Detailed Powertrain Dynamics Modelling in Dymola - Modelica

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Abstract: Two Modelica libraries for engine and powertrain modeling are presented called the Powertrain Dynamics library and the Engines library. Together, these libraries enable the modeling and simulation of powertrain systems including their fluid dynamic, pollutant emission, mechanical and thermal performance in one simulation environment (Dymola). The libraries are defined using the object orientated modelling language Modelica.

The libraries are used to study the response of the vehicle and powertrain during dynamic driving events such as vehicle launch, tip-in and tip-out driveability and powertrain nvh. The benefits of using a dynamic torque converter model compared to a steady state model for these applications are presented.

Keywords: powertrain dynamics, driveability, dynamic torque converter, wet clutch, automatic transmission, downsizing, turbocharging

1. INTRODUCTION

The transmission and driveline of a vehicle have a large influence on the customer driving experience and perception of quality, as well as the efficiency and performance of the vehicle. The influence of hybridization within a vehicle has greatly increased the architecture variants available to vehicle manufacturers and consequently has complicated the selection of the most efficient hardware solution.

The Powertrain Dynamics library has been developed as a commercial Modelica library to aid the evaluation of the many technology and topology options. It also provides the capability to model powertrain systems in detail to support the design and validation of the associated control systems and to optimize the vehicle's response to driver inputs.

The initial application of the library has been the modelling of transmissions and drivelines within automotive applications but it can be applied to any powertrain system. This paper explores some of the features of the library that are used in the simulation of vehicle transients such as initial launch, tip-in and tip-out and gear shifting.

The Engines library is a commercial Modelica library for the modelling and simulation of internal combustion engines. It provides models for mean value (cycle averaged) engine simulation and crank angle resolved simulation. This range of fidelity allows the engine models to be tailored to capture the appropriate effects for the analysis.

For tip-in and tip-out studies a mean value engine model that captures the air-flow and torque transients is appropriate but for detailed NVH investigations a crank angle resolved model is required. A common application of the library is to consider engine downsizing often in combination with the addition of electric drives to study the vehicle level effects.

2. POWERTRAIN DYNAMICS LIBRARY

2.1 Overview

Transmission and driveline systems comprise a number of key components that influence their dynamic behaviour and efficiency. The Powertrain Dynamics library has been developed to provide models for all of these components and assemblies as easy to use models. The design objective is to make it easy to assemble a MultiBody powertrain model and achieve good simulation performance and results without having to develop a detailed knowledge of the Modelica modelling language.

The range of components included the Powertrain Dynamics library and the fundamental approach used to model the mechanics are described by Dempsey and Picarelli (2009). Some major enhancements are described by Dempsey and Roberts (2012).

2.2 Dynamic Torque Converter

In automatic transmissions the engine and gearbox are coupled by a torque converter. This is typically modelled using the steady state performance curves for the torque converter that relate speed ratio, torque ratio and capacity factor (k-factor, MPC2000, or c-factor), see Figure 1 for an example. These are readily available from the torque converter manufacturers and make it easy to implement a steady state torque converter model. Most simulation tools only offer this type of steady state model that works well for drive cycle studies but is inadequate for the simulation of

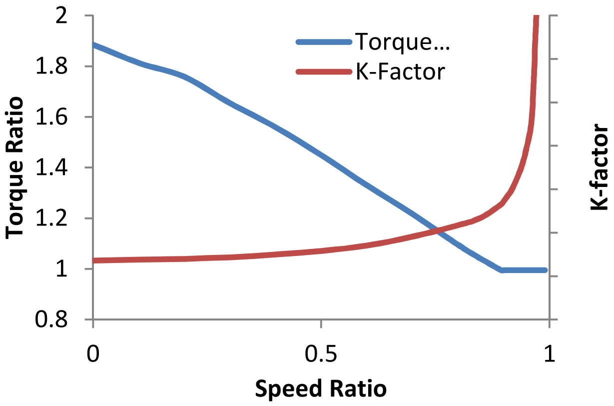

Figure 1: Steady state torque converter curves

transient events such as launch, tip-in, tip-out, gear shifting or powertrain NVH.

The problem is that models based on these curves cannot capture the transient behaviour of the torque converter which has a significant impact on the driving experience. During large transient events such as initial launch, gear shifting and driver tip-in and tip-out the transient response of the torque converter has an impact on the vehicle response and the perception of performance experienced by the driver.

A dynamic torque converter model has been developed to overcome this problem and enable the fluid inertia and stator dynamic behaviour to be included in simulations. The model is based on the nonlinear lumped parameter model derived in Hrovat and Tobler (1985) that describes the converter dynamics. The model has been implemented to fit within a common model architecture shared with the steady state torque converter model making it easy to switch between steady state and a dynamic modelling approach.

The basic layout of a 3 element torque converter is shown in Figure 2 with the key parts identified. The impeller is connected to the engine, the turbine is connected to the gearbox and the stator is connected to the gearbox housing via a one-way clutch. Energy is transferred between these 3 components by the hydraulic fluid within these control volumes (impeller, stator and turbine).

The moment-of-momentum equation is applied to each of these control volumes and relates the rotational velocity of the mechanical components and the torque to a fluid flow velocity along the torque converter rotational axis. This

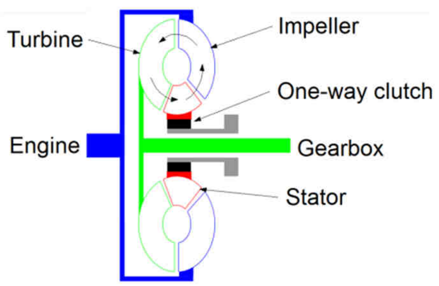

Figure 2: Torque converter mechanical schematic with fluid flow arrows in the driven condition

results in a single first order state equation for each element and for the impeller this gives the following equation:

$$I_i\dot{\omega}_i + \rho S_i \dot{Q} =$$

$$-\rho\left(\omega_i R_i^2 + R_i \tfrac{Q}{A}\tan\alpha_i - \omega_s R_s^2 - R_s \tfrac{Q}{A}\tan\alpha_s\right)Q + \tau_i \qquad (1)$$

This equation relates the speed of the impeller (ω_i), torque on the impeller (τ_i), its radii at the centre of its outlet port (R_i), the angle of the blade surface to the normal (α_i) and the fluid volume flow rate (Q) is related to the conditions at its input from the stator. The state equations for the turbine and stator are of a similar form.

The fluid state equation links the relationship between the fluid volume flow rate (Q) and the mechanical inertia velocities ($\omega_{i,t,s}$) using a conservation of momentum energy balance given by:

$$\rho(S_i\dot{\omega}_i + S_t\dot{\omega}_t + S_s\dot{\omega}_s) + \frac{\rho L_f}{A}\dot{Q} =$$

$$\rho\left(R_i^2\omega_i^2 + R_t^2\omega_t^2 + R_s^2\omega_s^2 - R_s^2\omega_i\omega_s - R_i^2\omega_t\omega_i - R_t^2\omega_s\omega_t\right)$$

$$+\omega_i\frac{Q}{A}\rho(R_i\tan\alpha_i - R_s\tan\alpha_s) + \omega_t\frac{Q}{A}\rho(R_t\tan\alpha_t - R_i\tan\alpha_i)$$

$$+\omega_s\tfrac{Q}{A}\rho(R_s\tan\alpha_s - R_t\tan\alpha_t) - p_L \qquad (2)$$

Where the p_L term represents the losses in the familiar form of shock losses from non-ideal flow conditions and fluid friction losses. These are defined as shock velocity coefficients ($Csh_{(i,t,s)}$) and a fluid friction factor (f).

$$p_L = \tfrac{\rho}{2}sgn(Q)\left(C_{sh,i}V_{sh,i}^2 + C_{sh,t}V_{sh,t}^2 + C_{sh,s}V_{sh,s}^2\right) +$$
$$\tfrac{\rho f}{2}sgn(Q)\left(V_i^{*2} + V_t^{*2} + V_s^{*2}\right) \qquad (3)$$

These equations fully characterize the dynamic behaviour up to sufficiently large frequencies (~50Hz) to model fast transient phenomena occurring during throttle steps and rapid speed ratio changes.

Due to the 'free body' formulation approach taken, the model relies upon knowing some key internal geometry parameters of the torque converter; most notably the radii and blade angles that are not normally released by torque converter manufacturers. These parameters have to be calibrated before the dynamic model can be used and this is done in two stages using the Optimization toolbox available for Dymola.

The first stage of the optimization process is to tune the model parameters so that the dynamic torque converter model accurately predicts the steady state performance. This is achieved using steady state simulation and comparing the quoted steady state performance curves with the results. To calibrate the transient response of the torque converter, additional experimental data captured under transient driving conditions is used. This approach does allow the user to tune these design parameters to obtain good agreement with experimental data.

3. VEHICLE SYSTEMS

The components described have been used to model two different powertrain configurations. Built using the templates provided in the library, they maintain the same high level vehicle architecture but they represent different physical systems. The template approach is based on the VehicleInterfaces library (Dempsey *et al*, 2006). Within the Powertrain Dynamics library this architecture has been extended to provide templates for common transmission and driveline arrangements.

This example represents a car with a mass of 1500kg using a chassis model with pitch, bounce and roll degrees of freedom as well as the longitudinal motion. The two powertrain configurations used in this study are: a four-wheel drive vehicle with a V6 engine; and a rear engined vehicle with an inline 4 cylinder engine. The engine and transmission assemblies are mounted in the vehicle body using an elastomeric mount model.

3.1 The Transmission

The transmission models are built using templates as shown in Figure 3. These split the gearbox into 3 main sub-systems, the engagement device, the gearset and the gear selection mechanism. An engagement device in the form of a clutch assembly or torque converter sits between the engine and the gearset. The gearset includes the gears, shafts, bearings and synchronisers or clutches used to engage different gears. The gear selection mechanism defines the actuation system that translates the driver movement of the hand lever or control system gear demand into actuation of a clutch or synchroniser.

The automatic transmission is a 6 speed gearbox consisting of a front Epicyclic and a rear Ravigneaux gearset with 2 brakes and 3 clutches to control the overall gear ratio (shown in Figure 3). The gearset is coupled to the engine via a torque converter. The speed and torque dependent losses are lumped for convenience and based on the current gear signal. Where the data is available, the losses can be distributed to the individual bearings and gear mesh models

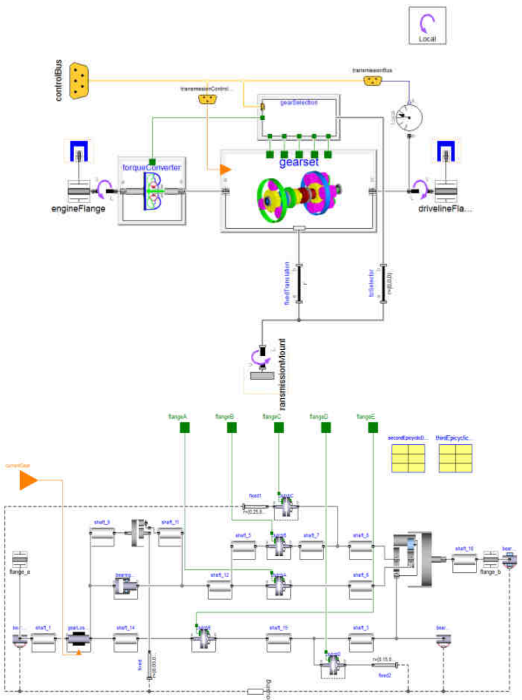

Figure 3: Model Diagram of automatic transmission (top) and gearset (bottom)

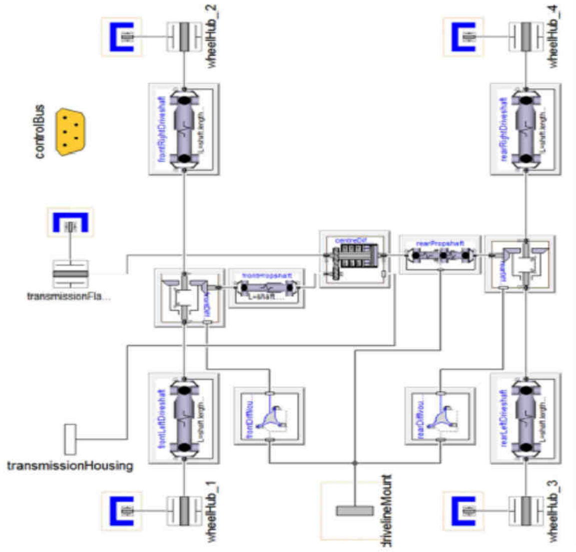

Figure 4: Template for four wheel drive

3.2 The Driveline

Figure 4 illustrates one of the driveline templates that are available. In this case it is a four wheel drive system that includes a central differential which is mounted to the transmission case. The front and rear differentials are independently, elastically mounted within the vehicle body. All of the components are replaceable so that the user can select the appropriate model for their application.

4. ENGINE MODEL

The engine models were developed using the Engines Library (Dempsey and Picarelli, 2009). This library comes in two versions with different capabilities: Mean Value Engine Models (MVEM) which means cycle averaged torque and emissions; and Crank Angle Resolved Engine Models (CAREM) which means crank angle resolution of air-flow, torque and heat release. Both versions model the intake and exhaust manifold fluid dynamics and heat transfer with varying levels of detail. The heat transfer models can range from models with no thermal resistance to ones which take into account the flow regime within the particular component (Depcik and Assanis, 2002).

The fluid flow models range from simple volume models to pipe models which include the fluid momentum dynamics enabling the fluid pressure pulsations and their effects on engine breathing and related performance to be studied. In MVEMs, the mass flow through the engine is calculated by means of an equation which relates the mass flow to engine speed, plenum pressure (load) and air temperature. Provided the engine technological content and calibration remains similar, the user can easily scale up or down the displacement of the engine. (Hendricks et al., 1996)

$$\dot{m}_{ap}(n, p_i) = \frac{V_d}{120RT}(s_i p_i + y_i)\frac{n}{1000} \tag{4}$$

Where the mass of fluid within the cylinder m is calculated for a given engine speed n (rpm) and intake manifold pressure p_i (bar) according to the volumetric displacement of each cylinder V_d, the molar gas constant R and the temperature of the working fluid T (K).

CAREMs on the other hand model the pumping through the valves, the heat release (Wiebe or table based Mass Fraction Burnt) for both SI (Spark Ignition) and CI (Compression Ignition) applications. Multiple heat release and injection per cycle can be included in the models.

All the fluid components in the Engines library are based on the Modelica Fluid library (Casella et al., 2006) which ensures compatibility with the latter and all derived libraries. The medium model is based on the Modelica Media library with customisations to achieve the level of performance required from this library. The medium model tracks 7 species throughout the air path of the engine so that fuel mass and the emissions composition can be traced.

The transients of the turbocharger, fluids and heat transfer in the air-path and torque output are captured as well as the multibody behaviour of the mechanical system. This model is shown in Figure 6. The air intake path comprises the air filter, turbocharger compressor including ducting, an air to air intercooler, throttle body, plenum volume and cylinder head port volumes. The exhaust path comprises the cylinder head ports and primary exhaust system coupled to the turbocharger turbine (Dempsey M., Picarelli A, Fish G., 2012).

The compressor is modelled using ellipse theory:

$$1 = \left(\frac{pressureRatio}{a}\right)^z + \left(\frac{m\_flow_{corrected}}{b}\right)^z \tag{5}$$

Whereas the turbine model uses Stodola's law:

$$m\_flow_{corrected} = K\sqrt{1 - \left(\frac{1}{pressureRatio}\right)^2} \tag{6}$$

Where K is the Stodola constant. Map based turbine and compressors are also available within the Engines library. In this case Ellipse based models are preferred for robustness at the boundary conditions. (Stodola, A., 1945)

Emissions after-treatment systems have been omitted from this engine model as they were not required for the purposes of this experiment; however, their associated pressure drops have been taken into account within the exhaust system. Both intake and exhaust volume models include heat transfer effects from the fluid to the pipe walls.

5. RESULTS

5.1 Studying the vehicle response during a tip-in test

The tip-in response of a vehicle effects the driver in many different ways. It impacts the performance feel, perception of

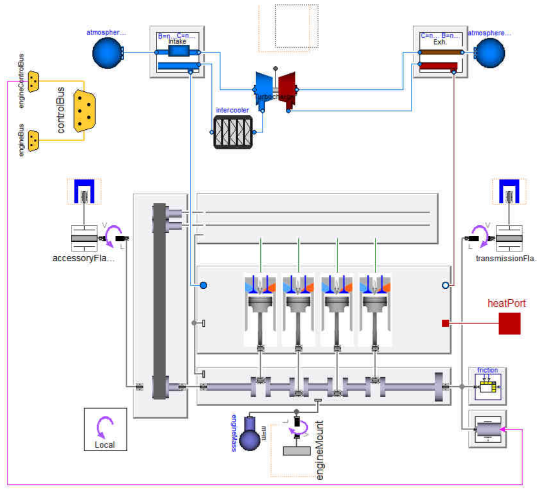

Figure 5: Inline 4 cylinder direct injection gasoline turbocharged mean value engine model diagram

quality and how smooth the vehicle responds. Using the described libraries, the response of a vehicle with two different engines has been compared. The first engine is a large capacity, naturally aspirated V6 engine and the transient vehicle response is compared to a smaller capacity turbocharged engine. Both engines produce similar peak power and torque and the rest of the vehicle model is the same including the automatic transmission, driveline and chassis.

The tip-in experiment starts with the vehicle decelerating with the accelerator pedal released. At the desired engine speed the driver presses the accelerator pedal quickly. The longitudinal acceleration typically exhibits an oscillatory response as the change in torque delivered by the engine causes the powertrain to cross backlash regions, twist the driveshafts and for the whole powertrain to rock on its

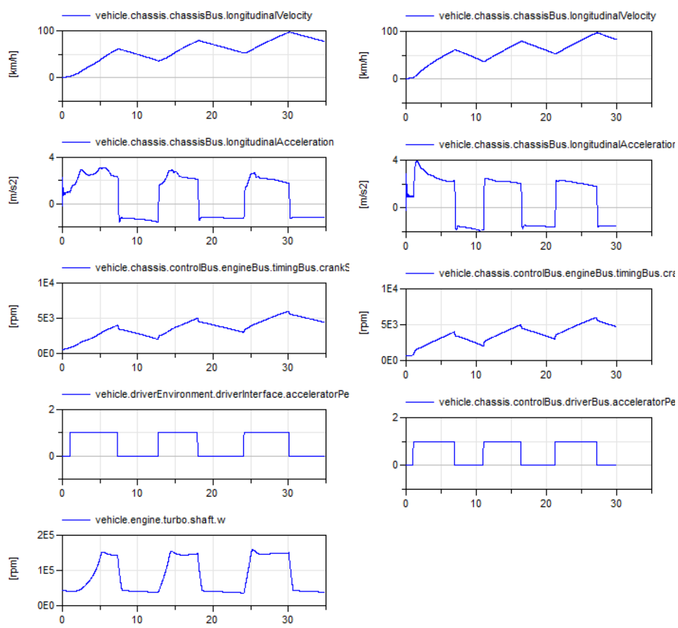

Figure 6: Vehicle simulation results for a 1.8l I4 DI SI Turbo (left) and 2.7l V6 DI SI NA (right). x-axis: time(s)

mounts.

The turbocharger lag on tip-in is visible within the vehicle acceleration plots (Figure 6, left) and reduces as the tip-in point engine speeds rise. This change is due to the turbocharger response. The torque converter lock-up clutch remains open throughout this experiment and the related effects can be shown in the engine speed trace where there is a momentary surge and dip of engine speed at tip-in and tip-out respectively.

5.2 Vehicle launch comparing the steady state and dynamic torque converter models

To illustrate the need for a dynamic torque converter model, the initial vehicle launch is simulated. In this experiment, the vehicle starts at standstill in 1st gear with the driver releasing the brake pedal and then applying the accelerator pedal. The engine is at idle speed and we are interested in the vehicle longitudinal response during the first few seconds of the vehicle launch to analyse what the driver will experience.

The only difference between the two tests is the torque converter model. This analysis focuses on the detailed differences in the vehicle response due to the use of a steady state and dynamic torque converter model. The longitudinal acceleration of this vehicle can be broken down into two phases, see Figure 7. Phase 1 occurs between 5.0 and 7.0s while the brakes are released and phase 2 begins as the driver steps across from the brake pedal to the accelerator pedal.

During phase 1 the acceleration profile is dominated by the release characteristics of the brake system. This is because while the vehicle is held stationary the torque converter is applying torque to the gearbox input. As soon as the friction torque in the brakes reduces below a certain level the vehicle will start to creep forward.

With the dynamic torque converter model we see an increased delay between the driver demand and the vehicle acceleration combined with an increase in the jerk (first derivative of acceleration) once the vehicle starts to accelerate. Both of these metrics are known to influence the drivers perception of driveability (Cacciatori, 2007).

Accurate prediction of these driveability metrics together with other measurements such as fuel usage, emissions and thermal effects enable the launch strategy within the engine control software to be adjusted and calibrated to deliver the desired balance between vehicle performance feel, fuel economy and emissions.

5.3 Torque pulsation propagation through the flywheel and torque converter

The effect of the torque converter to isolate vibration into the transmission is well known. To understand the effects of selecting a steady-state or dynamic model for the torque converter, two crank angle resolved engine models are used to compare the amplitude of the torque oscillations out of the torque converter into the gearset. The engines used in this experiment are a 2.7l V6 naturally aspirated engine and a 1.8l inline 4 cylinder turbocharged engine tuned for a similar mean torque output. This represents a downsizing strategy that would reduce the frequency of the torque pulsations at the flywheel due to the reduced number of cylinders but increase the amplitude of the torque oscillation to recover the same mean output torque.

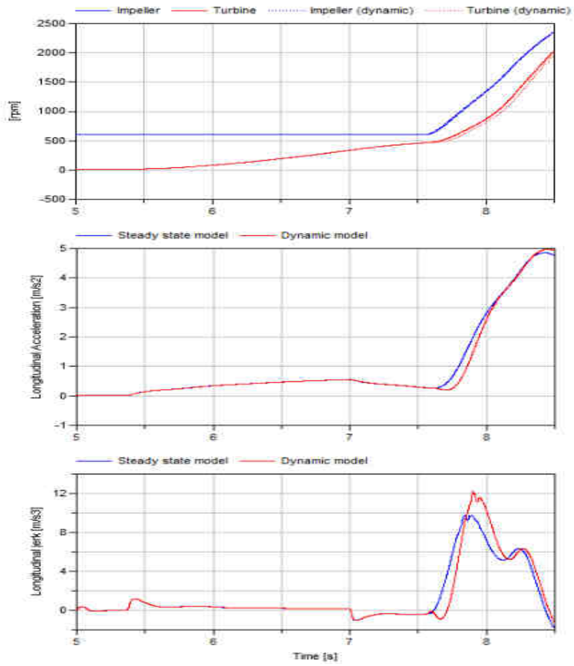

Figure 7: Impeller and turbine speed (top), vehicle acceleration and Jerk (bottom) comparison

The experiment holds the engine at idle (700rpm) and slowly increases vehicle speed up to a torque converter speed ratio of 0.85 in first gear. The amplitude response of the torque pulsations seen at the turbine are compared for the steady state and dynamic models. The amplitude response relates the mean turbine torque and impeller (engine) speed ($\bar{T}, \bar{w}$), with the instantaneous fluctuation (ΔT,w) resolved in crank angle degrees according to:

$$Amplitude = \frac{\Delta T_t}{\bar{T}_t} \Big/ \frac{\Delta w_i}{\bar{w}_i} \quad (7)$$

The amplitude approach reveals the damping properties of the torque converter when operating under fast transient conditions i.e. instantaneous crank speed and torque. Figure 8 shows the amplitude response for both the steady state and dynamic models against the torque converter speed ratio. With the steady state model, both engines generate the same amplitude response but with the dynamic model there are clear differences.

In both cases, the torque amplitude of the dynamic models is significantly reduced compared to the steady state model. The flywheel coefficient of speed fluctuation (C_s) is in the typical automotive engine range (0.1-0.2) in the idle condition and is defined as:

$$C_s = \frac{\omega_{max} - \omega_{min}}{\omega_{avg}} \quad (8)$$

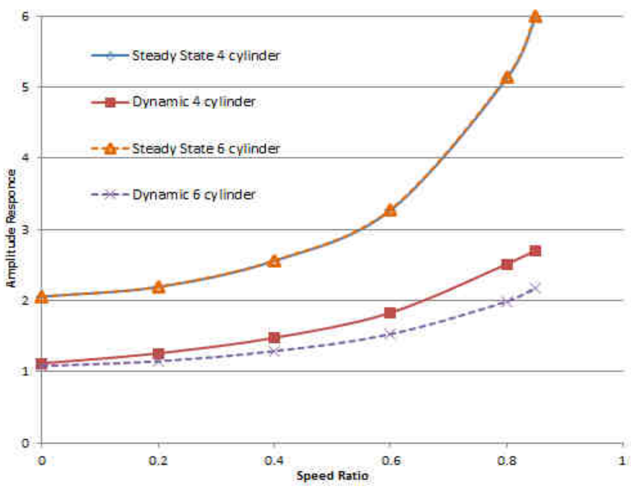

Figure 8: Amplitude response for both engines with steady state and dynamic torque converter models.

The second key difference in the model is that the dynamic model is able to capture the differences between the four and six cylinder engines torque profiles where the number of fluctuations in crank speed varies from 2 (for a four cylinder) to 3 (for the six cylinder). No difference in torque amplitude is seen in the steady state models.

Both the magnitude and behaviour of the results correlate well to the findings in Ishihara and Emori (1966) where the amplitude response was significantly reduced for the dynamic model across the speed ratio range and an increase in speed fluctuations per impeller revolution resulted in reduced torque amplitude i.e. increased damping.

6. CONCLUSIONS

An overview of the Modelica libraries for Engine and Powertrain Dynamics is presented, focusing on the prediction of dynamic driving events such as initial launch of a vehicle, the tip-in tip-out performance and the driveline torsional vibrations due to engine torque pulsations.

Some key areas of integrated powertrain modelling have been addressed through the introduction of a dynamic torque converter model integrated within a multibody vehicle model with crank-angle resolved engine model. It is clear from these experiments that a dynamic model of the torque converter coupled to a crank angle resolved engine in a common simulation tool can offer significant benefit when analysing the torsional characteristics of a powertrain under dynamic conditions both over a short timeframe (high resolution) and fast transients.

These enable more dynamic driving events such as launch, tip-in, tip-out engine idling vibrations using Modelica based models.

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