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Intelligent Belt Drive Systems in Hybrid Powertrains: a Multipurpose Test Rig

M. di Napoli * M. Strähle ** S. Ruzimov *
L. D. Suarez Cabrera * N. Amati * A. Tonoli *

* *Politecnico di Torino, Department of Mechanical and Aerospace Engineering, Mechatronics Laboratory, Corso Duca degli Abruzzi, 24, Torino, Italia (e-mail: maria.dinapoli@polito.it)*
** *Technische Universität Darmstadt, Karolinenplatz 5, 64289 Darmstadt, Deutschland*

Abstract: In traditional engine setups Belt Drive Systems (BDS) are in charge of power transmission from the crankshaft to the accessories. They are complex and critical dynamic mechanisms, involving contact mechanics and vibration phenomena. The hybridization of vehicles has increased the severity of the operating conditions of these systems that have become even more critical. The traditional alternator was substituted by a Belt-Starter Generator (BSG), an electric machine that can power the BDS in particular operating conditions to improve the Internal Combustion Engine (ICE) performance or to allow regenerative braking. The aim of the present work is to describe the design and the main characteristic of a test rig conceived to investigate in laboratory environment on the behaviour of belt drive systems in dynamic conditions. Two permanent magnet electric motors are used to replicate the dynamic behavior of crankshaft and BSG in a realistic, though controlled and repaetable, manner.

Keywords: Automotive Control, Hybrid Vehicles, Belt Drive Systems, Dynamic Modeling, Front-End Accessory Drives, Model Based Control

1. INTRODUCTION

Belt Drive Systems (BDS) or Front-End Accessory Drives (FEAD) constitute the traditional power transmission mechanism to power the main internal combustion ancilliaries such as the alternator, water pump and air conditioning pump. The torque generated by the Internal Combustion Engine (ICE) is transmitted by means of a serpentine belt that wraps around the driving and driven accessory pulleys of the drive systems.

BDS represent traditionally a complex and critical vehicle subsystem because of the performance specifications that need to be fulfilled. It usually in the severe ambient conditions of the engine compartment and is subject to highly dynamic excitations coming from the crankshaft harmonics. These harmonic excitation ,together with the inertia of the accessories (mainly the alternator), leads to vibrations of the belt and high tension fluctuations that can cause slippage and noise. To reduce these excitations a number of solutions have been developed including decoupling, filtering and overruning pulleys. The analysis of these phenomena led to the development of refined models of the belt pulley contact mechanics together with the definition of serpentine multi-pulley models to predict the dynamic response of serpentine belt-drive systems. A literature review shows that several research activities were carried out addressing separately the belt pulley mechanisms, see Bechtel et al. (2000), Rubin (2000), Hansson (1990), and the dynamic behavior of the transmission system, see Ulsoy et al. (1985), Hwang et al. (1994), Leamy and Perkins (1998). Only few attempts were done in the last 10 years to bridge the gap between research on contact mechanics and dynamic analysis by Leamy and Wasfy (2002), Leamy (2003), Kong and Parker (2003). Tonoli et al. (2006) analyzed the effect of shear deflection of the belt on the rotational dynamic behavior of the transmission.

Additionally, the advent of hybrid technologies has seen the rise of a class of micro-hybrids that changes the operating modes of the traditional belt drive systems. In this paradigm, the alternator is substituted with a Belt Starter Generator (BSG), an electrical machine able to work both as motor and as generator, causing a tight/slack span alternation when activated. The use of a BSG requires the introduction of a tensioning device able to keep the belt tension inside a safe range while preventing slippage facing the severe working conditions, see Cariccia et al. (2013). Several solutions have been proposed to satisfy this requirement, such as doble tensioners, decoupling tensioners and active electromechanical or hydraulica tensioners. With the addition of active devices, such as the BSG and complex tensioners, the intelligent BDS (iBDS) becomes a complex and challenging mechatronic system.

In this context, the present work aims to present a test rig that allows to study the BDS dynamics and power loss characteristics. Furthermore, the test rig offers major advantages over the utilization of traditional engine cells. Measurements obtained in such testing environments have a high level of uncertainty due to the uncontrollable irregularities that characterize the phiysical phenomena occuring into the ICE. The designed test rig allows the reproduction of a realistic and controllable testing environment. The use of two electric motors for the dynamic simulation of the

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Table 1. Nomenclature

$AC =$	air conditioning
$AT =$	automatic tensioner
$b =$	belt
$bp =$	transition between belt and pulley
$BSG =$	belt-starter generator
$CS =$	crankshaft
$e_{BSG/CS} =$	error of belt-starter generator and crankshaft control
$F_{pAT} =$	force applied on automatic belt tensioner
$i_{dk} =$	direct current ($k = BSG, CS$)
$i_{qk} =$	quadrature current ($k = BSG, CS$)
$IDL =$	idler
$I_{BSG/CS} =$	current on belt-starter generator and crankshaft
$I_{CScont} =$	control current on crankshaft
$J_{pi}, C_{pi}, K_{pi} =$	rotational inertia, viscous damping and stiffness of i-th pulley($i = AC, BSG, CS, IDL$)
$J_{bi}, C_{bi}, K_{bi} =$	rotational inertia, viscous damping and stiffness of the arc of contact of i-th pulley ($i = AC, BSG, CS, IDL$)
$J_{pAT}, C_{pAT}, K_{pAT} =$	rotational inertia, viscous damping and stiffness of the automatic tensioner pulley
$K_{ek} =$	electromagnetic motor constant ($k = BSG, CS$)
$L_{dk} =$	direct inductance ($k = BSG, CS$)
$L_{qk} =$	quadrature inductance ($k = BSG, CS$)
$m_{aAT}, C_{aAT}, K_{aAT} =$	mass, viscous damping and stiffness of the arm of the automatic tensioner
$M_k =$	torque applied by the motor on the k-th shaft ($k = BSG, CS$)
$M_{pi} =$	torque applied by the belt on i-th pulley($i = AC, BSG, CS, IDL$)
$M_{CS} =$	output torque from crankshaft motor
$M_{BSGact/cont/ref} =$	actual, control and reference torque on belt-starter generator
$M_{CSact/cont/ref} =$	actual, control and reference torque on crankshaft
$p =$	pulley
$p_k =$	number of pole pairs ($k = BSG, CS$)
$R_k =$	coil resistance ($k = BSG, CS$)
$R_{pAT} =$	wrap radius on automatic belt tensioner pulley
$R_{pi} =$	wrap radius on i-th pulley ($i = AC, BSG, CS, IDL$)
$T =$	belt tension
$V_{dk} =$	direct voltage ($k = BSG, CS$)
$V_{qk} =$	quadrature voltage ($k = BSG, CS$)
$\alpha_{AT} =$	wrap angle of the automatic tensioner pulley
$\theta =$	angular displacement of the pulley
$\theta_{BSGact/cont/ref} =$	actual, control and reference angular of displacement of belt-starter generator
$\omega_{BSGact/cont/ref} =$	actual, control and reference angular velocity of belt-starter generator
$\omega_{CSact/cont/ref} =$	actual, control and reference angular velocity of crankshaft pulley
$\omega_{pAC/AT/BSG/CS/IDL} =$	angular velocity of the air conditioning, automatic tensioner, belt-starter generator, crankshaft and idler pulley
$\omega_{BSG/CS} =$	angular velocity of belt-starter generator and crankshaft

BSG and the crankshaft of the ICE allows to reproduce the different operating conditions of the iBDS. In addition, it is fundamental for taking into account the crankshaft oscillations due to the overlapping of the harmonics. The harmonics are generated via the Electronic Control Unit (ECU) in a predictable and repeatable manner.
The aim of this work is to describe the design and the obtained characteristics of the belt transmission test rig, highlighting its versatility. At first the main components of the test rig are described and complete details regarding the control and monitoring system are provided. Secondly the model of the system, divided into its main components, is presented and used for the definition of the specifications of the two electric motors.

2. EXPERIMENTAL SETUP AND TEST RIG CHARACTERISTICS

The design was performed to obtain the maximum versatility and allow the test rig reproducing different kind of BDS, both for what the mounting solutions and the characteristic of the components are concerned. The aim of the present section is to give an overview of the test rig and illustrate its main characteristics.

2.1 Mechanical layout

Fig. 1 shows the geometric configuration of the test rig from the top view. The layout reproduces the setup of a real engine front end, where the BDS connects five components: crankshaft, BSG, air conditioning compressor, automatic tensioner, idler pulley. The power is transmitted by a V-ribbed belt with 5 ribs. The layout was reproduced in a horizontal plane to have a uniform distribution of the forces acting on the frame and to avoid possible bending stresses on the bearing structure. The mounting solutions of the pulleys were adopted to allow the substitution of each pulley with others of different radii or coupled with belts of different number of ribs or type. The crankshaft (1) and BSG (3) pulleys were mounted on the shafts of two BoschRexroth IndraDyn H electric motors. The crankshaft is powered with motor MSS182D-0260 and the BSG with MSS102D-0800. Their specifications are listed in table 2. The frameless configuration of the two motors and their liquid cooling allowed to design their case to obtain the best integration with the rest of the test rig. On the shaft of the two motors were mounted two equal modular magnetic encoders ERM 2984 by Heidenhain (line count 192, $1V_{pp}$ sinusoidal incremental signals, maximum rotational speed $47000 rpm$, power supply $5V_{dc}$). The angular speeds of the crankshaft and BSG pulleys are additionally monitored by means of two optical tacho sensors. These devices employ