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DYNAMIC SIMULATION OF AN INNOVATIVE PERMANENTLY ENGAGED MECHANISM FOR STARTING SYSTEMS

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Abstract. *Environmental challenges to reduce current emission levels place a strong pressure in the automotive industry. Alternatives to replace internal combustion engines have both technology and infrastructure constraints to allow wider spread of electric and fuel cell vehicles. Another option is to increase internal combustion engine vehicles efficiency. Following this direction, Stop-Start Vehicles (SSV), aiming to reduce fuel consumption and emissions, are a promising market trend. SSV impose a new challenge to current starting systems for internal combustion engine. Alternatives to improve starting systems may involve innovative One-Way Clutch design. One promising concept is the mechanical diode or ratchet-pawl configuration, a reliable option for high torque transmission and low friction wear during overrunning but has limited application in current starting systems. One potential constraint when dimensioning a pawl-ratchet is the impact noise generated by the strut during engagement. This paper presents a 1-D dynamic model, whose damping effect was evaluated in a prototype installed in a flywheel to start an engine in a test bench. The proposed design allows a more robust mechanical interface for starting systems and provides an option for the evolution of the starting system and the spread of SSV as a viable fuel efficiency alternative.*

Keywords: *Starting Systems, Stop-Start Vehicles, One-Way Clutch, 1-D Modeling and Simulation, Damping System*

1. INTRODUCTION

Annual carbon emissions from passenger vehicles are projected to climb more than 54 percent by 2030, reaching 4.7 Gt (gigatonnes) of CO_2 in that year, due to the increase in the number of vehicles on the road – from 730 million to more than 1.3 billion over this period – according to Eichlseder & Wimmer (2005).

Recent engine and alternative fuels developments for vehicle applications had shown the use of hydrogen fuel cells, plug-in electric and hybrid powertrains in which Internal Combustion Engines-ICE's are coupled to electric motors to replace pure internal combustion sources. Some researchers, like Christidis (2003), state some concern on the potential of upcoming technologies to replace current ICE in terms of several factors such as infrastructure, fuel availability and cost level.

Nevertheless, automotive market currently foresees a continuity of ICE as the main propulsion system, probably sharing the market with other types of propulsion systems, such as hybrids and electric. According to McKinsey & Company (2009), ICE is expected to remain as the dominant drive train in the future, relying upon new technologies to increase this engine efficiency. Among those technologies it can be noticed, for instance, HCCI (Homogeneous Charge Compression Ignition), Engine Downsizing and Fuel Direct Injection. HCCI promotes a higher efficiency of the Otto cycle by compression and heating of air-fuel mixture until the auto-ignition point (Carney, 2008). Engine downsizing focuses on increasing ICE specific power in kW/liter as described in the work by DeCicco, *et al.* (2001) and Fuel Direct Injection improves combustion efficiency by first compressing only air in the cylinder and then injecting fuel directly in the combustion chamber as described by Leduc (2003).

Following this direction, auxiliary starting system for ICE has also a potential to demonstrate evolution from the one-century old starter motor concept to the introduction of innovative concepts able to increase ICE efficiency. Mechanical connection design for starting systems has also been evolving from the standard, intermittent pinion-gear engagement to a permanent connection by means of gear set or belt system. This demand comes from the increasing presence of SSV (Stop-Start Vehicles), which are expected to grow steadily in the automotive market, from current 3 million units to 37.3Mi in 2020, representing in that year approximately 1/3 of light vehicles sales worldwide (Pike Research, 2012).

Therefore, this project motivation is to propose a new concept aimed to be an alternative Mechanical Interface to Starting Systems, based on a permanently engaged connection between ICE and Starter Motor, named herein Dynamic Coupling System or simply DCS. The proposed design has some critical challenges. This paper aims to propose, simulate and confirm experimentally the potential of the proposed design alternative as a feasible alternative for SSV starting systems.

Researchers have already demonstrated the contribution of the 1-D dynamic modeling and simulation in different types of automotive systems as, for instance, the modeling of gasoline (Li, 2005) and Diesel fuel injection system (Chaufour, 2003), cooling systems (da Silva, *et al.*, 2000) or the complete model of a motorcycle, from the engine to the tires (Botellé & Lebrun, 2003). In the work developed by Li (2005), the 1-D dynamic modeling is applied to investigate the damping technology used to control pressure pulsations that happen in the fuel injection systems due to the extremely fast opening and closing cycles of the nozzles. Conclusions of the research done by Li (2005), for instance, indicate that the simulation helped a broad understanding of the system behavior, resulting in an effective and reliable evaluation of the problem. This current research adopted a tool to study lumped parameter model simulation, known as LMS Imagine.Lab AMESim (Silva, 2005).

The paper structure is organized as follows: Next section presents a brief review on SSV and the definition of Mechanical Interfaces for Starting Systems, a new concept is presented and a 1-D model is set up for a lumped parameter dynamic simulation of the system. Following, simulation and experimental results are discussed. Finally, some conclusions point out the potential contribution of such type of innovation effort, which is aligned with current researches aiming to increase ICE efficiency and maintain it as a viable alternative for the automotive market.

2. STOP-START VEHICLES

In order to acquire its autonomous functioning, ICE´s demand startup assistance. Starting systems were first manually activated and then an electric motor with some specific functions was widely used both for Otto and Diesel cycles, which require an adequate air-fuel ratio or sufficient auto-ignition temperature, respectively. Starting system is comprised of a multi-domain set of mechanical, electrical and control components. The starting system is designed to transform the electrical power into mechanical power as described by Bosch (2011). Aiming to improve performance of current ICE, Stop-Start function has been evaluated as an option for reducing ICE emissions. SSV (Stop-Start Vehicle) that turns off the engine at idle is one technology aimed to improve ICE efficiency at a relatively low cost. It is more widely used in Europe than USA nowadays, fact explained by the EPA (US Environmental Protection Agency) driving cycle, which counts less urban-driving than highway cycles (USA, 2009). Vehicles equipped with this technology have an electronic management system that adds the functionality of the combustion engine to stop and automatic start. Basically, SSV operation can be explained assuming a vehicle which is stationary and in neutral, then Stop-Start Electronic Control Unit (ECU) shuts down the engine; when the driver engages a gear and step on the gas engine it is reconnected without additional intervention from the driver. The fuel consumption reduction, mainly greenhouse gas emissions, in heavily traffic areas of large cities, constitutes a major factor in the adoption of this technology. Fuel consumption in traffic of a big city could be reduced by at least 8%, according to estimates from manufacturers (Silva, *et al.*, 2009). Some SSV technologies in the market, as described by Portella, *et al.* (2009), adopts an intermittent mechanical interface between the electric starter motor and ICE, comprised of a standard pinion-ring gear connection and a control unit to assure the functionality of the automatic stops and starts. Therefore, this system still uses the conventional starter motor but it includes a complex electronic control device, along with an increase in the durability of critical components. With the improvements to expand its functionalities and respectively increase of the overall durability, for SSV, the starter motor cost is higher than conventional system. Extra costs come also from additional control strategy to ensure that the system is not triggered during parking maneuvers or to check whether vehicle battery has enough power for the next starting cycle. In the contrary, the electronic central unit (ECU) that controls SSV operation will not shut down ICE at halt.

3. MECHANICAL INTERFACE FOR STARTING SYSTEMS

Here, it is necessary a precise definition of the *Dynamic Coupling System* — known as DCS —configured as the integration of the mechanical components responsible for connecting the electric motor armature shaft to the ICE crankshaft and transmitting power between them. DCS for SSV using a non-conventional mechanical interface relies upon different configurations. One type is the BAS (Belt Starter-Alternator), which replaces both starter motor and alternator in an integrated assembly which is coupled to the combustion engine crankshaft via a belt (Wezenbeek, 2004). Another type of DCS is comprised by a direct connection between the engine and the gearbox. The so called crankshaft ISG, or C-ISG has a complex installation with extra packaging space requirements and additional cost as discussed by Viorel, *et al.* (2004). DCS using a conventional starter motor and One-Way Clutch in the interface of the flywheel and crankshaft can be found in the patent granted by Suzuki, *et al.* (2011). Most widely adopted Stop-Start Technology in current SSV (Stop-Start Vehicles) relies upon traditional pinion-gear mechanical interface or using a pinion-gear with permanently engaged mechanical interface (Asada, *et al.*, 2008).

As depicted in Fig. 1, DCS system boundaries (enclosed by dashed lines) comprises, in the particular case of conventional starting systems, of the following parts: (a) solenoid valve, (b) shift lever, (c) starter drive having OWC (One-Way Clutch) function, (d) pinion attached to the starter drive, (d) ring gear and the (e) flywheel where the ring gear is mounted. Also, the arrows in Fig. 1 indicate the input for the DCS as the power generated by the electric motor as well as the output as the power transmitted to the ICE crankshaft.

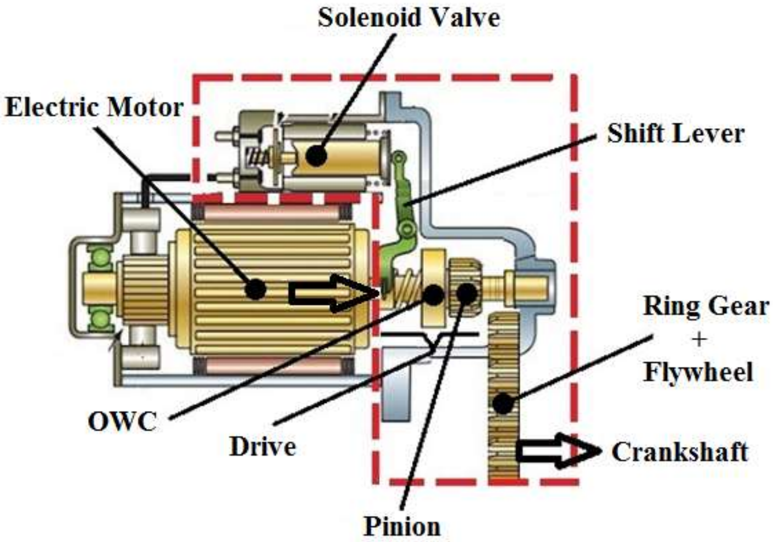

Figure 1. DCS (dashed lines) in Conventional Starting System.
Adapted from Autosystempro.com (2015)

4. NEW DCS CONCEPT AND SIMULATION MODEL

Proposed DCS concept as presented by Michelotti & Silva (2015) is based in a Permanently Engaged Mechanical Interface. The One-Way Clutch (OWC) is repositioned from the armature/pinion interface to the ring gear/crankshaft interface, allowing the ring gear to be kept in permanently engagement with the starter motor during ICE functioning. This strategy allows reduced noise and wear as the ring gear stands still during ICE functioning.

As can be noticed in Figure 2, this new concept has a ring gear (1) attached to the ICE flywheel (2) and a simple pinion gear (3) attached to the starter motor armature shaft (4) in constant meshing with the ring gear containing internal teeth profile (5). The same ring gear has a wedge profile (6) in the outside diameter. The wedge profile should engage to one or more pawls (7) located in the flywheel (2) that is then bolted to the engine crankshaft (8) and mounted coaxially to the ring gear. Some type of cushion effect is provided by a spring-damper mechanism (9) prior to full engagement and torque transmission, preventing noise and premature wear and/or failure of the one-way clutch system.

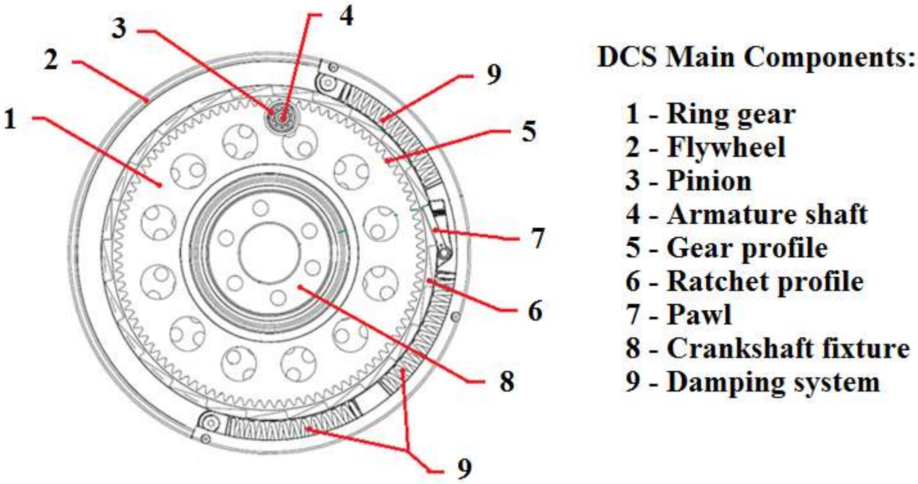

Figure 2. Components of the innovative DCS design concept

In the new DCS concept the electric motor continues to be part of the starting system. Despite its additional components in the ring gear/flywheel interface, the new concept simplifies the starter motor as it eliminates plunger in the solenoid, lever and starter drive. Therefore this concept can be considered a potential cost effective design compared to the current permanently engaged alternatives. Besides, this proposed DCS concept avoids changes in the engine block, one of the main constraints on existing concept based on lubricated sprags, as described by Asada, *et al.* (2008).

Considering the proposed OWC is based on a pawl-ratchet design, impact during engagement and overrunning is a key factor of success as low noise during engine startup is mandatory to allow acceptance of the new system in SSV. OWC based on a pawl-ratchet profile, also known as mechanical diode OWC, is discussed further in the work by Michelotti & Silva (2009). Subsystems aimed to damp excessive vibration levels when performing starting operations is the main focus of the research at this development stage. In order to demonstrate damping system potential, a 1-D dynamic simulation model is built and preliminary results are used to define the initial prototype and obtain experimental results. The simulation model to evaluate the damping system effectiveness is schematically shown in Fig. 3.

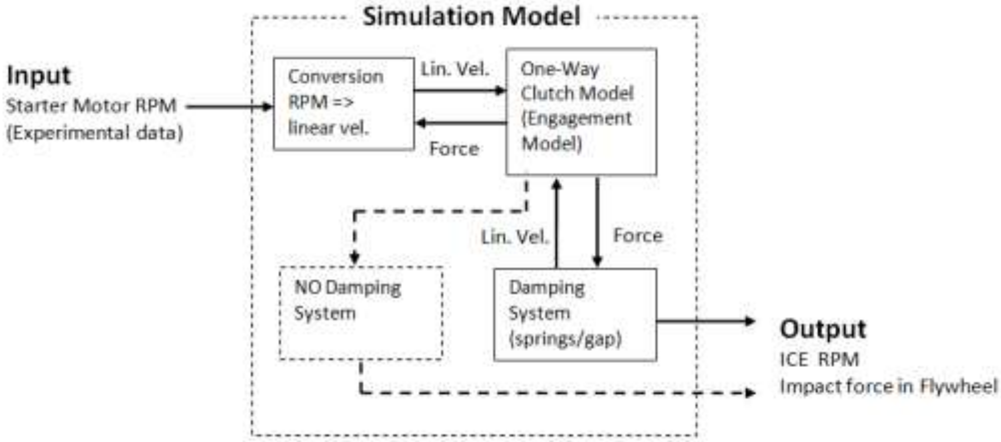

Figure 3. Schematic of the Simulation Model to evaluate OWC damping system performance

Input for the simulation model is based on experimental data collected during conventional start cycle in ICE test bench, and set as starter motor rotational speed (RPM) in the simulation model. Then it is transformed inside the model in a linear velocity based on the ring gear radius to generate the impact force in the OWC engagement model.

The OWC model or “engagement model”, depicted in Fig. 3, is based on the axial displacement of the ratchet gear in order to engage to the pawl in the flywheel. The pawl is mounted in a carrier which is able to slide along the flywheel inner race. To simplify the model it can be understood as an impulse, related to the variation in the quantity of movement of the pawl due to the force *F*, generated by the startup torque T_S; Considering this torque T_S is applied during a time interval Δt which, in the most critical condition, is a function of the maximum distance X between the pawl normal face and ratchet profile recess as shown in Figure 4, in innovative DCS with pawl-ratchet configuration. Considering ratchet profile start rotating it hits the face of the pawl. As the pawl is attached to the flywheel, this force generates a torque T_e to rotate the outer flywheel, which is ultimately attached to the ICE crankshaft.

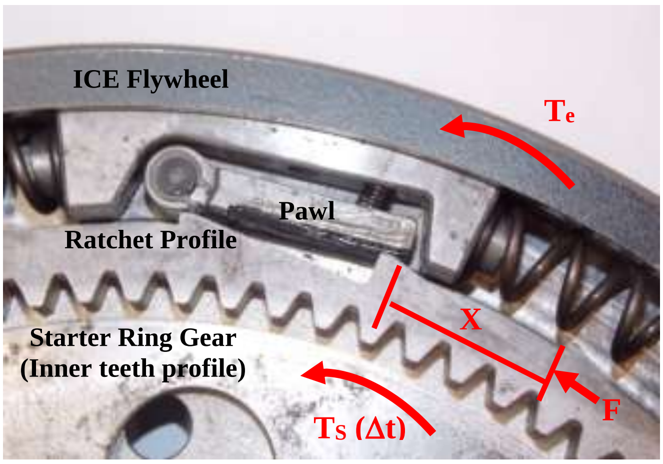

Figure 4. Pawl-ratchet OWC. Dimension “X” is the max. travel distance of the pawl during engagement

The simulation model of an innovative damping system with arc-springs was simplified as well, allowing to keep sufficient precision along with reduced simulation time and effort. A simple calculation of the maximum travel distance of the pawl considering actual angular displacement and respective linear displacement indicate the linear model can be used without compromising simulation results. Therefore, in order to simplify the model the arc-spring damper is modeled assuming linear spring models. The system is modeled as a dual-stage spring system with endstops and spring guide. The model includes friction and its parameters need to be refined based on experimental validation to better represent starting cycle times and refine impact forces.

Simulation model was implemented in the commercial software LMS Imagine.Lab AMESim in order to allow faster simulation runs and adjust model parameters, evaluating system performance based on the effectiveness of the damping system during OWC engagement. Simulation input parameters and state variables of the lumped parameter model are shown in Tab. 1. Next section describes simulation results as well as preliminary experimental data on a prototype of the innovative DCS system.

Table 1. Simulation model input parameters.

ID	Parameter	Value	ID	Parameter	Value
1	Angle between guides	15deg	8	Flywheel mass	3.2kg
2	Angle between endstop-pawl	195deg	9	Pawl mass	0.013kg
3	Angle pawl carrier	30deg	10	Pawl Carrier mass	0.03kg
4	Angle endstop	15deg	11	Ring gear mass	2.3kg
5	Ring gear diameter	232.0mm	12	Flywheel moment of inertia	0.016kg.m^2
6	Number of ratchet recess profiles	23	13	Ring gear moment of inertia	0.013 kg.m^2
7	Ratchet primitive diameter	245.0mm			

6. SIMULATION AND EXPERIMENTAL RESULTS

Simulation efforts have included the impact analysis aimed to adjust arc-spring stiffness. Components mass and packaging are constraints to the impact generated during engagement. As a design input the flywheel mass and inertial moment of the original engine was kept as close as possible in the new DCS design, to prevent compromising engine performance during startup cycle and normal operation. Arc-spring stiffness change is constrained by the installation space in the flywheel, considering ring gear and remaining system components integration in the same packaging space. Flywheel fixtures of the new DCS were also based on the existing one, allowing a "*plug-and-play*" configuration, without any required change to the existing ICE mounting fixtures or engine block.

Simulation comparison is performed considering an alternative model with NO damping system, as previously indicated in the simulation model schematically shown in Fig. 3. This condition represents default situation in this type of overrunning clutch. To compare the performance of the pawl-ratchet OWC with the damping system proposed herein a "worst case" scenario is considered. It assumes that the pawl is positioned in such a way that it needs to displace the longest travel distance to reach the next ramp in the ratchet profile, as previously depicted in Figure 4. In the new DCS concept design, this longest travel distance is 35mm. Simulation results indicated the pawl takes approximately 0.4s to hit the ratchet recess ramp during engine startup. Based on the "worst case" scenario the effect of the pawl-ratchet engagement during engine startup is simulated and the force generated is higher than 12 kN, as can be seen in simulation result shown in Fig. 5(a). This impact force would generate a huge amount of vibration and potential noise during ICE startup. Potential damage to the pawl and ratchet profile surfaces should be also a concern for high durability requirements of SSV.

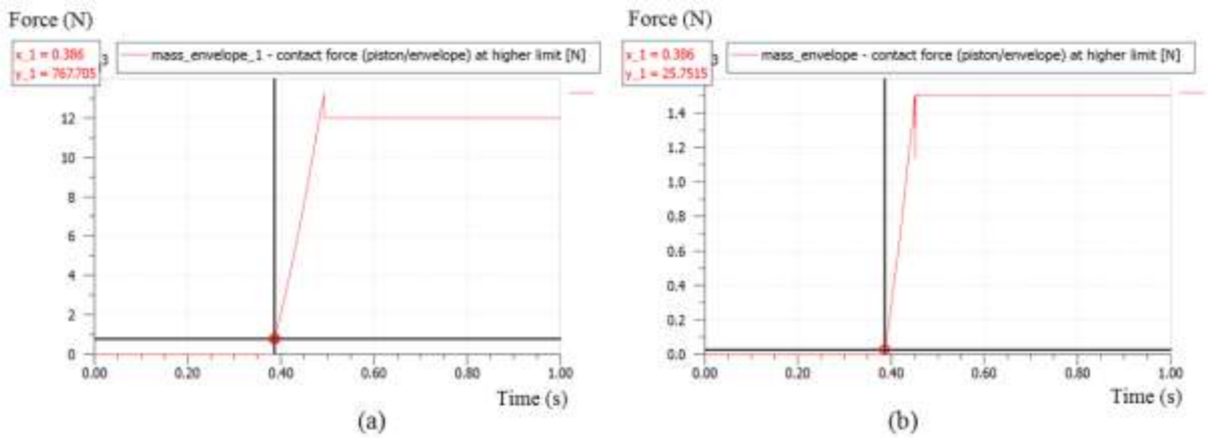

Figure 5. Impact force during pawl-ratchet OWC engagement (a) without and (b) with damping system

Following the analysis based on the same “worst case” scenario the effect of adding a damping system to the pawl-ratchet OWC was simulated and the force generated during engagement, as graphically represented in Fig. 5(b), was reduced to less than 1.5 kN. This condition represents almost 90% reduction in the original impact force during a standard pawl-ratchet OWC engagement considering the new DCS design proportions. Following this approach, the new DCS concept would generate reduced vibration and noise levels during ICE startup. Reduction in the impact force also contributes to an increased durability, as less damage would be generated in the contact regions with the successive impacts of the starting system throughout system lifetime.

In order to validate the proposed model, a prototype was built and installed in a test bench. The prototype is depicted in Fig. 6.

Figure 6. DCS Prototype installed in the test bench

Durability is not the target for the current project stage, nevertheless having the first prototype capable of startup ICE for more than a hundred cycles. Prototype noise during startup cycle was measured and peak of 89 dB(A) was below conventional system tested as baseline, which peak was 94 dB(A). The prototype was able to provide overrunning function with proper centrifugal effect of the pawl, preventing wear as per design intent. Moreover, it can be noticed in Fig. 7 that the new concept has also a potential to reduce starting cycle time, which is a very important factor to improve current Stop-Start systems and potentially spread the application of SSV in the market as a cost effective alternative. The appearance of the lines in graph (a) and (b), more straight in (a) and more stepped in (b) is related only due to different time step configuration during experimental data acquisition, and no evidence of any abnormal condition of the system can be correlated to this effect.

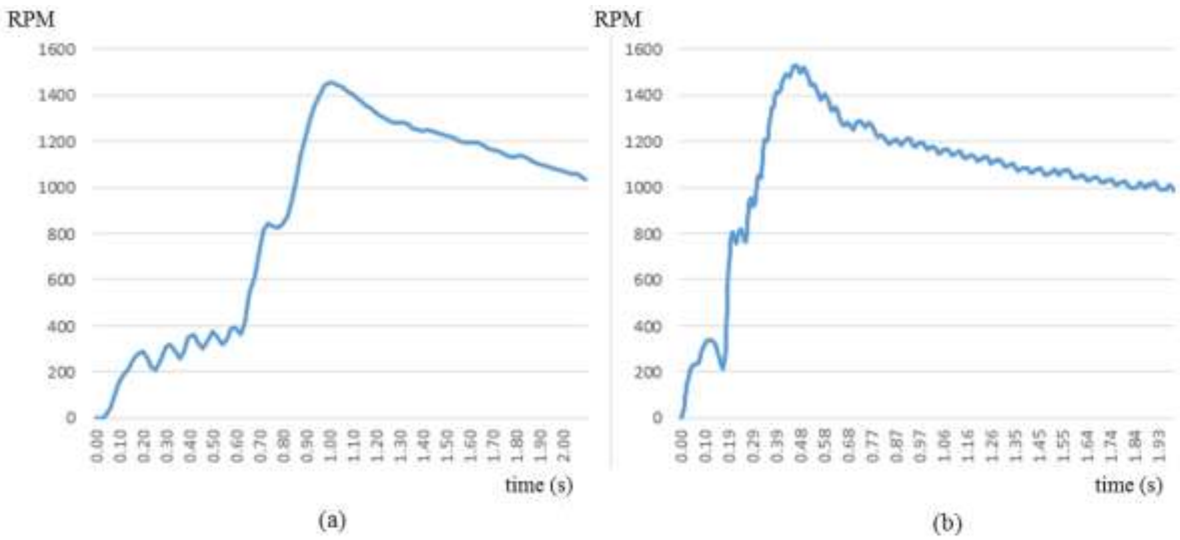

Figure 7. Experimental ICE startup with (a) standard mechanical interface and (b) DCS Prototype

7. CONCLUSIONS

Considering the lack of a cost-effective and higher durability mechanical interface for starting systems is preventing a wider spread of SSV in the automotive market, the objective of the present research is to evaluate, with the aid of 1-D simulation, an innovative DCS concept for automotive Starting System. A new DCS concept was developed as part of the present research, but not included in the present paper. This new design has a patent pending filling in 2012 (Brazil INPI BR102012029979-8). Proposed OWC relies on a pawl-ratchet design which is adequate for starting systems considering its high torque capacity but has a critical constraint, related to the impact generated during engagement for torque transmission. Common design alternatives, as increasing the number of teeth in the ratchet profile, along with increased number of pawls, are strategies normally adopted to minimize the travel distance and, consequently, reduce impact. Unfortunately, relying solely upon this strategy is not enough based on DCS requirements for SSV. Therefore a damping system was proposed in the innovative DCS design.

In the present research, a lumped-parameters model was developed and simulation results were able to point out a satisfactory performance of the proposed damping system. An experimental prototype was built and installed in an ICE test bench. Prototype tests confirmed damping system effectiveness to absorb impact during engagement. Based on the promising results described in the present work further refinement of the system is recommended, in order to achieve a robust design in terms of durability. Innovative DCS design also represents an advance in the State-of-the-Art related to permanently engaged mechanical interfaces for Starting Systems. Further works, considering both technical and economical validation of the system, are necessary to represent a truly alternative for a wider adoption of SSV in the automotive market.

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