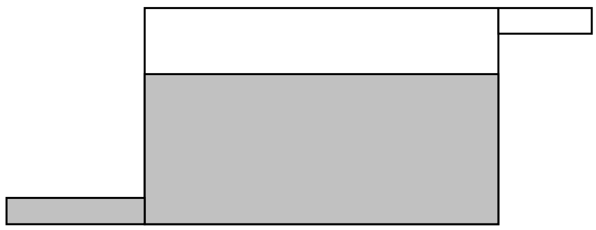

Figure 8 Fuel system tank with air and fuel.

Therefore, the fuel tanks have been modelled for JAS39 Gripen with a low order model where only the dynamics of the air has been modelled. To show this with an example, the low frequency dynamics of the air for an air-filled tank in Figure 8 can be modelled with the following differential equation.

$$\dot{p} = \frac{RT}{V}(\dot{m}_{in} - \dot{m}_{out}) \tag{5}$$

The differential equation of the fuel for a fuel-filled tank in Figure 8 with high frequency dynamics can be simplified to the algebraic equation in Eqn. (6) since $RT << \frac{\beta_e}{\rho}$.

$$\dot{p} = \frac{\beta_e}{\rho V}(\dot{m}_{in} - \dot{m}_{out})$$
$$\Rightarrow \quad \dot{m}_{in} = \dot{m}_{out} \qquad (6)$$

However, discontinuous effects such as the saturation of the tank must also be modelled correctly. In [3], the modelling work has been shown.

6 Model bandwidth, integration method and time step

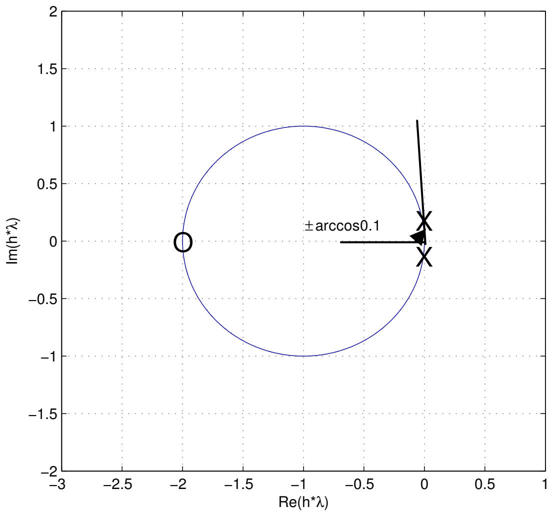

Figure 9 Illustration of Eqn. (5) and (6).

Figure 9 can be used to estimate which time step h that is suitable for a system model. When the system is a first order system, such as the tanks in a fuel system, and Euler's method is used, the time step should be chosen as

$$h << \frac{2}{\omega_b} \qquad (5)$$

See also O in the figure.

If the system is a second order system with low damping, such as in hydraulic actuators, where damping can be as low as $\delta_n = 0.1$, Figure 9 shows that that if Euler's method is used, the time step should be chosen as

$$h << \frac{0.1}{\omega_b} \qquad (6)$$

See X in the figure. Since the model will be prone to instability, Euler's method cannot be recommended for second order systems with low damping.

Nomenclature

b	Coefficient
h	Time step
j	Imaginary number
$\dot{m}_{in}$	Inlet mass flow of tank
$\dot{m}_{out}$	Outlet mass flow of tank
p	Total pressure in tank
R	Specific gas constant of air in tank
T	Temperature of air in tank
u	Input signal
V	Volume of tank
x	States
y	Output signal
β_e	Effective compression modulus of fuel and tank
δ_n	Damping ratio
λ	Complex number
ρ	Density of fuel
ω_b	Model band width
ω_n	Natural frequency
ω_m	Model bandwidth

References

[1] Bergman B and Klefsjö B. *Kvalitet från behov till användning*. 2nd edition, Studentlitteratur, 1995. In Swedish.

[2] Backlund G. *The Effects of Modelling Requirements in Early Phases of Buyer-Supplier Relations.* Linköping Studies in Science and Technology, Thesis No. 812, Linköping, 2000.

[3] Ellström H and Steinkellner S. Modelling of pressurized fuel systems in military aircrafts. *Proc. Simulation of Onboard systems*, Royal Aeronautical Society, London, 2004.

[4] Ljung L and Glad T. *Modellbygge och simulering.* Studentlitteratur, 1991. In Swedish.

[5] Söderholm P. *Maintenance and Continuous Improvement of Complex Systems, Linking*

Stakeholders requirements to the Use of Built-in Test Systems. Doctoral Thesis, Luleå University of Technology, Luleå, 2005.

[6] Lantto B, Ellström H, Gavel H, Jareland M, Steinkellner S, Järlestål, A and Landberg, M. Modelling and simulation of Gripen´s fluid power systems. *Proc. of Recent Advances in Aerospace Actuation Systems and Components*, November 24-26, Toulouse, France, 2004.