

Using Modelica for modeling and simulation of spark ignited engine and drilling station in IFP

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Abstract

Modeling and simulation are becoming more crucial since engineers need to analyze very complex systems composed of several components from different domains. Current tools used in IFP (French Institute of Petroleum) are generally weak in treating multi-domain models because the general tools are block-oriented and thus demand a huge amount of manual rewriting to get the equations in explicit form. The most popular tool used at IFP in simulation of 0D/1D systems and control design area is Simulink. In this paper, we present the use of the Modelica language in modeling and simulation of two industrial applications.

Keywords: Modeling; Modelica; Scicos; SI Engine; Drilling station

1 Introduction

Scilab¹ is a free and open-source software for scientific calculation and Scicos² is a toolbox of Scilab that provides an environment for modeling and simulation of hybrid dynamical systems [1, 2]. They can be compared with Matlab and Simulink, respectively. The underlying hybrid formalism in Scicos allows modeling and simulation of very general hybrid dynamical systems, *i.e.*, systems including continuous, discrete-time and event based behaviors.

Scicos supports acausal modeling or modeling physical systems with components. This has been done, in particular, by lifting the causality constraint on Scicos blocks and by introducing the possibility of describing block behaviors in the Modelica language. This extension allows the user to model physical systems de-

scribed by mathematical formula. Most physical components are more naturally modeled with components simply because physical laws are expressed in terms of mathematical equations [3].

Modelica is a modern object-oriented programming language based on equations instead of assignment statements. Modelica has a multi-domain modeling capability, *e.g.*, electrical, mechanical, thermodynamic, hydraulic, and control systems can be described by Modelica. Modelica programs are built from classes that contain elements, the variable declarations, and equations. In order to write a complicated model easily and efficiently, the model is decomposed into several components. Then, by interconnecting components the model is constructed [4].

In the following sections, we will present two industrial applications: drilling station and spark ignited engine. These applications have been already modeled in Simulink which is a popular tool at IFP mostly used for simulation of 0D/1D systems and control system design. In this paper, we will present the way these applications have been modeled with Modelica and simulated in Scicos.

2 Modeling a drilling station

Modeling in the oil and gas industry is used in several stages of operations, from exploration activity to refining of the crude oil. The purpose of modeling is to improve an understanding of the problems that are usually difficult or expensive to deal with in the real physical system. Drilling a well into a reservoir is an expensive, risky, and time-consuming process. So the problems and malfunctions should be detected as soon as they appear. Most of problems in drilling industry are due to lack of a complete knowledge about the environment and the process. Modeling and simulation are inevitable to detect and control of such problems. In previous works done at IFP a model of drilling station has been developed [5, 6, 7]. The particularity of this work, inspired directly from cited works, lies in using Modelica language and formal computing to

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¹www.scilab.org

²www.scicos.org

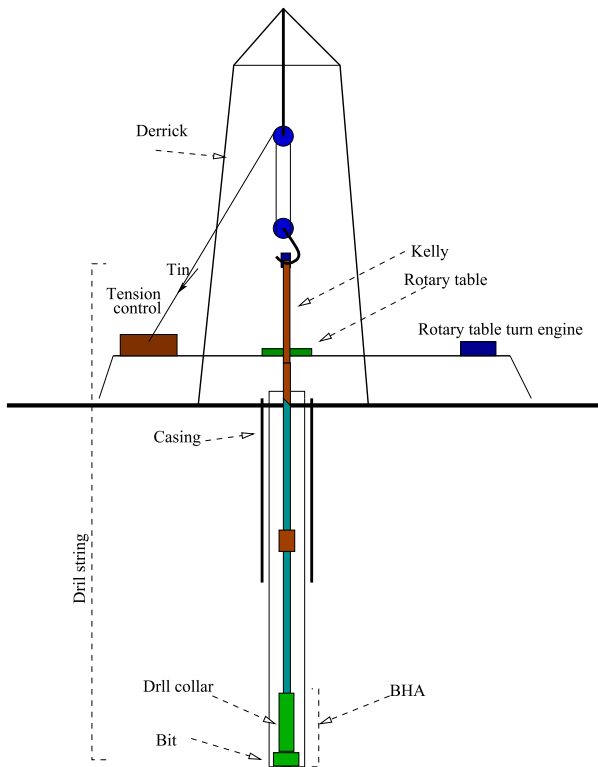


Figure 1: A schematic diagram of a drilling well station.

model and simulate the drilling well station model. A drilling well station is composed of several parts. The first visible part of a drilling well is the rig which is a structure housing equipments used to drill into underground reservoirs for water, oil, or etc. The basic components of a rotary drilling rig are the derrick and hoist, rotary table, kelly, drill pipe, bit, and pump as shown in Fig. 1.

The *derrick* is the support structure that holds the drilling apparatus and the drill string. The *drill string* consists of rotary table, kelly, drill pipe, drill collars, and bit. The *rotary table* is a circular table in the derrick floor which is rotated by the electrical or diesel engines. The *kelly* is a four or six-sided pipe that passes up through the rotary table and transfers rotary motion of the rotary table to the drill string. When rotated by the rotary table, the kelly is free to be raised or lowered by a cable connected to the top of the derrick down the kelly.

Drill Pipe is always the longest component in a drill string. Typically thousands of meters of drill pipe are used to drill an oil well. Drill pipe is manufactured in segments of 10 meters lengths. The top joint of the drill pipe is connected to the kelly. Bottom joint of the drill pipe is directly connected to larger diameter pipes called *drill collars*. One of the earliest problems

drillers encountered in rotary drilling was that of keeping their boreholes straight. The deeper drillers went, the more the boreholes deviated from vertical. Drill collars weigh more than drill pipe and are designed to lower the center of gravity of the drill pipe. This helps control drilling (e.g., making a straight hole) and prevents the pipe from kinking and breaking. Two to twenty drill collars are often used.

The *drilling bit* is the end of the drill string that actually cuts up the rock. The bit screws into the bottom of the drill collars. The most common bit is the tricone bit which has three rotating cones. The cones have teeth that are designed to chip and flake away the rock as the bit is rotated.

2.1 Model of the drilling well

The drilling model is a set of differential equations describing behavior of components of the drilling station, including the bit and the rock interactions. The model should be as simple as possible to explain the desired malfunctions. The diagram in Fig. 2 shows the model composed of four main components: a rig, a drill pipe, a drill collar, and a drilling bit. These component interact with each other via four main variables:

T : the torque that a component applies on another,
 F : the force that a component applies on another,
 Ω : the angular velocity of a component,
 V : the longitudinal velocity of a component.
 A more detailed description of components' model will be given in the following sections.

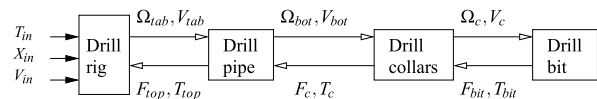


Figure 2: Connecting variables

The model is nonlinear and one-dimensional and provides several bottom/surface transfer functions which can be used for real-time estimation of borehole variables. Furthermore, the model can be used for stability analysis that is extremely important in controlling the drilling process. Another important use of the model is the simulation of transient and steady state behaviors.

2.1.1 Drilling rig

Drilling rigs may have very complex structure varying in form and size. From the modeling point of view the rig imposes the boundary conditions on the drill string structure. A first approach to model the rig is to

consider its geometric structure and the elements that constitute the rig. This may give an exact model, but it would not be practical. Because in fact this model would be very complex and numerically would be so slow that it could not be used in real-time applications. Another problem with this approach is the fact that it cannot be used for another rig.

In [5], the model of two mass-spring-damper has been proposed for the model of longitudinal motions of the drilling rig, as shown in Fig. 3. Although the model is simple, it can provide a very good low frequency response (up to 20 Hz) which is quit enough for our purpose. Further more, when the rig changes, unlike the first method which needs a complete new model, here we need just a new identification for parameters of the model.

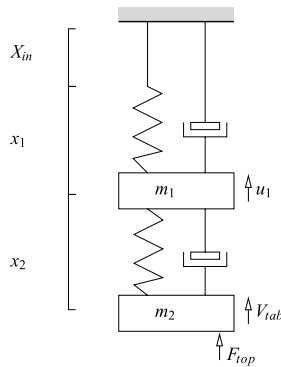


Figure 3: A mechanical model for the drilling rig

The mass m_1 and m_2 can be interpreted as the mass of the hook and the kelly, respectively [5]. F_{top} is the necessary force on the well surface to bore the drill string down into borehole. V_{tab} is the kelly's longitudinal velocity.

Rotary table is modeled as a rotating mass with inertial momentum. In Fig. 2, Ω_{tab} , T_{in} , T_{top} are the angular velocity of the rotary table, the torque applied on the rotary table, and the torque needed to turn the drill string, respectively.

2.1.2 Drill pipe

The drilling pipe is composed of multiple segments which are screwed together to construct a pipe with thousands of meters. Due its length, the drilling pipe exhibits torsional, longitudinal, and lateral motions. In this paper, only longitudinal and torsional motions are considered. Precise modeling of the drilling pipe needs complicated methods such as finite elements. In order to simplify the model, the drilling pipe is dis-

cretized to $N = 15$ sections, see Fig. 4. This modeling approach fulfills the precision requirements with a minimum number of variables [6].

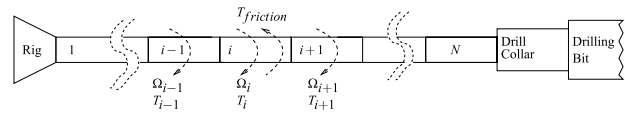


Figure 4: Discretizing the drilling pipe

Applying Newton's laws for rotation, we can obtain the model of each segment.

2.1.3 Drill collars

The drill collars are modeled in the same way as the drill pipe. Since, the length of the drill collars are smaller than that of the drill pipe, we do not discretize the drill collars and we consider a single rigid rod. In order to obtain the model of the drill collars, Newton's laws for rotation are used.

2.1.4 Drill bit

The model of the Rig, drill pipe, and drill collars are composed of two uncoupled dynamics: a longitudinal and a rotational dynamics. These two dynamics should be coupled in the drill bit model. Thus, beside the longitudinal and rotational dynamics in the drill bit, a coupling dynamics is necessary. The diagram in Fig. 5 shows these dynamics.

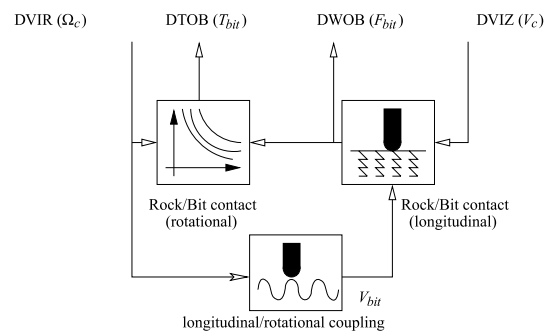


Figure 5: Drilling bit model

In Fig. 5, DVIZ, DVIR, DWOB, DTOB represent the downhole longitudinal velocity, the downhole angular velocity, the downhole weight-on-bit, and the downhole torque-on-bit, respectively. The DTOB (T_{bit}) which is the torque resistance against the rotation due to the rock/bit contact is computed by iso-weight tables. These tables are used to compute the necessary torque as a function of DWOB and DVIR (Ω_c). The

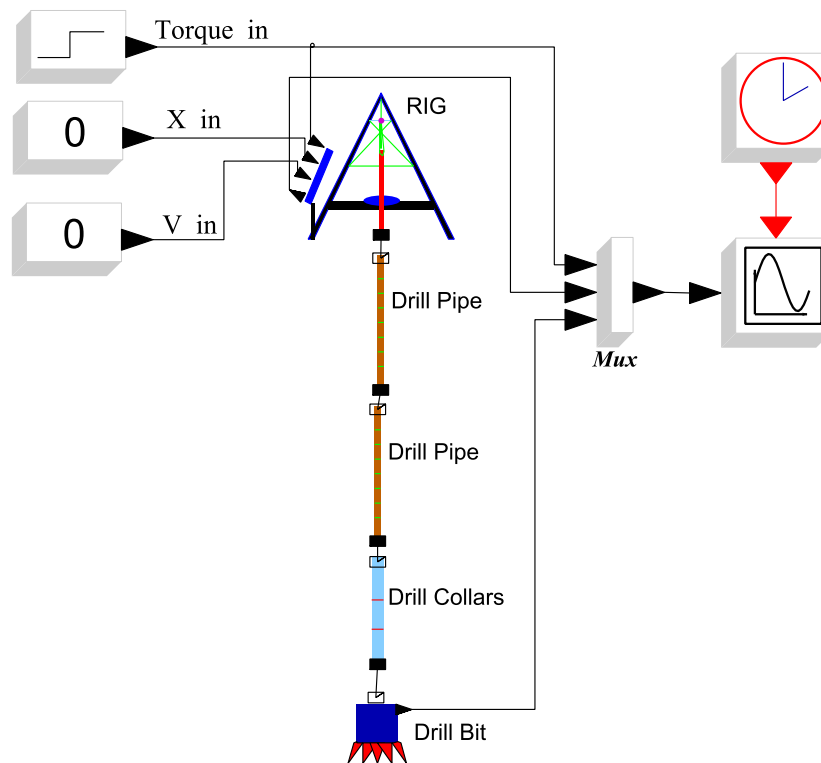


Figure 6: Model of the drilling rig in Scicos

bottom end of the drilling bit is a tricone transforming the rotational motions into longitudinal motions. Ω_c is computed as a function of V_{bit} and the geometric structure of the bit. The WOB is computed as a function of the axial speed of the tricone bit and the longitudinal speed of the bit.

2.2 Simulation example

For each component of the drilling well, *i.e.*, rig, drilling pipe, drill collars, and drilling bit, we have developed a Modelica model. The model of the drilling rig has three control inputs: the rotary table applied torque (T_{in}), the longitudinal speed of the kelly (V_{in}), and initial position of the kelly (X_{in}), see Fig. 2. Thus, the `rig` block has three explicit inputs. Each Modelica model is considered as an implicit block in Scicos. These blocks should be connected to build the model of the drill well.

The Scicos diagram constructed by connecting developed Modelica blocks is shown in Fig. 6. This Scicos

model is composed of four implicit blocks and five explicit blocks. `Rig`, `drill pipe`, `drill collar`, and `drill bit` blocks are implicit blocks (written with the Modelica language). There are three explicit blocks providing input variables of the `rig` block. There is a `scope` block to visualize output variables in the model, and a `clock` block to activate the scope block to sample its inputs. Note that the connection type between the implicit blocks is different from that between explicit blocks. These connections represent physical connection, *i.e.*, there is no flow direction.

With the the developed model, the user is able to simulate the model in different situations. Unwanted vibration/oscillation is a well known recurrent phenomenon in rotary drilling that may cause catastrophic bit failures [5, 6, 7, 8, 9]. This phenomenon is the result of torque fluctuations due to Coulomb frictions. These frictions are included in our model, so it should be possible to simulate this phenomenon which is known as stick-slip. In order to demonstrate this phenomenon, the simulation is started at steady state an-

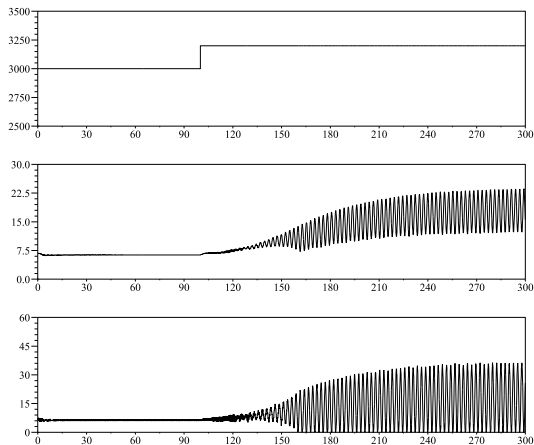


Figure 7: simulation of a drilling station exhibiting oscillations in the rotation speed

gular speed of 66 rpm. The input torque is $T_{in}=3000$ N.m., $X_{in}=-0.03$, and $V_{in}=0$. With these inputs, the system is stable. At $t=100$ sec, the torque is increased to 3200 N.m. which sets off the oscillation. The simulation result is given in Fig. 7. In the top subplot, the input torque applied on the rotary table is shown. The middle subplot shows the angular velocity of the rotary table, and the bottom subplot shows the angular velocity of the drilling bit.

3 Mean value SI engine

The model of the SI engine described in this section is a nonlinear, low frequency model of a fuel-injected four cylinders SI engine which is generally referred to as a *mean value* model. Mean value engine models attempts to capture dynamics in a time-scale spanning over several combustion cycles. Fast events are not of interest other than their effects on a larger scale. Most cyclic dynamics are modeled by their average value over a cycle. The speed and torque output of the engine and the pressure in the inlet manifold are the aspects of most interest in mean value engine model that we have developed. Mean value engine model generally represents a basis for the development of different engine control strategies.

The model of the overall engine is composed of several components. In order to develop the model of the SI engine easier, the engine subsystems including the air throttle, the intake manifold, exhaust gas recirculation (EGR), the canister purge mechanism, sensor dynamics, combustion chamber, and the load are modeled. Inherent system delays in the four-stroke engine cycle including the induction-to-power stroke delay, effects

of the air/fuel ratio or fuel richness are not modeled in this work. The system including fundamental components, sensors, and actuators is illustrated in Fig. 8.

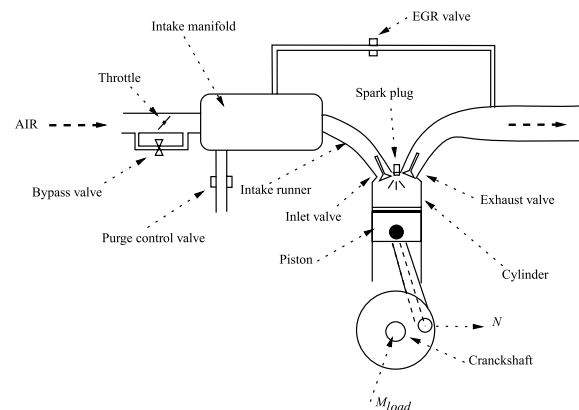


Figure 8: Principle sketch of SI-engine

3.1 Model of the SI engine components

In this subsection, a brief description of the engine components and their corresponding Scicos block is given, more details are given in [10]. These components are shown in Fig. 9.

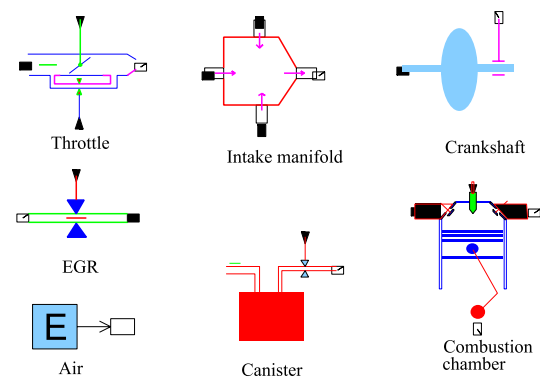


Figure 9: Scicos toolbox for engine components

3.1.1 Air intake throttle

The air throttle that controls the air flow rate into the air manifold and the combustion chamber can be modeled as a flow restriction. The model of a flow restriction highly depends on the pressure difference across the restriction, if small enough, the gas density is considered equal on both sides, *i.e.*, the gas is considered as an incompressible fluid. If, on the other hand,

large pressure differences can be expected the restriction should be modeled assuming compressible fluids. We have assumed that there is no back flow and the temperature is unchanged across the throttle [11, 12]. When the engine is in idle mode, the necessary air for the maintaining the minimum power of the engine is supplied through an air passage, called air bypass passage. The bypass area is controlled by the engine control unit (ECU).

The schematic of the throttle block in Scicos is given in Fig. 8. The air throttle component modeled with Modelica has two implicit ports and two explicit inputs. In Fig. 9, the square ports are implicit and triangle ones are explicit. Implicit ports represent inlet and outlet air flows and explicit input ports represent control signals. The implicit ports are modeled with the `connector` keyword in Modelica.

3.1.2 Exhaust gas recirculation (EGR)

In order to reduce harmful emissions resulting from the combustion, some of the exhaust gas is diverted back into the combustion process. In this method the inlet and exhaust manifolds are connected with a pipe and the recirculated gas flow rate is controlled by a valve [12]. The EGR control valve is modeled as a restriction [11, 12]. The schematic of the EGR block in Scicos is given in Fig. 9. The EGR block has two implicit ports and one explicit input port representing the control signal of the EGR valve.

3.1.3 Canister

Most of the hydrocarbon emissions in modern cars are from the exhaust, but a considerable part also comes from evaporative losses in the fuel tank. Most modern cars use an evaporative emissions management system to reduce these emissions. The basic function of this system is to trap and store the fuel vapors from the fuel tank in a canister until the engine is started. Then after the trapped fuel vapors is drawn into the engine by intake air manifold and combusted. In order to control the flow of vapors into the engine, a purge control valve with no back flow is used. The canister purge valve is modeled as a restriction [11, 12]. The schematic model of the Canister block in Scicos is given in Fig. 9.

3.1.4 Intake Manifold

The air flowing through the air throttle, the EGR, and the canister are mixed in the intake manifold and are

send into the combustion chamber through the intake runner. We have assumed an isothermal manifold heat transfer, *i.e.*, constant manifold air temperature. The air in the intake manifold is composed of fresh air, fuel, and burnt gas. The concentrations can be described as functions of the partial pressures of fuel and air in the intake manifold. Using the ideal gas law, we can obtain the model of the intake manifold pressure. In SI engines, the inlet manifold pressure is reduced by the throttle in order to control the output torque. The flow rate in the intake runner is imposed by the pumping mechanism of the combustion chamber and the crankshaft rotation [11, 12].

The manifold air pressure sensor (MAP sensor) response is not as fast as the variation of pressure in the manifold, so its dynamics cannot be ignored and a first order filter is used to estimate the manifold pressure. The schematic of the manifold block in Scicos is given in Fig. 9. The block has four implicit ports and one explicit output port representing the MAP sensor output.

3.1.5 Combustion chamber

The combustion chamber is the heart of the engine. The air/fuel mixture flows into the cylinders and reacts and usable energy is extracted from the heated gas which is then expelled. In this work, the effects of the air/fuel ratio are not modeled. The cylinder is continuously swept by a piston which is connected to the crankshaft via a rod. The top of the cylinder houses intake and exhaust ports and a spark-plug in SI engines. The cylinder and the crankshaft have two important roles: torque generation and air pumping. When gas burns and expands, the piston is forced down. The downward movement is then transformed into rotational movement. The applied torque on the crankshaft depends on several parameters, such as the air/fuel mixture ratio, spark ignition time, manifold pressure, angular velocity of the crankshaft, etc. Since there is no accurate and simple physical model describing the generated torque, it is customary that a map is used. This map gives the optimum generated torque as a function of the manifold pressure (P_{man}), and the angular velocity of the crankshaft (ω). Thus, the optimal obtainable torque is defined as

$$\tau_{gen}^{opt} = F(\omega, P_{man}).$$

This map gives the value of the produced torque regardless of other important effects such as the effects of spark advance. Adjusting the spark advance timing, we can optimize engine efficiency to deliver peak

combustion pressure when the piston reaches about 10° after top dead center angle. Incorrect spark timing can have a significant effect on emission output and vehicle drivability. The amount of the spark advance needed by the engine varies as function of the number of different operating conditions. The coolant temperature, fuel quality, and engine load are just a few of the many factors that can significantly impact ideal ignition time [13, 14, 15]. The effects of the spark timing on the produced torque is obtained by using an experimentally obtained map. The map that we have used in our simulation gives the spark advance efficiency or the ratio of the produced torque with respect to the optimal torque, *i.e.*,

$$\eta = \frac{\tau_{gen}}{\tau_{gen}^{opt}} = H(|SA|)$$

where $|SA|$ is the absolute value of the spark advance timing. Note that $H(0) = 1$ and $|SA| < 40^\circ$.

The up/down movement of the cylinder creates a pumping effect; when the piston moves downward, the air is inhaled from the intake manifold and when the piston moves upward, the burnt air is exhaled to the exhaust manifold. In an internal combustion engine, the pressure on the intake side will normally be lower than on the exhaust side. Pumping gas from low to high pressure costs energy and this energy is taken from the crankshaft. The amount of the pumped air depends on several variables such as the cylinder volume, the angular velocity of the crankshaft, pressure in the intake manifold, pressure in the exhaust manifold, and the air temperature. Again, since there is no accurate and simple physical model describing the amount of the pumped air, a map is used to describe the total gas flow rate as a function of manifold pressure (P_{man}) and engine speed (ω). The maps used in our model have been obtained at IFP for a four cylinders SI engine. The schematic of the combustion chamber block in Scicos is given in Fig. 9. This block has three implicit ports for the air intake runner, the exhaust outlet, and the connection with the crankshaft. The block has one explicit input port representing the spark advance signal coming from the controller.

3.1.6 Crankshaft dynamics and perturbations

The crankshaft dynamics are modeled using the Newton's second law for rotating masses. All perturbations due to instabilities in combustion, differences in generated torque in cylinders, and variations in fuel injection in different cylinders are modeled with noise generator blocks (explicit Scicos blocks). This perturba-

tions represent the load applied on the engine including controllable loads such as effects of A/C or anti-frost systems on the engine and uncontrollable perturbations modeled with a zero mean random noise. The schematic of the crankshaft block in Scicos is given in Fig. 9. This block is connected to the combustion chamber block via an implicit port representing the mechanical connection of the crankshaft to the combustion chamber. The block has an explicit output port providing the angular velocity.

3.2 Simulation example: idle speed control

In this section, the engine components are assembled to construct the model of an SI engine, see Fig. 10. The engine model is then used to validate start-up and idle speed control strategies. The controller can be developed with standard (explicit) Scicos blocks. Its modeling with explicit blocks in Scicos has the advantage of using the rich control toolbox of Scilab.

In our model, the selected controller is relatively simple, *i.e.*, a PI controller. This controller will be active as soon as the engine speed exceeds 700 RPM. During the start-up phase, the spark advance is set to 20° and the throttle bypass area is 15%. When engine speed superseded the 700 RPM threshold, the control is handed over to the PI controller that adjusts the spark advance and the bypass area as a function of the reference speed, *i.e.*, 750 RPM, instantaneous MAP sensor and the engine speed. The simulation results of an engine start-up and the idle speed control is given in Fig. 11. In this simulation, in order to test the idle speed controller, different loads (τ_l) are applied at instants $t=20$ sec and $t=40$ sec, see the bottom plot of Fig. 11. In the top plot of Fig. 11, the engine speed is shown. The engine speed is relatively regulated around 750 RPM in spite of the loads and random perturbations. The middle plot of Fig. 11 gives the intake manifold pressure that decreases from atmosphere pressure as engine starts up and varies as load changes.

4 Future Works

The Modelica compiler used in Scicos has been developed in the SIMPA³ project with the participation of INRIA, IMAGINE, EDF, IFP, and Cril Technology. Recently, the ANR⁴/RNTL SIMPA2 project has been

³Simulation pour le Procédé et l'Automatique

⁴French National Research Agency

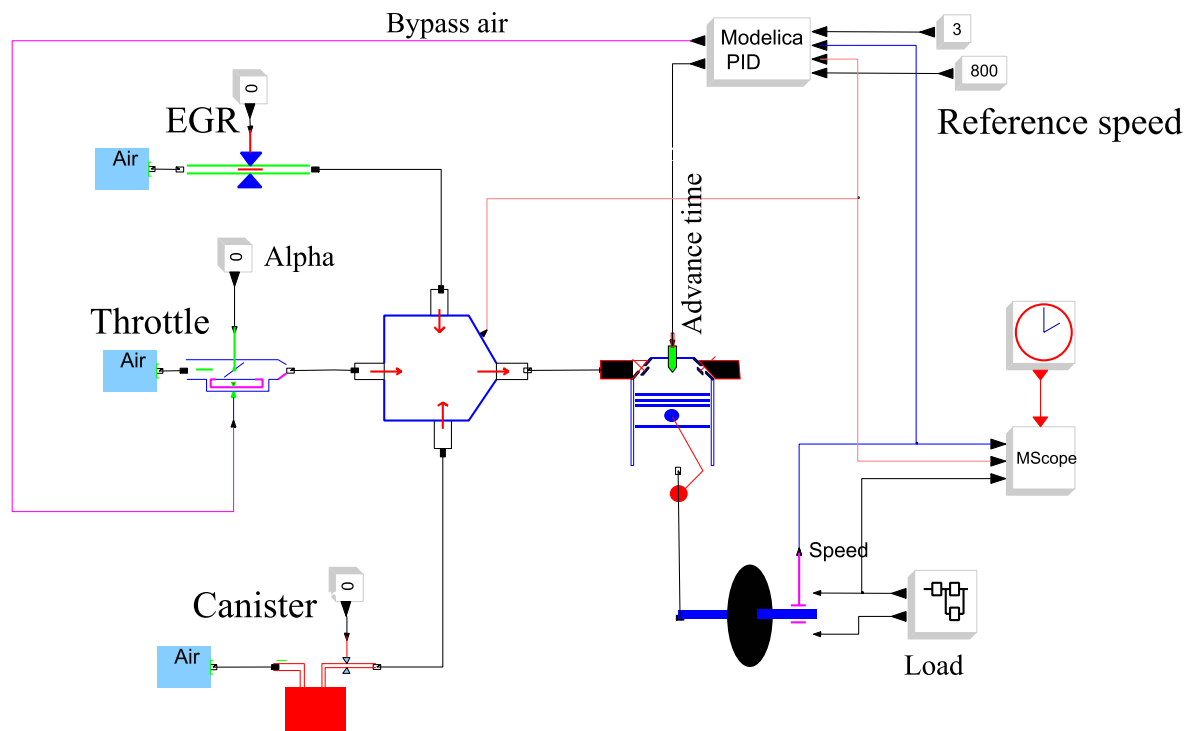


Figure 10: The Scicos model for a mean SI engine

launched to develop a more complete Modelica compiler. The main objectives of this project are to extend the SIMPA compiler to fully support inheritance and hybrid systems, give the possibility to solve inverse problems by model inversion for static and dynamic systems, and enhance initialization of Modelica models.

5 Conclusion

In this paper, we modeled a drilling station and a mean value SI engine with Modelica in Scicos. It should be noted that these models have been already modeled and simulated in Simulink at IFP. The modeling in Modelica was performed in order to compare two modeling environments. Modeling in Modelica has several advantages: Modelica is a declarative language with which very general hybrid systems can be modeled. The Modelica models are independent of the simulation tool and can be simulated in any Modelica simulator. Another important advantage of using Modelica lies in the symbolic manipulation of mod-

els. Because it gives the possibility of several simplifications such as efficient discontinuity handling, index reduction, and generation of the analytical Jacobian. Another advantage of Modelica models comparing to Simulink models is the facility in model construction and navigation in the model. For example, the model of the drilling station in Simulink is composed of more than 500 blocks distributed in 116 subsystems whereas the Scicos model is just composed of 9 blocks. The model of the SI engine in Simulink is composed of 203 blocks distributed in 30 subsystems whereas the Scicos model is composed of 20 blocks. The reduced number of blocks helps the user to construct and debug the model easier and faster.

6 Acknowledgements

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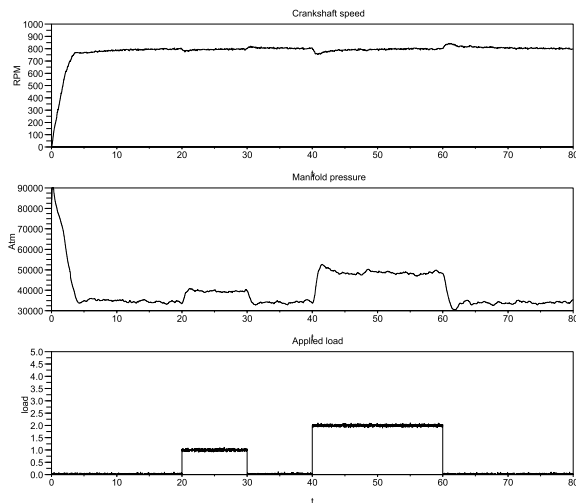


Figure 11: simulation result for start-up and idle speed control of the engine

References

- [1] Campbell S. L., Chancelier J.P., Nikoukhah R., Modeling and simulation in Scilab/Scicos, Springer Verlag publishing, 2005.
- [2] Chancelier J. P., Delebecque C. , Gomez C., Goursat M., Nikoukhah R., Steer S., An introduction to Scilab, Springer Verlag, Le Chesnay, France, 2002.
- [3] Najafi M., The Numerical Solver for the Simulation of the Hybrid Dynamical Systems, Doctor of Science Thesis, Paris XII University, 2005
- [4] Fritzson P., Principles of Object-Oriented Modeling and Simulation with Modelica 2.1, Wiley-IEEE Press, 2004.
- [5] Pavone D., and Desplans J.P., Analyse et Modélisation du comportement dynamique d'un rig de forage, *IFP report No 42208*, 1996.
- [6] Pavone D., and Desplans J.P., Analyse, Modélisation et élimination du stick-slip observé sur les expériences de Norvège, *IFP report No 41317*, 1994.
- [7] Rey-Fabret I., and Mabile C., and Oudin N., Detecting whirling behavior of the drill string from surface measurements, Proc. SPE 72nd, annual technical conference and exhibitions of the Society of Petroleum Engineer, San Antonio, USA, pp 223-232, 1997.
- [8] Dufeyte M.P., and Henneuse H., Detection and monitoring of the stick-slip motion: field experiments, Proc. SPE/IADC Drilling conference, Amsterdam, Netherlands, 1991.
- [9] Dawson R., and Lin Y. Q., and Spanos P.D., Drill string oscillation, Proc. Spring. Conf. of Society for experimental Mech, Houston, June, 1987.
- [10] Najafi M., Modeling complex systems with Modelica in Scicos: Application to mean value spark engine, *ESM'2007*, Westin Dragonara Hotel, St. Julian's, Malta, 2007.
- [11] Nakayama Y. and Boucher F., Introduction to Fluid Mechanics, Arnold, London, Great Britain, 1999.
- [12] Silverlind D., Mean Value Engine Modeling with Modelica. M, Department of Electrical Engineering, Linkoping University, Master's thesis, 2001.
- [13] Heywood J.B., Internal Combustion Engine Fundamentals. McGraw-Hill series in mechanical engineering, international edition, 1988.
- [14] Aquino C., Transient A/F control characteristics of the 5 liter central fuel injection engine. In Society of Automotive Engineers technical paper, 1981.
- [15] Degobert P., Automobiles and Pollution. In Society of Automotive Engineers, Inc. Translation of Automobile et pollution, 1995.