

Anti-Jerk & Idle Speed Control with Integrated Sub-Harmonic Vibration Compensation for Vehicles with Dual Mass Flywheels

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ABSTRACT

Over more than 20 years 50 million LuK dual mass flywheels (DMF) have been produced for use in passenger cars and light trucks. A typical DMF consists of two flywheels connected by long travel arc-springs. It is located between the combustion engine and the clutch or automatic transmission. The DMF reduces driveline oscillations by mechanically decoupling the transmission from the periodic combustion events that excite the engine crankshaft. Existing engine control systems are generally designed for conventional single mass flywheel (SMF) systems. In the future, to facilitate the best possible control of engines equipped with DMF systems, these conventional control systems may require modification or even replacement. With the integration of the highly non-linear DMF, the complexity, and thus the order of the powertrain system increase. Beside important effects like significantly reduced gear rattle and booming noises, the protection of transmission components, lower engine idle speeds and consequently better real world fuel consumption, the higher system complexity increases the probability of inconvenient side effects like jerking and / or sub-harmonic vibrations (SHV). Jerking is a surging type of oscillation at the driveline's first natural frequency. This effect is generally excited by rapid engine and / or load torque changes. SHV are limit cycles which can occur in systems subject to both open- and closed-loop control. The frequencies of SHV are lower than the ignition frequency of the combustion engine. Both jerking and SHV are subjectively disagreeable to the driver and should be compensated for as far as possible in the engine controller design. In this paper novel model based controllers are described, which minimise the incidence of and also compensate for both jerking and sub-harmonic types of vibrations. Permitting active damping of these unpleasant oscillations in idle, drive, tip-in / tip-out and coast. For cost effective

controller design and real-time implementation a linear state space model with a low system order is preferred. Therefore, a reduced state space model of the driveline including the DMF is introduced. In order to achieve a high degree of modelling fidelity a state observer has also been developed and implemented. This allows the reconstruction of system state values that are not easily or economically measured e.g. driveline load. The controllers developed have been integrated within an overall engine management system model to simulate interaction with other commonly used control algorithms e.g. cylinder balancing. By implementing intelligent strategies for controller activation and deactivation, negative side effects (e.g. cross compensation interactions) are avoided. These newly developed engine control concepts provide a good basis for improving passenger comfort and vehicle driveability by reducing both jerking and sub-harmonic vibrations in the driveline.

INTRODUCTION

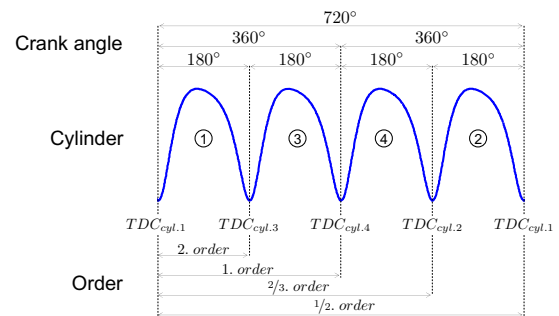
In recent years both common-rail diesel and direct injection gasoline engine technologies have been widely adopted within the automotive industry. The main reasons for the growing market share of such direct injection technologies are the higher efficiency and hence the lower fuel consumption achieved, combined with improved control of the combustion process which facilitates reduced exhaust gas emissions and improved NVH (noise vibration harshness) compared to conventional indirect injection engines. The rapid progress in the development of engine technologies like direct fuel injection via common-rail technology, turbocharging and high performance engine ECU (electronic control unit) with torque based management have pushed the diesel engine to a level almost equal to that of the gasoline engine in terms of real world performance and driveability. Diesel as well as direct in-

Diagram illustrating the components of a clutch assembly, labeled as follows:

- Starter ring gear
- Primary flywheel
- Flange
- Cover
- Shell
- Arc springs
- Secondary flywheel

Basically, the DMF consist of two rotating flywheel inertias connected by long travel arc springs. More detailed information about the DMF can be found in [1]. The principal advantage of the DMF is the almost complete elimination of secondary flywheel and thus gearbox input-shaft speed oscillations. This eliminates annoying gear rattle as well as other noises and vibrations, allowing the engine to be driven at lower speeds, which in turn improves real world fuel economy. Due to its excellent vibration isolation and damping attributes, the DMF is today an inherent part of many vehicle drivelines. Even in low-cost budget cars has the DMF established its market position. However, despite all of these advantages, the DMF increases the driveline system complexity. Analytically, the DMF is a spring-damper element with strongly non-linear behaviour. Due to its capability of temporary energy storage, it produces a reaction torque on the combustion engine and thus affects the crankshaft speed signal, which is extensively used by the engine ECU. Conventional ECU systems for anti-jerk, idle speed and cylinder balancing control do not take this fast changing torque reaction on the crankshaft into account. Therefore, in this paper, a new method which includes the system dynamics of the DMF is introduced.

In the highly non-linear internal combustion engine idle speed control loop sub-harmonic vibrations (SHV) can occur. Here, sub-harmonic means, that the frequency of the vibration is an integer fraction of the engine's firing frequency. A four-cylinder four-stroke engine exhibits second order firing, which means that two combustion events occur per crankshaft revolution. Commonly observable sub-harmonic vibrations for four-cylinder engines with DMF have 0.5th, 0.66th and first orders (Figure 2).



Sub-harmonic vibrations during engine idle [2] are typically excited by sudden changes in engine or driveline load. Load changes at the crankshaft and the essentially rigidly connected primary flywheel are induced by the inadequately compensated switching of high electrical loads or the air conditioning system. Sub-harmonic vibrations are excited by both positive and negative load steps. Driveline load changes on the secondary flywheel of the DMF can also provoke SHV.

One might incorrectly suppose, that idle SHV are mainly due to the non-linear behaviour of the DMF. However, idle SHV are also observable in vehicles fitted with conventional single mass flywheels; even on those with perfectly balanced engine cylinders. An important question is therefore, which parts of the highly non-linear ISC loop provoke and / or exacerbate sub-harmonic vibrations. In order to answer this question, the so-called *Harmonic Balance Method* [3] has been used to analyse the non-linear engine idle speed control loop [2]. Idle SHV are limit cycles in the non-linear closed-loop system that comprises the engine, including DMF if fitted and the control sys-

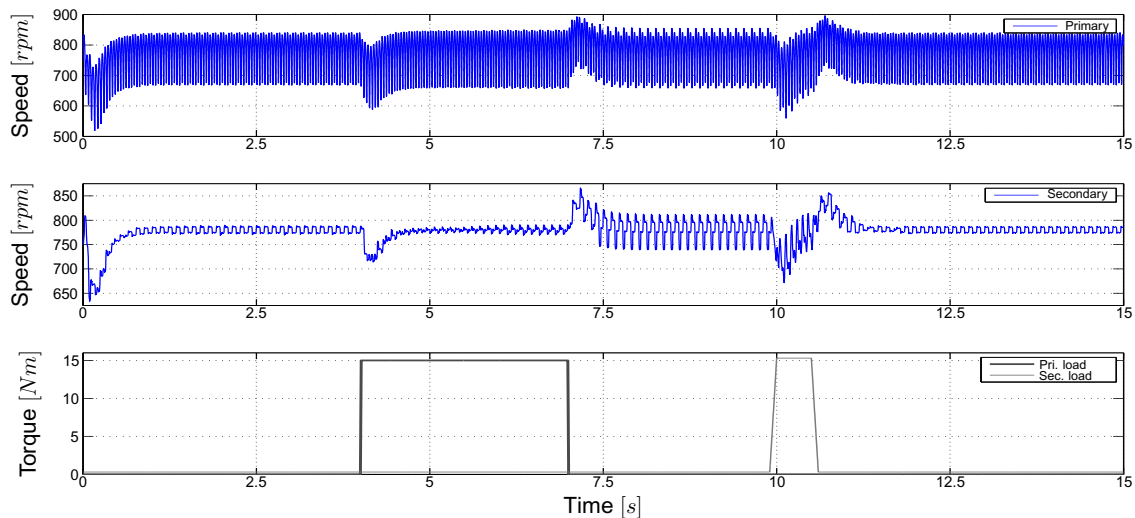


Figure 4: Validation of the conventional PI idle speed controller (ISC)

tem. In order to reduce idle SHV, the open loop gain K as well as the total dead time of the ISC loop have to be minimised.

Figure 4 shows simulation results for a conventional PI-ISC system according to reference [2]. At $t = 4\text{ s}$ a primary side load torque is switched on. The engine speed decreases slightly but soon recovers to the idle speed setpoint $n_{setp.}$. During the high load phase, negligible sub-harmonic vibrations occur. However, after the load is switched off at $t = 7\text{ s}$, both the engine and secondary flywheel speeds include very strong sub-harmonic vibration components. These oscillations remain until just after $t = 10\text{ s}$, when a short impulse acting on the secondary DMF side is introduced and the engine speed returns to its original condition before any load changes were applied. Note that if the impulse at $t = 10\text{ s}$ had not been applied and the load had instead been held constant, these unpleasant idle SHV would not have decayed and would have been sustained i.e. a stable limit cycle existed.

Even with the utilisation of intelligent gain scheduling [2] the proportional part of a conventional PI-ISC cannot always be set to a low enough value to guarantee that SHV will not occur. Furthermore, if the proportional gain is set too low then the idle speed controller may be unable to fulfil its basic function of regulating the mean engine speed i.e. a completely unstable idle speed and / or inadequate load rejection may result. Analysis of the closed-loop idle system shows that the total system dead time and thus the incidence of SHV, can be significantly reduced by using the latest (i.e. up to date) tooth-to-tooth (i.e. incremental) engine speed information, in place of the commonly used average (e.g. filtered over 180° crankshaft angle on a 4-cylinder application) engine speed signal which is often last updated well before top dead centre (e.g. 50 to 100° crankshaft angle). One other significant disadvantage of conventional PI-ISC systems is that regulation only occurs in the idle operating point, and therefore any improvements (e.g. minimisation of SHV) to the idle controller will

obviously only apply in the idle mode. Therefore, in this new approach general state space controllers are introduced, which permit a significant reduction in SHV, as well as driveline jerking vibrations, across virtually the whole working range of the engine i.e. idle, tip-in, drive, tip-out and even coast.

REDUCING SHV WITH STATE SPACE CONTROL

In order to reduce sub-harmonic vibrations across virtually the whole working range of the engine, two complementary model based controllers were developed; one specifically for neutral idle, the other for the idle drive, drive and coast modes.

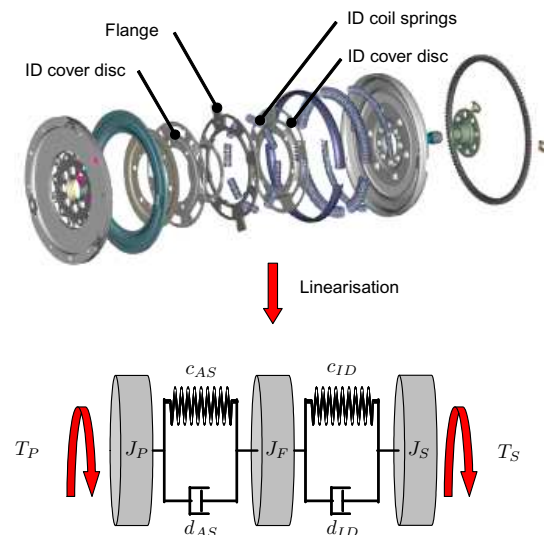


Figure 5: Linear DMF model including optional inner damper (ID)