Verification of the Haldex LSC System Performance

Edo F Drenth
Control Software
Haldex Traction AB
Instrumentgatan 15
SE 261 24 Landskrona
Sweden
e-mail: edo.drenth@htse.haldex.com

Introduction
Haldex Traction AB develops and produces new active controlled AWD systems. The Haldex *L*imited *S*lip *C*oupling system is used in the Volkswagen A4 platform (Golf, Bora, Octavia, …).
It all started of in 1992 when Haldex acquired a patent from former rally driver Sigge Johansson. The same year contacts with VW were initiated. Before electronics were introduced in 1994 the system was purely self-regulating hydraulic-mechanical. With the introduction of electronics and communication with other ECU's, like engine management and ABS, the application possibilities increased tremendously. A letter of intent was acquired in 1996 and serial development started. Two years later in 1998 Haldex Traction had its start of production.

System Function Description
The Haldex LSC pumps a hydraulic fluid as a function of difference rpm between the front and rear axle differential. Independent of the sign of the difference rpm the flow has the same direction, which is important for the systems control authority. With help of a throttle valve a pressure can be built up. The hydraulic pressure in its turn clamps a clutch package. This clamped clutch package will thus be able to transfer torque over the Haldex LSC unit.
The Haldex LSC is provided with an ECU that with help of signals from the CAN bus controls the throttle valve in order to get the desired torque transfer.

Control Possibilities
With an extended well-known bicycle model it can be proven that torque distribution has an influence on the vehicle handling characteristics. The yaw-rate gain becomes a function of both the forward velocity and torque distribution. The torque distribution influenced changes in handling characteristics are rather complex and non-linear models have to be used to analyze the theoretical results more in detail. Active controlled AWD creates the possibility to increase the fun to drive factor without jeopardizing dynamic vehicle safety.
Special attention has to be paid to tire models. Because the Haldex LSC is a so-called on-demand system, the tire's effective rolling radius is a very important measure, which can not be neglected.

System Performance Verification
To ensure the Haldex LSC system's performance a tremendous amount of physical tests on test benches and in car are performed. In order to save cost, decrease development time and increase knowledge of the Haldex LSC as a system, virtual tests are performed.

Virtual tests are performed with ADAMS[1] and MATRIXx[2]. The Haldex LSC hardware together with a vehicle is modeled in ADAMS, whereas the control algorithms are modeled in MATRIXx. Even so Haldex' production code can be linked into MATRIXx and by means of ADAMS/Controls communicate with the Haldex LSC model in ADAMS.

Co-Simulation

The bottleneck in the co-simulation execution speed is the information exchange frequency. In order not to increase simulation times, less interesting controllers can be modeled in ADAMS (continuos controller). For example we are interested in the steer angle because this measure is important for determining the desired yaw-rate. Since displacement feedback gives rise to numerical problems, steering wheel torque has to be used as the feedback signal to the vehicle model. A controller has to be created which has negligible dynamics e.g. relative large feedback gain and bandwidth. Since a discrete time domain controller is limited in feedback gain and bandwidth for reason of stability, a continuos time domain controller in ADAMS is preferred.

For similar reasons, modeling of the Haldex LSC and/or its components in MATRIXx (in conjunction with ADAMS co-simulation) is not recommended even if we are interested in the first order dynamics only. Gain and time constant vary greatly within the area of operation.

Co-Simulation Benefits

Of course virtual testing always gives the opportunity to save cost and reduce development time. Co-Simulation in particular has some additional benefits.

Software development related benefits:

- Haldex LSC control algorithms can be designed in a specialized control software simulation package like MATRIXx, where those algorithms can be tested against a virtual vehicle on the engineers' desk.
- Haldex' production code, which is C, can be linked into MATRIXx, which in its turn is connected to a virtual vehicle by means of ADAMS/Controls. This way co-simulation enables the software engineer not only to debug on syntax, but also on functional level.
- Regression tests and tests with customer specific software are possible since MATRIXx' User Code Blocks can be linked against the Haldex' software configuration management (ClearCase[3]). This way the engineers can be guaranteed to work with the latest software.

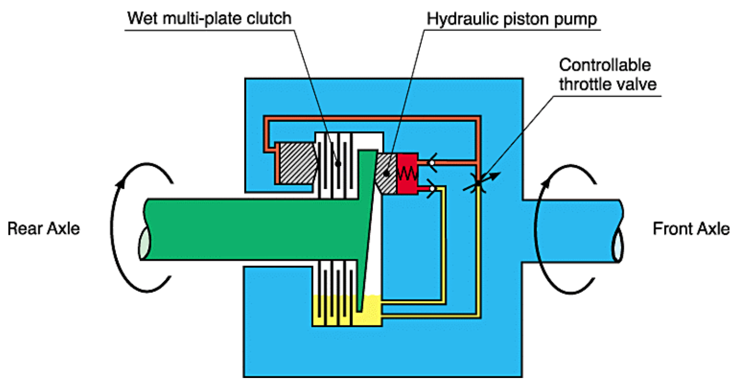
Hardware related benefits:

- More realistic load cases than bench testing. E.g. pressure rate is influencing the difference rpm, which is fixed in bench tests.
- Co-simulation enables us to explore the interaction between longitudinal dynamics (traction) and lateral dynamics (handling)
- Well conditioned standard drive cases, which may be non-physical, can be tested for increased understanding. Example: Constant vehicle velocity with different levels of engine torque

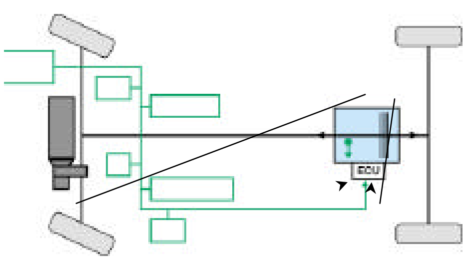
---

[1] ADAMS is a registered trademark of Mechanical Dynamics, Inc.
[2] MATRIXx is a registered trademark of Integrated Systems, Inc.
[3] ClearCase is a registered trademark of Rational Software Corporation

Haldex Limited Slip Coupling
System Function



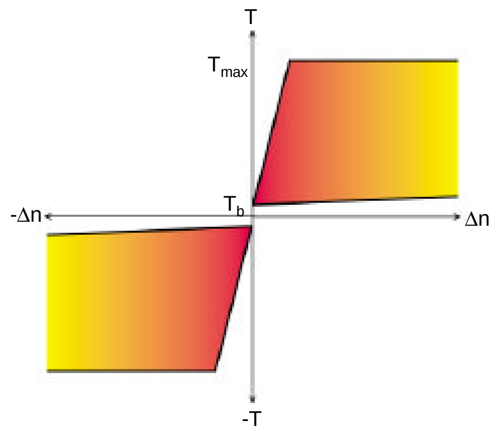
Haldex Limited Slip Coupling
Software Program Structure



Application Software
- Traction and Vehicle Dynamics
- ABS / TCS / ESP Interaction
- Emergency Operation Strategies
- In-signal Failure Detection

Base Software
- Valve and Pump Control
- Temperature Compensation
- CAN Communication
- Diagnostic System (K-Line)
- Internal Failure Detection
- Memory Management

Haldex Limited Slip Coupling
Torque Transfer Characteristics



Theoretical Analysis
Bicycle Model

Steady-State Yaw-Rate Gain

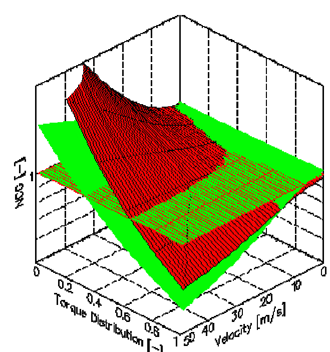
$$\frac{r}{d} = \frac{(C_1 + F_{x_1})C_2 l u}{C_1 C_2 l^2 - m u^2 C s}$$

Understeer Gradient

$$h = -\frac{Cmg}{C_1 C_2}\frac{s}{l}$$

Rewrite Yaw-Rate Gain

$$\frac{r}{d} = \frac{\frac{C_1 + F_{x_1}}{C_1 l} u}{1 + h\frac{u^2}{gl}}$$



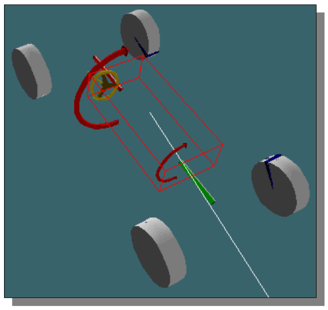
Normalized Yaw-Rate Gain

Assume $C_i(F_{x_i}, F_{z_i})$

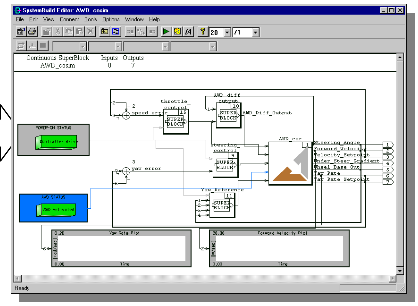
acceleration
deceleration

Haldex Limited Slip Coupling

Dynamic Simulation Modeling



Co-simulation



ADAMS model:

- Independent suspension
- Engine Torque Map
- Tire models
- Steering system
- Haldex LSC hardware

MATRIXx model:

- Speed control
- Yaw rate control
- Drive case
- Haldex LSC software

Haldex Limited Slip Coupling

Co-Simulation

Why Co-Simulation?

- A vehicle and its components like tires with combined slip, steering system and Haldex LSC are relative easy modeled in a MBS software like ADAMS
- Control algorithms are easier modeled, modified and verified in a special code like MATRIXx
- Haldex' production source code (C) can easily be linked into MATRIXx

Performance & Safety in Vehicles

Important modeling issue

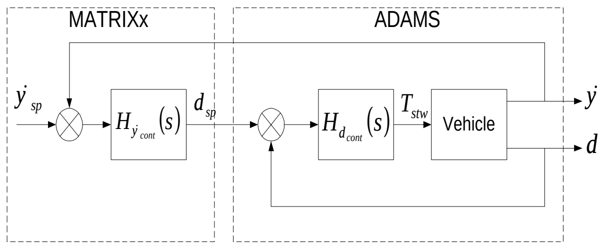
- Determine (closed loop) system eigen frequencies (ADAMS/Linear)
- Make sure the by MATRIXx controlled (sub)systems have a significant lower eigen frequency than the co-simulation information exchange frequency
- For the sake of simulation execution speed some controllers may be created in ADAMS (ADAMS/Controls, continuos controllers)

Example: Yaw-Rate Control

$$\frac{r(p)}{d(p)} = \frac{(maup + C_2 l + ma\dot{u})(C_1 + F_{x_1})u}{m^2k^2u^2p^2 + mu\{C(q^2 + k^2) + mk^2\dot{u}\}p + C_1C_2l^2 - mu^2Cs}$$

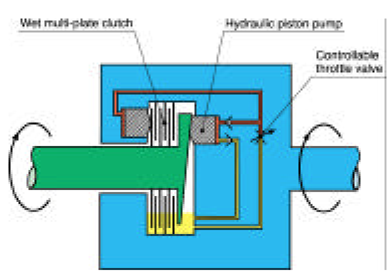
- Vehicle’s yaw-rate determined by vehicle’s forward velocity and steer angle
- At given velocity ($\dot{u} = 0$) yaw-rate is controlled by steer angle
- Feedback of displacements (steer angle) is numerical unstable (forces/torque’s can become infinite)
- Solution: Cascade control

Example: Yaw-Rate Control



Haldex LSC Model Description

- The Haldex LSC is a complex hydraulic-mechanical unit
- For system performance verification higher order dynamical aspects will be neglected
- The main aspects of the Haldex LSC can be described by a hydraulic pump with flow dependent on the difference in rotational speed and a throttle valve that controls the actual internal pressure
- The torque transfer over the Haldex LSC is linear function of the pressure



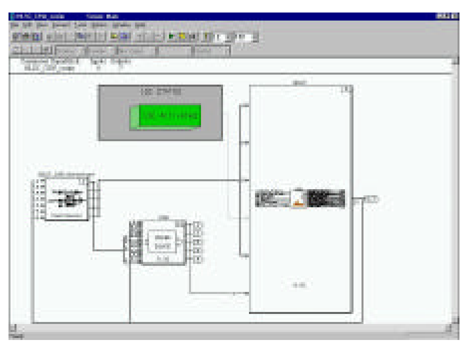
Haldex LSC Non-Linear Differential Equation:

$$\dot{p} = c\left(kw_{\Delta} - \frac{\Delta p}{d}\right)$$

c	hydraulic- and mechanical compliance
Δp	pressure difference over throttle valve
k	deplacement
ω_{Δ}	rotational velocity difference
δ	control signal (throttle valve)

Co-Simulation Benefits (I)

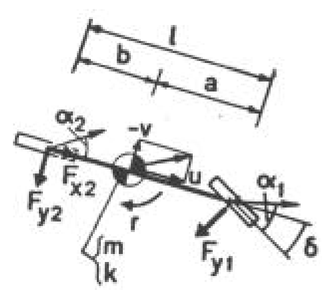
- Co-Simulation enables both syntax and **functional** debugging of Haldex LSC's software
- Co-Simulation enables us to test the Haldex LSC at a **system** level, rather than component level
- More **realistic load disturbances** compared to bench testing
- Less physical prototypes (expensive) of electronic hardware needed



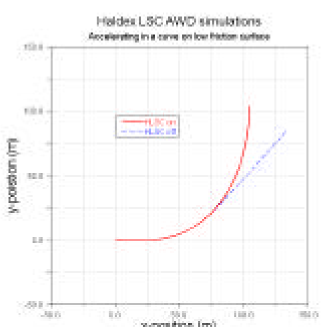
Haldex Limited Slip Coupling
Co-Simulation

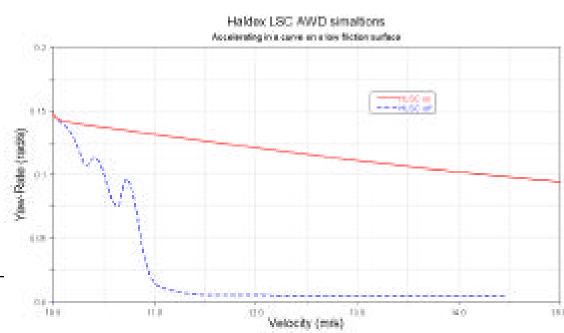
Co-Simulation Benefits (II)

- Explore the interaction between longitudinal dynamics (traction) and lateral dynamics (handling)
- Well conditioned standard drive cases, which may be non-physical, can be tested for increased understanding
  Example: Constant vehicle velocity with different levels of engine torque



Haldex Limited Slip Coupling
Simulation Results





- Enhanced vehicle handling and stability
- Enhanced vehicle traction
- Enhanced vehicle safety

Future for Co-Simulation

- So far Co-Simulation is mainly used for verification of existing product. For the next generation Haldex LSC these Co-Simulation tools will be used in the design phase (on-going).

- The hydraulic unit may be modeled more in detail (ADAMS/Hydraulics?) to understand more of the dynamics at Haldex LSC component level.

- Auto-code generation with MATRIXx will be investigated.