High Fidelity Anti-Lock Brake System Simulation Using Abaqus and Dymola

Summary

Accurate simulation of an anti-lock brake system (ABS) requires detailed modeling of separate subsystems in different physical domains. Creating refined models of the brake, wheel, and control components with a single analysis tool is difficult, if not impossible. The strategy of co-simulation can be adopted to meet this challenge; different simulation tools can be used simultaneously to create multi-disciplinary and multi-domain coupling.

In this Technology Brief, a co-simulation approach using Abaqus and Dymola is used to achieve a realistic system-level simulation of an ABS. The tire, wheel, brake caliper mechanism, and road are simulated with a detailed Abaqus finite element model while the brake system control algorithm and hydraulics and are simulated with Dymola.

Background

An anti-lock brake system can be viewed as an assembly of mechanical and logical subsystems. The mechanical system consists of the tire, wheel, disc, and brake caliper hardware, while the logical system consists of the hydraulics and control electronics.

Abaqus, with its strong nonlinear continuum capabilities and versatile modeling features, has proven to be a valuable tool for tire simulations. Dymola, with its ability to efficiently model logical abstractions, is an ideal candidate for the simulation of the hydraulic and control systems.

Neither tool in isolation is an ideal choice for conducting a high-fidelity system-level simulation of the entire ABS. To this end, a co-simulation approach is demonstrated in which Abaqus and Dymola are coupled at run-time to simulate the dynamics of the system in a way that cannot be achieved with either software acting alone. The structural response of the wheel system and the logical response of the control system are exchanged between Abaqus and Dymola in a synchronized manner. The braking loads thus applied to the wheel are controlled by the ABS electronics logic based on input from the mechanical system.

Analysis approach

For this study, a single wheel with no suspension components is considered. To enable co-simulation, the Abaqus and Dymola models must have a communication interface. This is achieved by defining sensors and actuators in the Abaqus model that deliver and receive signals to
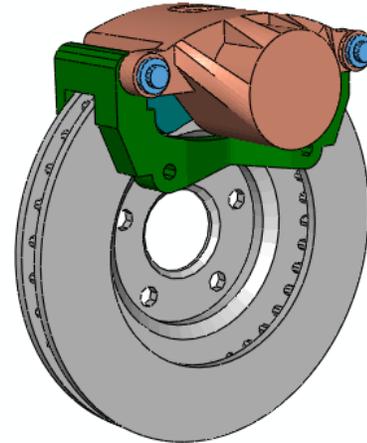
Key Features and Benefits

- Abaqus and Dymola co-simulation allows for the coupled, time domain simulation of compliant structures embedded in complex, logically controlled systems

- Accurate, detailed static and dynamic non-linear tire modeling in Abaqus

and from the Dymola logical model. The braking analysis consists of slowing the wheel assembly from an initial velocity of 10 m/s with a ramped brake pedal force.

The mechanical state of the brake system is used as the controlling signal; it is used by Dymola to actuate the caliper in the Abaqus model such that braking forces are applied and modulated so that the wheel will not lock, or fully slip on the road. This workflow is discussed in detail in the following sections.

Brake control system model in Dymola

The block diagram of the Dymola logical model is shown in Figure 1. The braking system consists of a single brake caliper cylinder connected to a master cylinder via a three port valve. The three port valve has three modes of operation: a pressure increase mode in which the master cylinder is connected to the slave, a hold mode in which all ports are disconnected, and a pressure decrease mode in which the slave cylinder is connected to a tank. This system represents the simplest form of ABS implementation in which brake fluid is not returned to the master cylinder until the braking event has taken place.
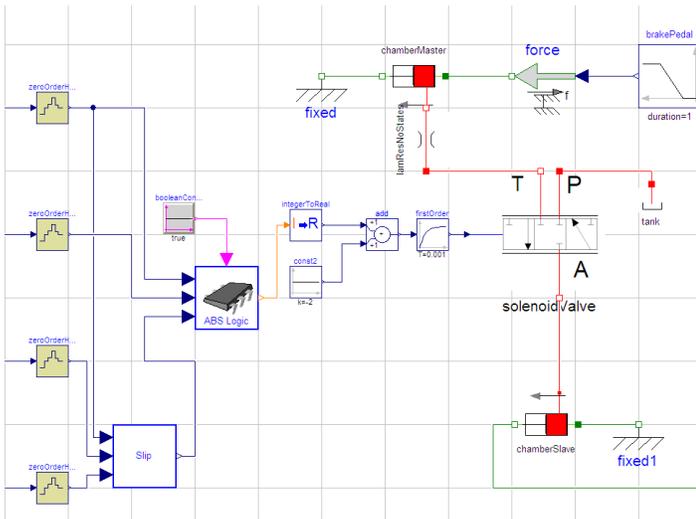
Figure 1: Block diagram of the brake system logic and hydraulics

The control mechanism is simulated by making the operating state of the three port valve depend on wheel acceleration and slip. In the control algorithm [1], the required inputs are wheel angular velocity ω, angular acceleration $\dot{\omega}$, rolling radius r and hub longitudinal velocity v_x. The input signals to the controller are sampled with a period of T_s = 1 ms. The longitudinal slip is calculated as

$$\lambda = \frac{v_x - r\omega}{v_x}$$

The ABS is triggered when the wheel deceleration falls below the prescribed threshold -*a*. At that moment, pressure is held constant until the slip exceeds a threshold λ_T, at which point pressure is dropped to a certain value.

Pressure is then held again until a positive acceleration *A* is reached. Now the pressure is increased until the acceleration drops to *a*. At this stage pressure is increased slowly via alternate hold and increase commands. This process allows the peak portion of the friction characteristic curve to be traversed slowly before the unstable side of the curve is reached. The cycle begins again once the −*a* acceleration threshold is crossed.

Aside from this regular control cycle, the controller is deactivated when the longitudinal velocity is under a certain level. In addition, a timeout parameter is used to reset the ABS control algorithm if it remains in one state for an extended period of time. This is necessary to prevent the controller to be locked when brake action is no longer required.

This is a rule-based algorithm, which is popular in production systems. An alternative is to use a model-based algorithm, an example of which can be found in [2].

Tire, road and brake model in Abaqus

The Abaqus model, shown in Figure 2, includes the tire, wheel, brake caliper and rotor subassembly, and the road. The tire is first pressurized and placed in contact with the road under the vehicle weight acting on the wheel. A steady state transport analysis is then performed in Abaqus/Standard to compute the state of stress and deformation in the tire corresponding to a given forward velocity with no braking. Optionally, a cornering radius can be specified as well.

The tire in its free-rolling condition is then imported into Abaqus/Explicit for the braking co-simulation with Dymola. As Abaqus/Explicit computes the state of stress and deformation in the rolling tire, the wheel angular velocity and acceleration are communicated at frequent intervals to Dymola via the Abaqus sensors. The required braking pressure is computed by Dymola and communicated back to Abaqus/Explicit to be applied to the brake caliper cylinder. The brake pads are pressed against the brake rotor to produce a braking torque that decelerates the wheel assembly.

Co-simulation scheme

The following non-iterative co-simulation scheme is used:

- At each time increment of the Abaqus simulation, sensor information is computed and communicated to Dymola via a socket-based interface.

- Dymola reads the Abaqus sensor information as inputs to the control logic and integrates in time with an increment size equal to that used by Abaqus/Explicit. The actuating signal computed in Dymola is communicated back to Abaqus, which applies this newly computed load in the next increment.

- The process is repeated until the simulation time is completed.

Co-simulation results

Figure 3 shows the hub longitudinal and circumferential velocities during the co-simulation. A difference between the two quantities represents a slipping condition. The slip
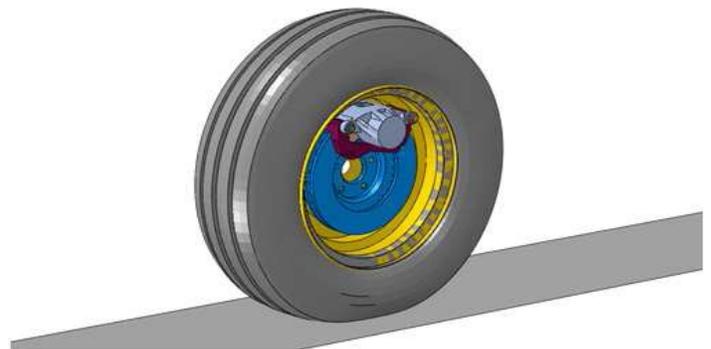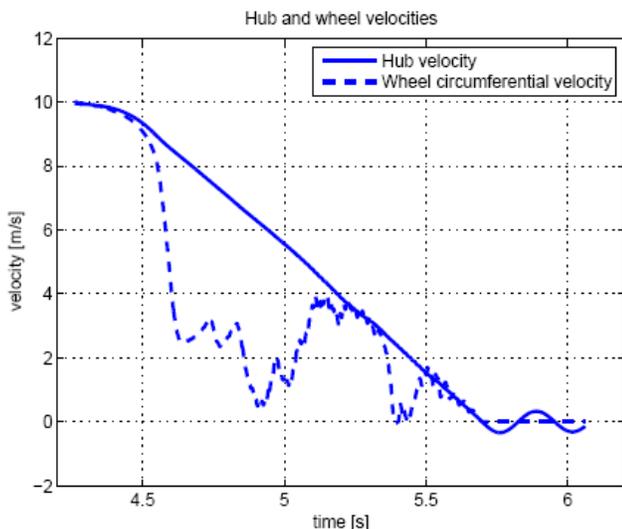

Figure 2: Abaqus tire, road and brake model

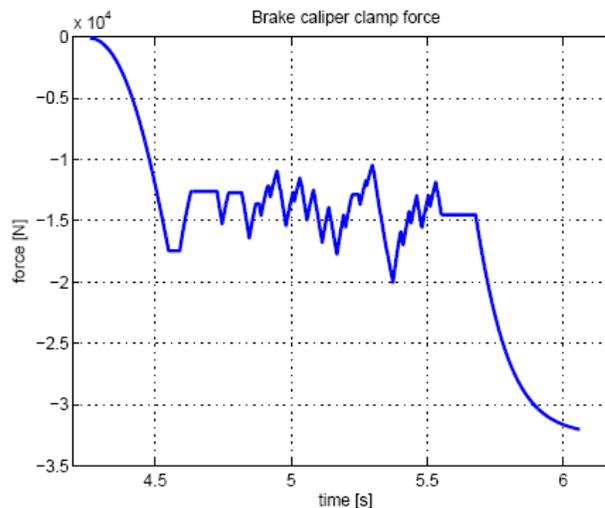Figure 3: Hub longitudinal and wheel circumferential velocities during co-simulation

Figure 4: Brake caliper clamping force during co-simulation

is initially large, but the controller is able to prevent wheel lock. Figure 4 shows the brake caliper clamping force during the co-simulation. The rapid force build-up and release phases are clearly visible.

Conclusion

In this Technology Brief, a co-simulation scheme for analyzing an anti-lock braking control system is developed. A high-fidelity tire model in Abaqus is combined with a hydraulic braking control system model in Dymola, highlighting how different simulation packages can be integrated to perform realistic system-level simulations. The existing advanced tire modeling capabilities in Abaqus can thus be applied to a larger class of real-world operating conditions. The co-simulation approach can be extended to full vehicle models under varying road conditions, hydroplaning analyses, and optimization.

References

1. Horst Bauer, editor, "Bosch Automotive Handbook", Robert Bosch GmbH, 4th edition, October 1996.
2. Stefan Solyom, Anders Rantzer, and Jens Lüdemann, "Synthesis of a model-based tire slip controller", Vehicle System Dynamics, 1(6):477–511, June 2004.

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, please see the following Abaqus Version 6.12 documentation references:

- "Amplitude curves," Section 33.1.2 of the Analysis User's Manual
- "VUAMP," Section 1.2.7 of the User Subroutines Reference Manual
- User's and Installation Guides for Logical-Physical modeling using Abaqus and Dymola, SIMULIA Answer 3617
- Abaqus/CAE Plug-in for Logical-Physical modeling with Dymola, SIMULIA Answer 3618

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