

Application of the Hardware-in-the-Loop Technique to an Elastomeric Torsional Vibration Damper

Alexandre Schalch Mendes
MWM International Engines

Pablo Siqueira Meirelles
UNICAMP

ABSTRACT

This work describes the development and use of the Hardware-in-the-Loop (HIL) technique to evaluate the dynamic behavior of a torsional vibration rubber damper (TVD) used in a spark ignition internal combustion engine. The TVD was adapted to a test bench designed for this research and the HIL technique was applied considering the simulated dynamic response of the crankshaft. The results of the torsional vibration amplitudes are compared with measured values in a steady-state well identified condition, to experimentally validate the proposed mathematical model and the possibility to use the HIL technique to evaluate dampers and crankshaft behavior in realistic long term tests, where the rubber degradation also affects the dynamic response of the system. Finally, it was concluded that simulated and measured signals presented a good correlation in some engine operational conditions, reaching the objectives of this study.

CITATION: Mendes, A. and Meirelles, P., "Application of the Hardware-in-the-Loop Technique to an Elastomeric Torsional Vibration Damper," *SAE Int. J. Engines* 6(4):2013, doi:10.4271/2013-01-9044.

INTRODUCTION

The Hardware-in-the-Loop technique can be considered a relatively recent method whose usefulness derives from the development of computational resources with capability for processing huge amounts of data in short period of time. This is the main characteristic that enables the real-time response of dynamic systems in HIL testing, by processing sensor information and providing almost instantaneous calculations, adjustments and feedback.

W. Grega [1] presents the basic concepts and practical applications of HIL simulations. His article describes the various steps in the assembly of the HIL system, starting with the development of a model that mathematically represents the real system and the physical hardware, for which there is usually little information about its dynamic behavior due to unknown properties, or due to the lack of data required to create an accurate mathematical model. His work presents hardware and software features commonly employed to develop tests with the HIL technique in both industrial and research environments. He presents a case study involving the tuning of a controller for ventilation systems, and concludes by describing the main advantages of the

technique, focusing on the low cost of the experiments and the possibility of the researcher experimentally verifying the results of theoretical problems with complex solutions.

Another study that uses the HIL technique to evaluate the real-time behavior of a nonlinear, unstable and variant system in time is presented by P. S. Shiakolas and D. Piyabongkam [2], who propose a control system for a magnetic levitation device (Maglev). These authors used MathWorks tools such as MATLAB-SIMULINK, Real-Time Workshop (RTW) and xPC Target toolboxes, as well as National Instruments data acquisition devices and Microsoft Visual C++ compiler. One advantage of the combined use of RTW and xPC Target is that the user does not have to know the low level programming codes used in real-time controllers. These authors conclude by describing some of the limitations of the xPC Target Version 1.0. The critical limitation is the impossibility of using files such as MATLAB m-blocks in SIMULINK, i.e. all the elements of the model need to be implemented as SIMULINK blocks, which precludes the creation of more sophisticated control algorithms. Another limitation of TargetScope is that its graphics do not present maximum and minimum values in the y-axis, which limits the analysis or comparison of signals only to a qualitative form.

In the host computer, numerical values are shown that allow for quantitative assessments.

B. K. Powell et al. [3] describe the application of the HIL system to the powertrain of a hybrid electric vehicle. The authors elucidate the evolution of an existing control system in vehicles and powertrains, aiming to reduce its complexity in order to maintain the products technically competitive. The control systems used in modern vehicles and powertrains are becoming more sophisticated, mainly due to more stringent emission standards and because the tests or numerical simulations for many control problems do not provide reliable results in several operational conditions. Tests can often be representative but, due to the large number of variables and existing parameters, it is not always possible to reproduce faithfully all the actual situations and conditions. In terms of simulations one can even consider combinations of multiple parameters, but because of the difficulty in obtaining accurate mathematical models for complex systems, it is often impossible to reproduce actual events. The combination of simulations running in real time or coupled to actual subsystems or components is perhaps the most efficient way to develop vehicles and powertrains. HIL emerges from this proposal, which is essentially a mixture of theoretical modeling and analysis of physical parts interacting with each other in real time, whose results can be accessed and analyzed accurately. The results are presented for the simulated engine mass flow, according to the crankshaft angle, considering different types of numerical integrators, and a comparison is also made of the torques generated in the thermodynamic model and the actual engine in different operating conditions. The outputs of the internal combustion engine model are used as commands for the dynamometer that drives the electric motor, transferring the torque to the wheels. The rotation of these components is used as feedback for the model in real time to simulate the vehicle's actual operating conditions in the laboratory.

HIL can be applied to many types of systems, such as aerospace, automotive, chemical, and others. The studies relevant to this article are concentrated in the automotive area and include several studies applied to vehicle systems and subsystems. Another application of the HIL technique was evaluated by J. C. Lee and M. W. Suh [4], who examined the simulation of vehicle braking and traction control systems (ABS / TCS). The ABS system provides maximum braking efficiency, reducing the distance traveled by the vehicle until it becomes fully stationary. On the other hand, TCS is a control device that provides stability during acceleration, preventing tire slippage in all pavement conditions. The development of these safety devices requires extensive testing with many vehicles in different road conditions, involving heavy investments in time and money. The use of HIL to reduce these variables is considered in the model, which includes hydraulic equipment, control valves, actual subroutines and also models of the vehicle, tire and powertrain dynamics. The ABS / TCS hardware simulator comprises a conventional brake system, a hydraulic control

unit (HCU), the electronic control unit (ECU) of the ABS / TCS, brake actuators, a signal processing unit, a spinning wheel simulator, control valves and a graphical unit interface for observing the results. This part of the software includes vehicle dynamics, the engine braking and acceleration model in different scenarios, and changes in direction and in track conditions. The authors conclude by describing the advantages of developing new simulation techniques, which are enabled by the processing capacity of microprocessors in computers and in the electronic modules of vehicles. Thus, it is possible to simulate ABS and TCS systems in real-time using personal computers, which are economically attractive. They also point out the capacity to develop and employ logic controls for failure diagnostics.

R. Isermann et al. [5] presented the HIL technique applied to control systems for engines and vehicles. Initially, they presented three types of numerical simulation methods: simulations without time constraints, those performed in real time, and simulations faster than real time. The simulation of a component is performed in real time when the input and output signals present the same time-dependent values of the actual component in dynamic operation. This becomes a problem in computing dynamic processes, which are faster compared than the processing time required for calculation algorithms. A model of an internal combustion engine was developed in order to consider the superposition of the single-cylinder dynamic torque, considering the following objectives: restrict the complexity of the model, perform the exact calculation of the average torque during the working cycle, obtain a good reproduction of the fluctuation of the torque to enable adaptation of the model to real engines, and include multi-dimensional engine operation maps. The authors present a mathematical model that determines the cylinder pressure traces analytically and compares them to the curves measured in a dynamometer. The vehicle model takes into account its longitudinal dynamics and includes the models of the clutch, transmission, brakes and retarder. Aerodynamic resistance, rolling resistance and ramp angles are also considered. To visualize events and all the relevant quantities during testing, a PC machine with a graphical interface that simulates the truck panel was used. To ensure the repeatability of the tests, a driver model was developed to follow a predefined course that acts upon the accelerator, brake, clutch and gear shifts. The authors conclude by presenting the results of three HIL simulations of an eight-cylinder Diesel engine with 420 kW applied to a 40-ton truck. The figures in the paper illustrate the variations in torque, engine speed, vehicle speed, and fuel consumption, as well as torque and speed variations as a function of increasing road ramp angles. To conclude, the authors highlight the reduction in time and costs of product development achieved by using the HIL technique, and point out the possibility of checking the vehicle's behavior in response to faulty sensors, actuators and the engine itself.

Basically, the HIL technique offers great advantages when the characteristics of the analyzed part are too complex

to be modeled mathematically, or are even unknown. The part of the system that can be defined and simulated numerically is the *software*, while the other part, which is instrumented with sensors and actuators, is the *hardware*.

The main aspect of this technique is that the tested *hardware* is subjected to excitation signals that result from the feedback of the sensor signals used to capture specific quantities, which will be controlled in a closed-loop configuration to provide actuation signals exactly like those emitted by real systems.

In the study described in this article, the torsional vibration damper (TVD) was selected as hardware due to the nonlinear properties of the rubber used to reduce crankshaft vibrations. The stiffness and damping coefficients of the components exhibit significant variations as a function of the temperature and excitation frequency, which are difficult to model mathematically.

THEORETICAL MODELING

Basically, TVDs are used in internal combustion engines to reduce the amplitude of torsional vibrations. TVDs can be applied generally to crankshafts and camshafts, because these components present non-constant torques that generate irregular rotational movements.

The engine considered in this study possesses the following characteristics:

- Engine displacement: 1.8 liters
- Fuel: ethanol
- Maximum power: 85 kW at 5600 rpm
- Maximum torque: 175 Nm at 2800 rpm

The system is basically composed of a crankshaft, connecting rods, complete set of pistons, flywheel and damper. Figure 1 illustrates the rotating parts of the system that was the object of this study. Only the pistons and connecting rods are not included in this figure.

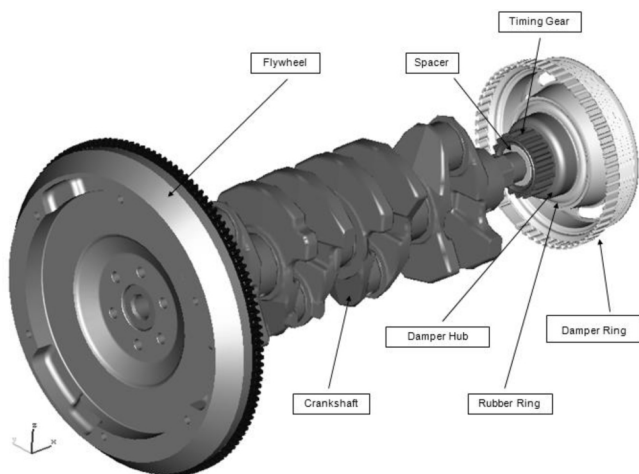


Figure 1. Engine rotating parts

The next section gives a brief overview of the main equations for the mathematical modeling of the crankshaft mechanism.

Crank Mechanism Kinematics and Dynamics

Considering the kinematic and dynamic equations of the crank mechanism, the torque acting on the axis of the crankshaft of a single-cylinder engine can be determined using the equations described below. Figure 2 shows the geometric data and symbols used in the deduction of the equations.

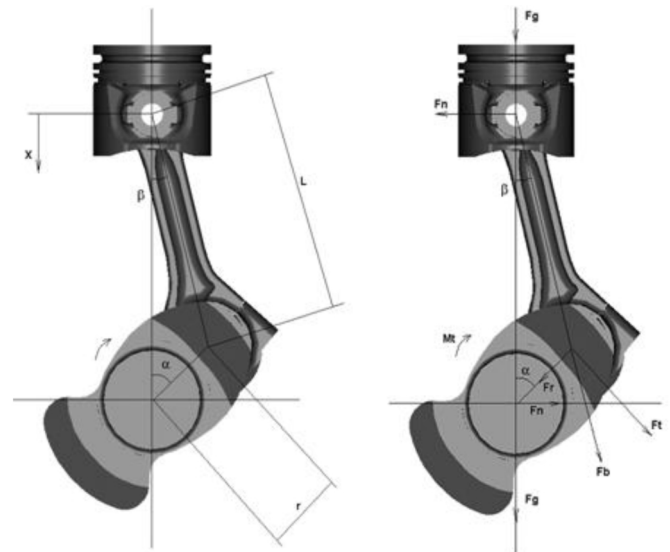


Figure 2. Details of the crankshaft mechanism

The inertia force is a function of the crankshaft angle (α) and is generated by the reciprocating movement of the masses. It is dependent on the piston's complete mass, the conrod's reciprocating mass, the piston's half stroke, and the crankshaft's angular velocity. This force can be calculated by using the following equation given in F. Brunetti and O. Garcia [6]:

$$F_{ia}(\alpha) = m_a \cdot r \cdot \omega^2 (\cos \alpha + \lambda \cdot \cos 2\alpha - \frac{\lambda^3}{4} \cos 4\alpha + \frac{9\lambda^5}{128} \cos 6\alpha) \quad (1)$$

The other load acting on the piston is generated by combustion. Considering the variation of the cylinder's internal pressure as a function of crankshaft angle and piston diameter, this load can be determined during two complete revolutions of the crankshaft, as follows:

$$F_g(\alpha) = p(\alpha) \cdot \frac{\pi \cdot dp^2}{4} \quad (2)$$

Figure 3 shows the cylinder pressures measured as a function of the crankshaft angle at several engine speeds (supplied by the engine manufacturer).

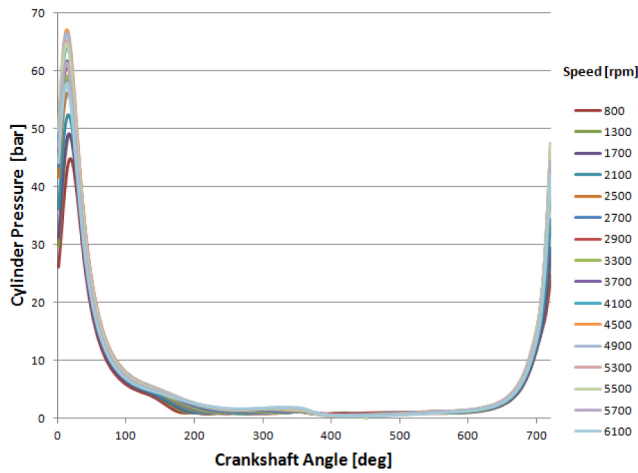


Figure 3. Measured internal cylinder pressures

Thus, it is possible to apply these two piston working loads to the crankpins, using Equations 3 and 4, which are the tangential forces due to the reciprocating masses and the cylinder internal pressure, respectively. The focus of this study is only on the torsional effects acting upon the damper.

Thus, the radial load on the crankpins was not taken into account.

$$F_{ta} = F_{ia} \cdot \frac{\sin(\alpha + \beta)}{\cos \beta} \quad (3)$$

$$F_{tp} = F_g \cdot \frac{\sin(\alpha + \beta)}{\cos \beta} \quad (4)$$

The resulting tangential force on the crankpin, multiplied by the half stroke of the piston, will result in the total torque on the crankshaft.

$$\vec{F}_t = \vec{F}_{tp} + \vec{F}_{ta} \quad (5)$$

$$M_t(t) = F_t \cdot r \quad (6)$$

To exemplify, Figure 4 shows the torque acting on the crank throw at 1250 rpm.

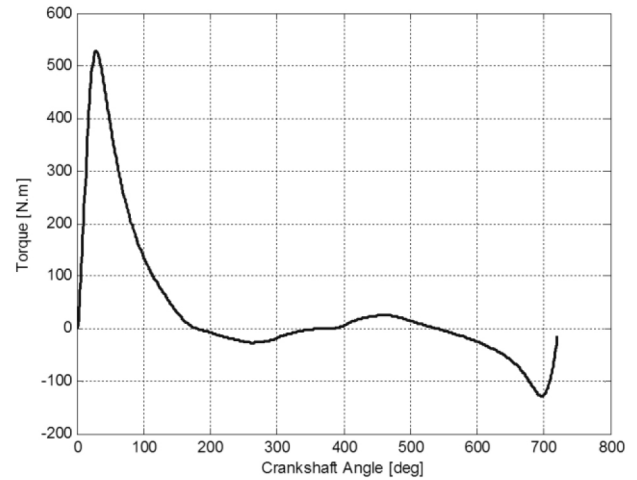


Figure 4. Torque acting upon crank throw at 1250 rpm

Crankshaft Elastic Mass System and Calculation of the Dynamic Steady-State Response

The driving torque acting on the axis of the crankshaft, considering the component as perfectly rigid, was determined previously. The model developed in this section will consider the elasticity of the crankshaft in order to determine the actual dynamic response of the system.

The component will be reduced in a torsional spring and concentrated inertia model to determine the angular displacements at the damper hub, which will be applied to the HIL experiment. Figure 5 shows the elastic model of the engine rotating parts, highlighting the simulated portion of the model (software) and the tested part (hardware).

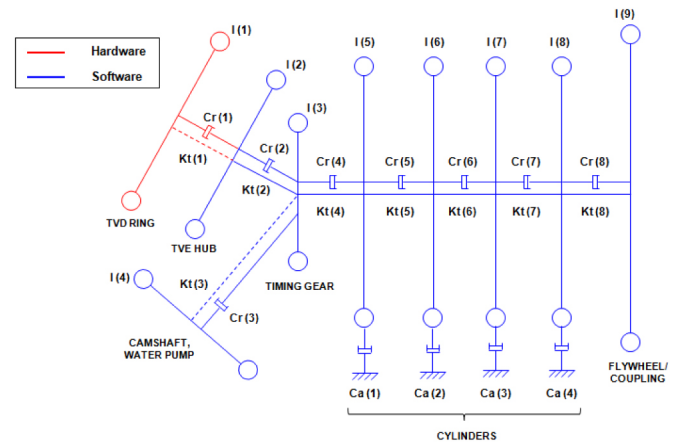


Figure 5. Complete elastic model of the engine rotating parts

Using numerical simulation software, it is possible to determine the inertia and torsional stiffness to build an equivalent elastic model, which will be used to calculate the