

DEVELOPMENT OF CANDU PROTOTYPE FUEL HANDLING SIMULATOR −CONCEPT AND SOME SIMULATION RESULTS WITH PHYSICAL NETWORK MODELING APPROACH

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Abstract

This paper reviewed the need for a fuel handling(FH) simulator in training operators and maintenance personnel, in FH design enhancement based on operating experience (OPEX), and the potential application of Virtual Reality (VR) based simulation technology. Modeling and simulation of the fuelling machine (FM) magazine drive plant (one of the CANDU FH sub-systems) was described. The work established the feasibility of modeling and simulating a physical FH drive system using the physical network approach and computer software tools. The concept and approach can be applied similarly to create the other FH subsystem plant models, which are expected to be integrated with control modules to develop a master FH control model and further to create a virtual FH system.

Nomenclature

Acronym	**Description**
CANDU	CANada Deuterium Uranium
COG	CANDU Owners Group
FH	Fuel Handling
FM	Fuelling Machine
FMS	Feedback Monitoring System
NPP	Nuclear Power Plant
OPEX	Operating Experience
PHT	Primary Heat Transport
VR	Virtual Reality

1. Introduction and need for fuel handling simulator

The CANDU fuel handling system provides facilities for the storage and handling of new fuel, on-power refueling of the reactor, and transfer of irradiated fuel from the reactor to the storage bay. On-power refueling is a unique feature of the CANDU system, where two fuelling machines, one on each reactor face, work in a coordinated fashion to insert new fuel bundles into a fuel channel and retrieve the irradiated fuel at the other end of the channel. The operations of the two FMs and their coordination are remotely controlled by computer.

The fuel handling systems are safety related as their operations involve on-line interactions with the PHT (Primary Heat Transport) system, including numerous actions to open and close fuel channels at the PHT system boundary and spent fuel discharge from a FM through the spent fuel port reception bay to the spent fuel storage bay. Any human error in the operations and inadequacies in the design may lead to unplanned outages, derates, or radioactive leaks and, as such, have significant impact on personnel safety and power productivity. Therefore, the fuel handling system designs must strictly comply with all safety requirements and follow conservative decision-making principles, and the operations mustconform to rigorous procedures to ensure the power plant's safety, productivity and reliable operation.

Over the past decade, the fuel handling systems have been experiencing performance degradation problems as most of the operating CANDU stations are at their mid-life or approaching the end of their service life. As reported from thestudy conducted by a COG (CANDU Owners Group)joint project on CANDU Fuel Handling Benchmarking [1], there has been a clear increase in unplanned fuel handling related production losses and an upward trend in significant unplanned events. In Canada, fuel handling events reported to COG have accounted for a significant portion of the total OPEX events, and the production losses caused by fuel handling related events have increased rapidly from $4.5 million in2006 to $95.5 million in 2008[2].The analysis in Reference [3] shows that the significant causes of CANDU fuel handling events are mainly related to human performance (41%), design configuration, analysis, and equipment performance (40%), and management (19%).

All stations have recognized that human performance is a key area for improvement in fuel handling operations. However, human performance problems continue to occur due to knowledge and skill weaknesses. This was mainly attributed to lack of well defined training programs for initial and requalification training of fuel handling operators, maintenance and technical staff. One of the contributing factors to this problem is that many stations do not have up-to-date training facilities or FH simulators [4]. Use of simulators for continuing training of FH operators and maintenance personnel has been recommended to all stations to achieve excellence in FH operations[1].

FH design is another predominant area for safe operations and equipment performance improvement. AECL (now Candu Energy) conducted an internal assessment of CANDU fuel handling events based on the COG OPEX database and AECL FMS information in 2010 [5]. This analysis focused on the design related fuel handling events that caused station forced outages, reactor trips and derates, whichare potentially preventable through design change or enhancement. A systematical review of major fuel handling events revealed that the biggest contributor to the station forced outage, trips, and derates was a loss of fuelling due to the FMbeing stuck on the reactor face (fuel channel), andsuch events usually resulted in long station outages.Most of these events were caused by component failures in the subassemblies of the FMs. Therefore,fuel handling design plays a critical role in the reliable operation of the FM subassemblies / equipment. Enhancement of the FH design is needed to optimize component and subassembly design, and improve the equipment reliability. The improved FH design should allow for easy preventative maintenance, quick repair and replacement of the failed equipment/components to minimize the overall fuelling machine or station down time.

The FH engineering design process has been dominated by traditional design approaches for many years and now needs new computer based design methods and simulation tools to advance the design process. Powerful mathematical computing processes combined with advanced animation and interaction capabilities will enable designers to perform design tasks in a much more effective and efficient way for various design analyses, rapid prototyping, testing design options with different equipment configurations, addressing critical or complicated design issues, validating product performance, simulating failure scenarios and visualizing the results etc.

2. Review of simulation technology application on FH simulator development

Computer software based modeling/simulation technology has become an increasingly important tool for engineering design analysis and validation, personnel training and qualification. In combination with advanced Virtual Reality (VR) technology, the simulation has the advantage of offering users the opportunity to not only visualize, but also to interact and navigate with the systems or situations in a computer-generated artificial environment (or virtual environment) without any risks associated with the real environment.

There are many reported discussions and applications of VR based simulation technology used in nuclear power plants for planning and operations, engineering design, and field operator/maintenance staff training [6, 7, 8,9]. The notable reported work is the development of the VR based training systems to support on-site fuel processing for the Russian RBMK-type NPPs[10]. Similar to CANDU fuel handling process, the refueling operations on the RBMK type nuclear power plants take place while the reactor is at full power. In the first phase of the project, a VR based Refueling Machine (RM) simulator was created for online refueling operation training. With the successful deployment of the RM simulator to the Leningrad NPP, the work moved into development of the VR based simulation systems specifically for RM maintenance personnel training, which was implemented in an immersive virtual environment. The project continued to extend the VR based training system for the entire on-site fuel handling cycle, including spent fuel handling, since 2008. At the time this work was reported, all the Russian RBMK- based NPPs had such training systems deployed and actively used in training. The accomplishment of this project shows that the VR based simulator is a proven and valuable training tool for operators and maintenance personnel of nuclear power plants. It significantly improved training effectiveness and provided deeper and better understanding of the systems and component behavior in a simulated real time environment.

There are different uses of VR simulation technique depending on the purposes and requirements of the applications. For the purposes of CANDU FH personnel training and design enhancement, it is conceivable that one type of VR based simulator can be the virtual FH system mechanisms and the associated reactor operating environment in a 3D graphical display. The users could visualize, for example, the fuel changing operations by observing the interactions and movements of each system or subsystem involved in real time. It would allow users to acquire the FH knowledge and technical information in a more realistic and direct way than from any documents, drawings, flow sheets, etc. For FH operational training, the VR based simulator could comprise the FH control panel in the Main Control Room, either in a 3D screen display or a 3D immersive display. With the ability to interact with the control panel, the FH operators would become more involved in various normal and abnormal scenarios during training with the real results of their actions displayed. The VR simulator for FH maintenance procedural training is expected to be different from the one used for FH operational training, as it is highly desirable for the trainee to immerse themselves in the virtual environment and interact with the objects (tools, equipment, etc.) in it. The VR simulator implemented in a 3D immersive display would be preferred for procedural training purposes, albeit at a higher cost.

Regardless of the type of the VR based simulation, it is the FH knowledge, expertise and procedural information embedded in the simulation system that support and drive the animated simulation. The strength of such a simulation system will not only allow the users to experience the consequences of malfunctions (due to either system failures or operator human errors) and observe the invisible process operations with an improved view of scenarios in 3D VR environment, but it also offers a means to capture the core design knowledge and operational expertise into the simulation knowledge base which will prevent further loss of FH expertise due to retirement or leave of subject matter experts.

Engineering design knowledge and modeling are considered to be an essential part of the knowledge base for the FH simulator, especially for FH design enhancement. Engineering models mathematically describe the physical system behaviours, and compute the system's process or motion parameters during execution of the simulation. The outputs of such simulation can be used directly to drive 3D VR animation for real time visualization of the FH system operations. It is believed that the combination of engineering modeling and 3D VR animation will eventually provide a high fidelity FH simulation system.

3. Top level module of CANDU prototype FH Simulator

Development of a CANDU prototype FH Simulator (based on the latest CANDU 6 design) has been initiated by FH Engineering at Candu Energy in 2011. The FH Simulator, once developed, is intended to be used as:

1) An engineering design tool to test, verify and validate design changes, especially under failure conditions impossible to test with actual hardware systems.
2) A training tool integrated with 3D graphical display to enhance the current FH Customer training programs.
3) Integration with the CANDU 6 Simulator (C6SIM), which is an analysis tool used to model the dynamics of the reactor process and control systems.

The plant model of the FH physical systems first needs to be derived based on a review of the primary FH system structure/functions and the "laws of nature" prior to integration of the FH control algorithms into the simulation system. The fuelling machine heads, their support systems (carriages and bridges, etc.), and the associated auxiliary systems are the primary component of the fuel changing operations. Each FM head comprises several major subassemblies – snout clamping, ram assembly, magazine, and separator assembly, etc. – each essential for fuel changing operations at the reactor face. The carriage and bridge systems provide the horizontal and vertical motions of the FM head, allowing its traverse to access all fuel channel end fittings at reactor face. All FM head subassemblies and support systems are driven by either hydraulic or electrical power systems during the fuel changing.

The top-level module of the plant model for each FM head and associated support systems is shown in Figure 1, which is used for initializing the plant model development.

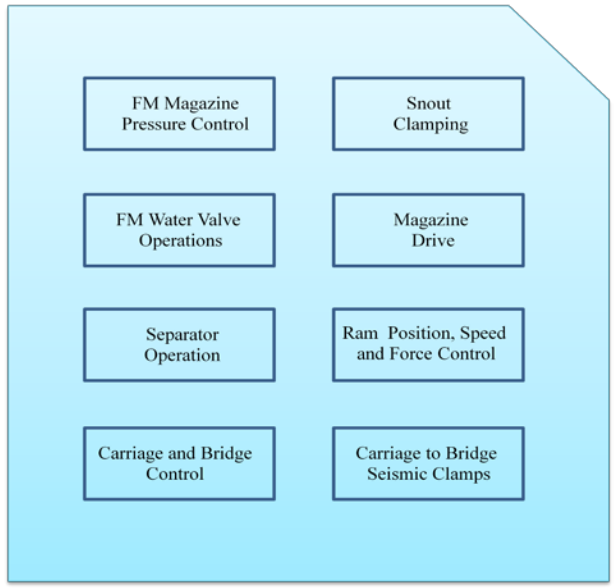

Figure 1Top level module of FH plant model for CANDU prototype FH Simulator.

The sequential operations and synchronization of the two fuelling machines are controlled by algorithms residing in the software programs andembedded in the interlock hardware and local control devices. Figure 2 shows the top-level module of the complete FH Simulatorwith the control algorithms included. The simulation outputs can be directly used to create and drive the virtual FH subsystems/assemblies in a 3D virtual world using software graphical tools.

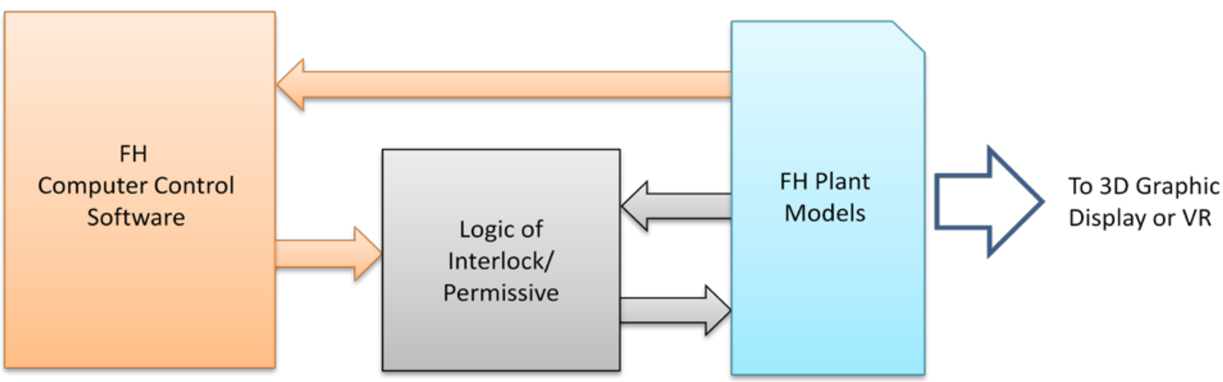

Figure 2Top level module of CANDU prototype FH Simulator model.

4. Modelling methodology

From a modular perspective, each FH subsystem shown in Figure 1 can be typically divided into a drive system and its related mechanical load system. The drive system often comprises several functional devices at equipment level, and each functional device performs a required and unique function for the operation of systems. Modeling a drive system first requires developing a mathematical model for each functional device, and then integrating them by arranging these models according to the designed configuration. Modeling a mechanical load system requires mathematically characterizing the load with typical mechanical parameters such as mass, inertia and friction without delving into the complex structures of the mechanical subassemblies.

When modeling a physical system, a complete mathematical model should ideally include the description of the transient and steady state performances of each functional device in order to fully capture the system performance characteristics under the defined operating conditions. However, this often requires significant analytical and computational effort in order to derive the detailed equations and solve them for a practical solution. Since the momentum effects of moving parts of the functional devices in FH drive systems are generally negligible (compared to the forces or torques generated by the drive systems) and the transient response of functional devices is often much faster than that of the mechanical load systems, the dynamic behaviours of the functional devices will not be considered during the modeling. This significantly simplifies the modeling process without losing the validity of the simulation.

MATLAB/Simulink software tools are used to develop the engineering model of the prototype FH Simulator. Simulinkis a software environment on the MATLAB platform for multi-domain simulation and Plant Model-Based Design[11,12]. The Simulink product family includes a number of specific toolboxes, which allow users to create a system model using a traditional approach with mathematical function language or a physical network approach with physical domain specific modeling language, or a combination of both for a multi-domain system. The traditional approach is also referred to as input-output method in which a physical system (plant) is represented as a transfer function with input(s) and output(s). In the physical network approach, physical components of the system are described using parameters that correspond to physical quantities. Thus, a system model could be constructed in physical network diagram similar to how the physical system would be assembled. This approach allows users to describe the physical structure of a system rather than the underlying mathematics. Currently, there are several modeling tools under the Simulink Physical Modeling family that support the physical network approach. Among them, SimHydraulics [13]and Simscape[14] have been used in the development of the FH sub-system plant models (to be discussed in the later sections).

Prior to using any physical component functional blocks in the libraries of Simulink Physical Modeling tool boxes, it is important to note that all mathematical equations, assumptions and limitations behind each Simulink component block must be verified to ensure conformance with the requirements and conditions of the system being modeled.

There is always a trade-off between the model accuracy (fidelity) and computing efficiency when building a complex system model for a physical system. This is anticipated to become increasingly critical as the FH system plant model eventually grows to include all sub-system plant models in Figure 1. Making appropriate assumptions and approximations during the task definition, component block selection, and model construction is extremely important in order to simplify the model structure so that the simulation computing converges reliably to an acceptable solution, while capturing all required system performance behaviour.

5. Modelling fuelling machinemagazine drive

As shown in Figure 1, the FM magazine drive is one module of the FH Plant Model for the FH Simulator. The function of the FM magazine assembly is to store and carry fuel bundles, various channel components, and tools required during on-line fuel changing. The assembly has a 12-station magazine rotor with each station housing a pair of fuel bundles or a tool assembly. The magazine is rotated and positioned at any one of the twelve stations through a set of indexing and gear reduction mechanisms driven by the FM magazine hydraulic control system.

The interface requirement between the plant model and the control/interlock model needs to be first clearly defined. The inputs to the magazine plant model are the computer control signals to the two hydraulic directional control valves which actuate and control the rotation of the magazine in a clockwise or counter- clockwise direction. The outputs from the plant model are the angular position of the magazine rotor shaft and the angular position of the camshaft that drives the indexing mechanism. These outputs are the feedbacks to the FH control computer for positioning control and monitoring during magazine movement.

The simulation is to imitate the operation of the FM magazine drive system over time given a computer control signal to energize one of the hydraulic directional control valves. The developed plant model for the magazine drive is considered as a "base" model that includes only the primary functional devices of the physical system, and not the accessories that have negligible effects on the overall system performance. The base model may be further modified or expanded as required to suit different requirements of the simulation application. The plant model does not include control and interlocks and associated instruments, which are created as separate modules as indicated in Figure 2.

The model that represents the magazine drive is further divided into three sub-models: hydraulic power supply model, hydraulic drive model, and mechanical loading model. The modeling process of each of these is described in the following subsections.

5.1 Modelling FH hydraulic power supply

The function of FH hydraulic power supply model is to simulate the continuous supply of kinetic and pressure energy to the FM magazine drive and other FH drives that are operated hydraulically. Based on a review of the physical FH hydraulic power supply system configuration and operation, the primary functional devices in the hydraulic power supply system that were included in the base model are the main discharge pump (pressure compensated variable displacement type), an accumulator near the main pump discharge line to dampen pump pressure and flow fluctuations, a pressure relief valve for over pressure protection, and a check valve to prevent reverse flow in the supply line. Although the actual system consists of numerous hydraulic equipment, accessories, instruments, and sensors, these selected functional devices are considered to be sufficient to represent the hydraulic power supply system performance for the purpose of simulating continuous hydraulic power supply in terms of pressure and flow under the defined operating conditions.

During the modeling process, the component model for each of hydraulic functional device was first created by properly selecting its hydraulic component block from the SimHydraulics library and configuring the block parameters with the data extracted from manufacturers' catalogues, design documents, or the best approximation based on the subject expertise. The created functional device models were then integrated to form the system model in accordance with the arrangement of the FH hydraulic flow sheet. Each model was thoroughly tested to check its performance through simulation runs before the integration.

Figure 3 shows the model configuration for the FH hydraulic power supply system, where the "Ideal Angular Velocity Source" in the model represents the electrical motor that drives the main pump at the design speed of 1500 RPM.

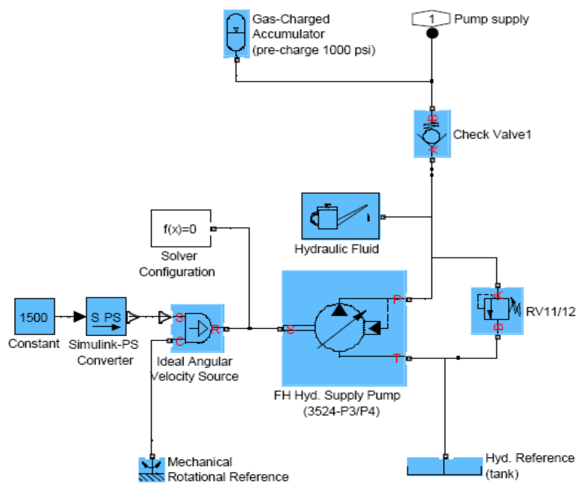

Figure 3 Model of FH hydraulic power supply.

5.2 Modelling FM magazine drive

The magazine is driven by an oil hydraulic motor through a worm gear reduction unit and cam/indexing assembly. The function of the FM magazine drive model in the FH Simulator is to simulate control (modulation) of the supplied fluid energy in forms of pressure, flow rate, and direction of fluid flow in order to meet the requirements for torque, velocity, and rotational direction of the hydraulic motor. Given a control command to energize one of the two directional valves (depending on the direction of the magazine rotation) and with the supplied hydraulic power from the hydraulic power supply model, the FM magazine drive model computes the hydraulic motor's shaft speed, angular position, and torque.

The physical magazine drive system consists of a pressure reducing valve (PRV), two directional control valves, a pressure compensated flow control valve (FCV), two pilot operated check valves, a bi-directional hydraulic motor, and other accessories. All of these valves and the motor are considered to be the primary functional devices in the base model.

During the modeling process, each functional device was modeled individually using the similar method in modeling the hydraulic power supply system. The model of each functional device was tested and interconnected as shown in Figure 4 to form the “meter-out” control circuit according to the designed configuration.

A first order transfer function was added to each directional control valve block to create a time delay that simulates the response time of energizing the directional control valves. The pressure compensated flow control valve was modeled with a pressure compensator and an orifice connected in series. The flow control valve model (the pressure compensator and orifice) needed to be carefully tuned to ensure that the valve model operates within the defined pressure regulation range of the compensator in order to simulate the constant flow control function. If the flow control valve was “mistakenly” operated out of the defined range, the simulation could run into a numerical difficulty (solution does not converge), or the valve’s failure to control the flow rate to the set point.

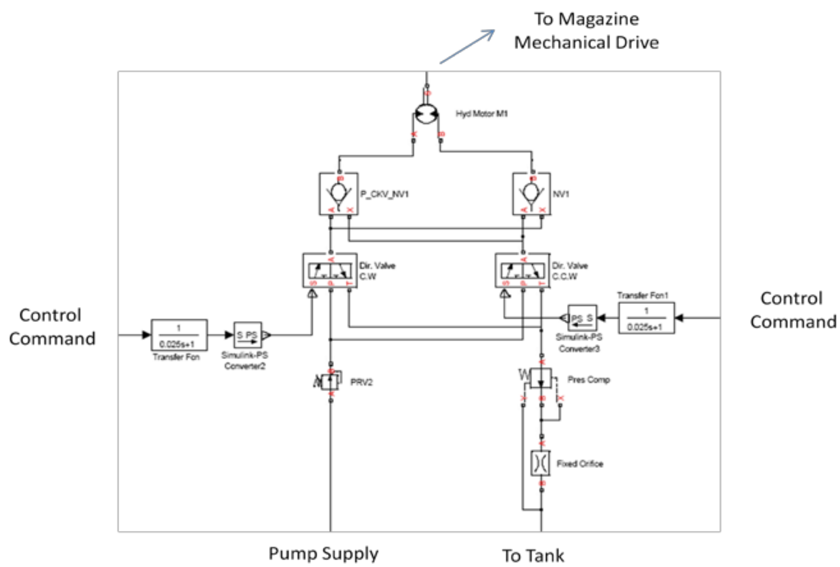

Figure 4Model of FM magazine hydraulic drive

5.3 Modeling FM magazine mechanical load system

Modeling the FM magazine mechanical load system requires mathematically characterizing the magazine mechanical motion using basic elements of the mechanical rotational system. Transmission of mechanical power from the hydraulic motor shaft to the magazine rotor is essentially through two sets of gear systems: a worm drive reduction gear unit and an indexing drive gear set (the magazine roller geared with the camshaft).

The worm gear unit was modeled using an ideal mechanical “Gearbox” function block from the Simscape Foundation library and parameterized by the gear ratio. The indexing drive gear set was modeled with a customized mechanical functional block (Roller Gearbox) that was created using the Simscape language. The Roller Gearbox simulates the special function of the indexing drive gear set: the roller gear follows the camshaft (at the specified gear ratio) as the camshaft rotates 3/4 of each turn (i.e. 0 - 270 degrees) while the magazine moves from one station to the next; the roller gear remains stationary as the camshaft continues to finish the last 1/4 of the turn, i.e. the roller gear does not rotate and does not transmit the mechanical energy while the magazine dwells at the station.

The lumped moment of inertia for the magazine assembly was estimated based on the estimate of the moment of inertia for each sub-assembly. The lumped moment of inertia was modeled by an ideal mechanical rotational inertial component from the Simscape Foundation library. The parameter of this component reflected the moment of inertia at the hydraulic motor shaft.

All torque loads applied to the magazine rotor shaft and camshaft were modeled separately using the damping elements from the Simscape Foundation library. The values of the torque loads were approximated using the torque measurements averaged over the previous FMs' tests. The damper represents the resistive torque loads reflected at the magazine rotor shaft and camshaft.

Figure 5 shows the model of the magazine mechanical load system. Rotational Sensors 1 and 2 represent the potentiometers for the angular position feedbacks of the magazine rotor shaft and the camshaft respectively. They are the model outputs fed backs to the FH control computer for positioning control and monitoring purpose.

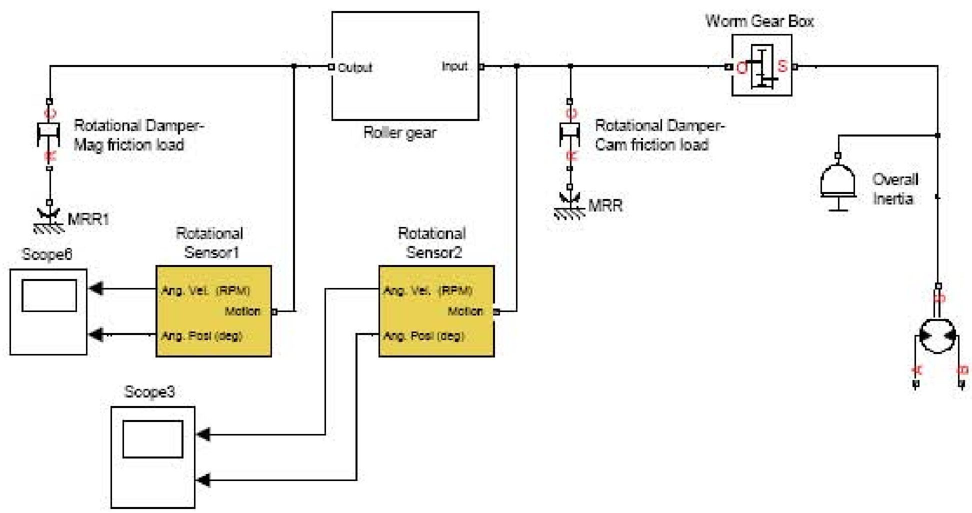

Figure 5 Model of FM magazine mechanical system.

6. Simulation and results

With all three models integrated, the simulation of the magazine drive was executed by energizing one of the directional control valves. The simulation results for magazine clockwise rotation (the directional valve, Dir. Valve. C.W. was energized) are shown in Figures 6 - 8. The discussion pertaining to these results applies equally to the simulation of the magazine rotation in counterclockwise direction (energizing the directional valve, Dir. Valve C.C.W.).

The simulation duration was set to approximately 40 seconds in simulation time after the directional valve is switched on, which allows the simulation run to cover a full magazine rotation through its twelve stations (the magazine is designed to take 36 seconds in one revolution including dwell time). The computed magazine angular position and speed in simulation are shown in Figure 6. The comparison between the simulated and the designed nominal positions in degrees is summarized in Table 1.The comparison between the simulated magazine speed (0.2334 rad/s) and the designed nominal speed (0.2327 rad/sec.) is indicated in the 2nd chart of Figure 6.

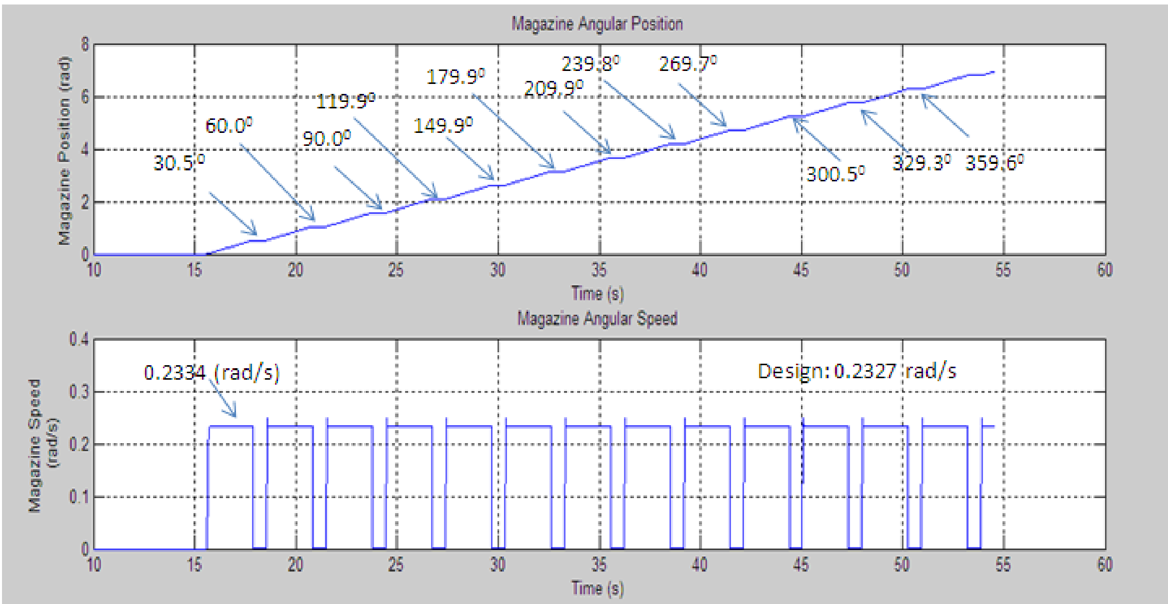

Figure 6Simulated FM magazine angular position and speed.

Magazine Station #	1	2	3	4	5	6	7	8	9	10	11	12
Simulated Position	30.5	60.0	90.0	119.9	149.9	179.9	209.9	239.8	269.7	300.5	329.3	359.6
Designed Position (Nominal)	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	360.0

Table 1 Comparison between the simulated and the designed nominal positions for magazine

The simulated speeds and positions for the indexing cam drive shaft and hydraulic motor are shown in Figures 7 and 8 respectively. The camshaft is driven by the hydraulic drive motor through the worm drive reduction gear unit with a reduction ratio of 40:1. The comparison between the simulated and the designed nominal speeds and positions at simulation time of 25 second is shown in Table 2. The similar comparison can be made at any other simulation time to observe the closeness between the designed and the simulation result.

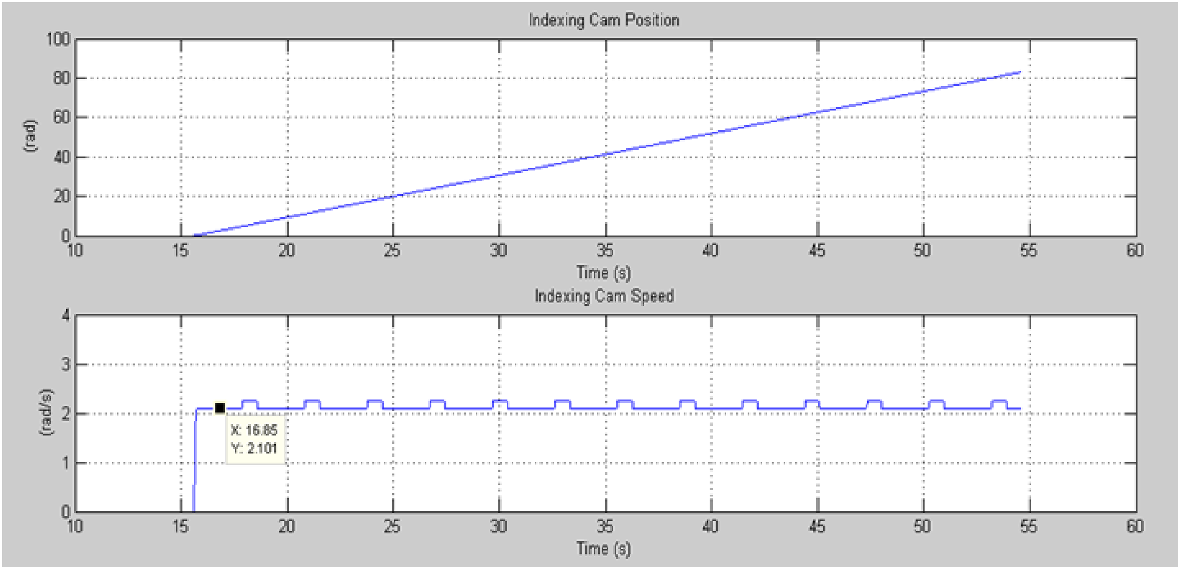

Figure 7 Simulated indexing camshaft angular position and speed.

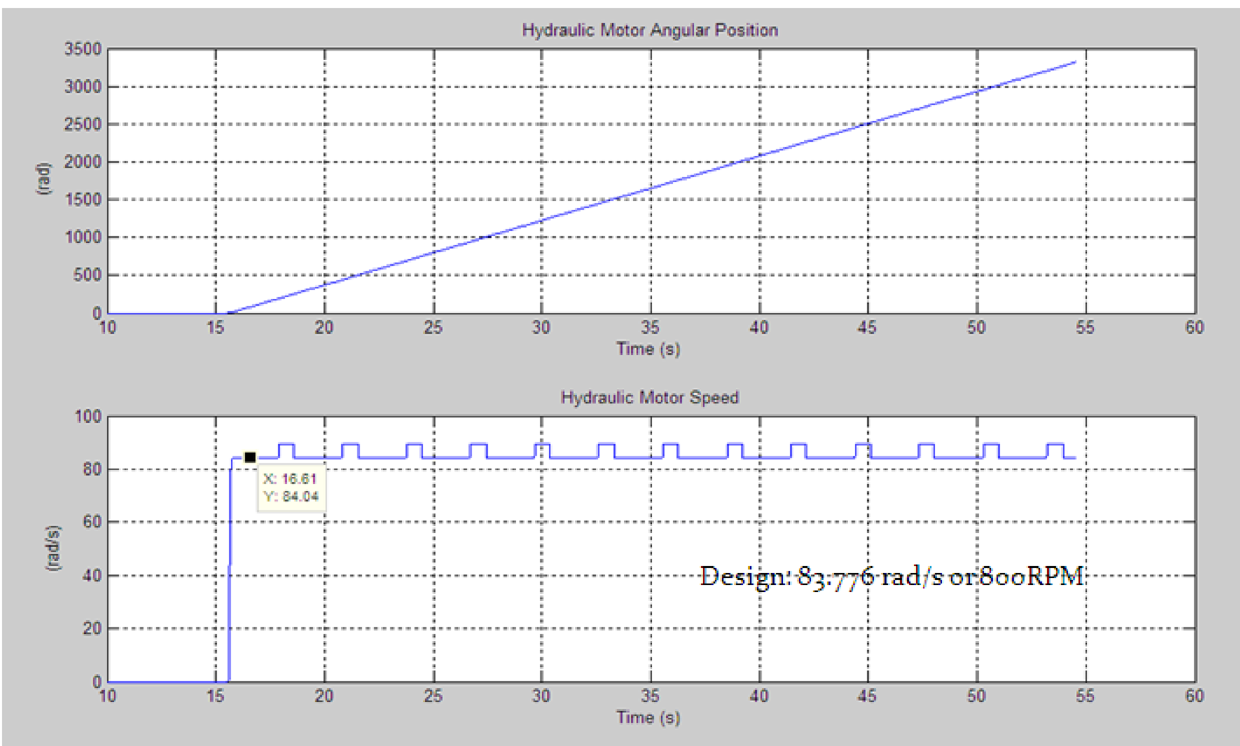

Figure 8 Simulated hydraulic motor shaft angular position and speed.

Parameters at Simulation Time of 25 sec.	Indexing Cam		Hydraulic Motor	
	Shaft Position (Radius)	Shaft Speed (Rad/sec.)	Shaft Position (Radius)	Shaft Speed (Rad/sec.)
Simulated Values	20.09	2.10	803.50	84.04
Designed Nominal	19.90(Note 1)	2.09	795.91(Note 1)	83.78

Table 2 Comparison between the simulated and the designed nominal positions of the indexing cam and hydraulic motor

Note 1: the nominal angular positions in the table are derived from the designed nominal speeds at simulation time of 25 seconds (or approximately 9.5 seconds after the directional valve is energized).

The comparison in the tables shows that the developed plant model is able to simulate the magazine drive system reliably and accurately under normal operating conditions. The simulation accuracy of all results is very satisfactory over the entire simulation period. The produced model outputs (magazine position and indexing camshaft position) can be reliably used as feedbacks to the computer control, and as inputs to create animated 3D VR animation for real time visualization of the FH magazine rotation from one station to next during its operation.

7. Summary and conclusions

This paper reviewed the need for a FH simulator in training FH operators and maintenance personnel, in FH design enhancement based on OPEX and the potential of using VR based simulation technology to develop a prototype FH simulator. The top level module of the CANDU prototype FH Simulator and the modeling methodology in the development of FH physical system models (plant models) were introduced. Modeling and simulation of the FM magazine drive plant (one of FH sub-systems) was described to demonstrate the process of creating a plant model for a typical FH sub-system using the physical network approach and MATLAB/Simulink software tools. The model performance was validated by the comparison of the simulated results with the designed performance.

The work presented in this paper has established the feasibility of modeling and simulating a physical FH drive system using the physical network approach and computer software tools. The established concept and approach can be applied similarly to create the other FH subsystem plant models (Bridge and Carriage, B-ram, C-ram, Snout clamp, etc). The developed FH plant module, once completed, is expected to be integrated with Control and Interlock modules as shown in Figure 2 to create a master FH control model. With the model validated, the plant model outputs can be reliably used to create a virtual FH system (environment) using 3D VR technology.

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