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Thermal modeling of a hydraulic hybrid vehicle transmission based on thermodynamic analysis

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ABSTRACT

Hybrid vehicles have become a popular alternative to conventional powertrain architectures by offering improved fuel efficiency along with a range of environmental benefits. Hydraulic Hybrid Vehicles (HHV) offer one approach to hybridization with many benefits over competing technologies. Among these benefits are lower component costs, more environmentally friendly construction materials, and the ability to recover a greater quantity of energy during regenerative braking which make HHVs partially well suited to urban environments. In order to further the knowledge base regarding HHVs, this paper explores the thermodynamic characteristics of such a system. A system model is detailed for both the hydraulic and thermal components of a closed circuit hydraulic hybrid transmission following the FTP-72 driving cycle. Among the new techniques proposed in this paper is a novel method for capturing rapid thermal transients. This paper concludes by comparing the results of this model with experimental data gathered on a Hardware-in-the-Loop (HIL) transmission dynamometer possessing the same architecture, components, and driving cycle used within the simulation model. This approach can be used for several applications such as thermal stability analysis of HHVs, optimal thermal management, and analysis of the system's thermodynamic efficiency.

1. Introduction

Hybrid vehicles have become a popular alternative to conventional powertrain architectures by offering improved fuel efficiency along with various other environmental benefits. Currently, the on-road hybrid vehicle market is dominated by hybrid electric vehicles (HEVs). However, the lesser known and commercialized hydraulic hybrid vehicle (HHV) has several benefits which make it the superior technology for certain applications [1,2]. Among the benefits HHVs possess over HEVs are lower component costs, more environmentally friendly construction materials, and higher power densities throughout but especially in their energy storage media. This last characteristic is particularly advantageous as it enables HHVs to capture a much higher percentage of the kinetic energy available while braking, a regime which HEVs often struggle with due to the relatively low power density present in their batteries [3–6]. This greater capacity for recovering kinetic energy while braking makes HHVs the most effective hybrid architecture in urban environments with frequent stops and starts, and ideally suited for applications such as refuge trucks [7], and buses [8]. In contrast HEV's energy storage media has a higher energy density than HHVs, which makes certain system architectures such as plug-in HEVs viable, an approach not practical for HHVs [2]. Also, there have been several studies on hydraulic-electric synergy systems, which use advantages from both types of hybrid vehicles [9,10].

Hydraulic hybrid transmissions have been investigated by numerous researchers and institutions since the 1970's. The areas of research for HHVs include parameter design studies and the propulsion characteristics [11], energy management optimizations [12,13], control strategies for various system configurations [14], the effect of system parameters on series hybrids [15], and proposals for novel hybrid architectures [16] among many others. For thermal studies on hydraulic systems, there have been several studies in system scale like hydrostatic transmissions [17–19], and electro-hydraulic actuators [20–22]. Also, thermal behaviors of hydraulic components have been studied until recently for hydraulic units [23,24] and accumulators [25,26]. One area which has not been covered thoroughly in the past is a detailed examination of the thermal characteristics of the hydraulic hybrid system.

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The motivation behind developing a thermal model of an HHV's transmission is to gain a deeper understanding of the system's thermal performance, and key influencing factors, without relying on experimental data. This will enable HHVs to be designed more efficiently by identifying and addressing potential issues with the transmission's thermal performance prior to hardware testing. While sometimes overlooked, maintaining system temperature within an acceptable range is essential for maximizing the performance, efficiency, and longevity of HHVs. Specifically, temperature has a direct impact on oil viscosity which in turn strongly influences efficiency. If excessively high oil temperatures are present, the oil's viscosity may drop too low as to impair the load carrying ability of lubricating interfaces within the positive displacement machines resulting in excessive wear and in extreme cases catastrophic failure. Excessive oil temperature may also harm other system components such as seals and elastomeric accumulator bladders while also causing oil degradation. On the opposite end of the spectrum, low oil temperatures may negatively influence system response and lead to damaging cavitation erosion.

In this paper, a simulation model of a series HHV's transmission is suggested comprised of both a hydraulic system model, and a thermodynamic model, using a lumped parameter modeling approach. This model is then compared and validated with measurement data generated on a Hardware-in-the-Loop (HIL) transmission dynamometer possessing the same architecture and component sizes used in the simulation model. Both the simulation model and HIL test rig were controlled to track the FTP-72 driving cycle to provide a realistic sampling of driving events. A novel simulation method for capturing fast thermal transients within the hydraulic system is then proposed and explored. Finally, applications of the thermal model are described such as a thermal stability analysis of the HHV system, optimization of the packaging of hydraulic components, system cooler, and analysis of the system's thermodynamic efficiency. Though a series hybrid transmission was explored in this paper, the proposed modeling and analysis approach presented herein may be applied to a variety of HHV architectures.

2. Architecture of a series hydraulic hybrid transmission

HHV system architectures can generally be classified as either series, parallel, or power-split depending upon the way power flows through the system. For this work, a series HHV was chosen as it is a common hydraulic hybrid configuration. Additionally, it is sufficiently complex as to allow the findings to be extrapolated to the more advanced power-split architecture. Fig. 1 shows a general circuit for a series HHV.

Series hybrids consist of minimum of two positive displacement machines (hydraulic units) connected in series between the engine (unit 1) and driveline (unit 2). These hydraulic units, which function as both pumps and motors, convert power between the mechanical and fluid domains. Both units 1 and 2's physical construction is such that the volume of fluid they transfer per shaft revolution can be infinitely varied between zero and some maximum value. Thus a continuously variable transmission is formed when at least two of these variable displacement units are placed in series. A hybrid transmission is formed by placing an energy storage device in series between the energy converters. In hydraulic hybrids, energy is stored mechanically in a hydro-pneumatic accumulator where highly pressurized nitrogen gas is further compressed by additional oil entering the device. Storing mechanical energy in this manner, rather than chemically as occurs in the batteries of HEVs, is one of the principle reasons HHVs are able to rapidly store all of the kinetic energy recovered during regenerative braking.

Series HHVs may operate in several different modes while driving and braking. The process begins with unit 1 converting mechanical power from the engine into the fluid domain. This power may then be immediately converted by unit 2 to mechanical power applied to the driveline for driving, stored in the accumulator for future use, or some combination of the two. Alternatively, the entire power required by unit 2 for driving may be supplied by the accumulator. During regenerative braking, unit 2 moves over-center resulting in the direction of fluid flow reversing. Now instead of consuming fluid from the hydraulic system and functioning as a motor, unit 2 begins pumping fluid into the hydraulic system. In this way, unit 2 converts mechanical power from the driveline into fluid power enabling the vehicle's kinetic energy to be recovered for future use. Table 1 summarizes the principle modes of operation for a series HHV. Most all of these modes are seen to some extent in both the experimental measurements on the test rig, and the simulation detailed in this study.

3. Hydraulic and thermal system modeling

Modeling the HHV's thermal characteristics began by first constructing the hydraulic system model. The choice to base the thermal analysis on a hydraulic simulation model, rather than simply using measured data, was twofold; first a hydraulic simulation model provided greater resolution of dynamic system characteristics than were practical to measure on the transmission, and second the thermal modeling approach detailed in this work is intended to proceed system testing in which case no measurement data would be available. However, for this work the hydraulic simulation model was partly constructed using measurement data in order to aid in developing and validating the thermal system model which was this investigation's principle goal. Once complete the hydraulic system model was ran over the FTP-72 driving cycle while pressures and flow rates passing through each component were recorded. Next the system was divided into a series of thermodynamic control volumes which were then described by lumped parameter thermal models. From here the results from the hydraulic system model were fed into the thermal model and used to predict individual control volume temperatures. Finally, results from the thermal model were compared with measurement data and then used for further thermal analysis.

3.1. Hydraulic system model

A lumped parameter hydraulic system model was built in MATLAB Simulink using accepted and previously validated modeling techniques. Governing equations were included for those components which could be accurately described analytically, while empirical models, based on steady state measurements, were used to describe the positive displacement machine's loss characteristics.

Fig. 2 shows the block diagram of the dynamic model of the powertrain. The author used the same approach for the dynamic model of the powertrain with a model of engine dynamics, vehicle dynamics, and a dynamic model including nonlinear loss model of the hydraulic hybrid subsystem. More details about the dynamic system model shown in Fig. 2 can be found in Refs. [27,28]. In interest of brevity, only those equations directly related to the flows and pressures of the hydraulic system are included in this paper, in Eq. (1) through Eq. (10).

Flow rates in and out of the hydraulic units while pumping are described by the following equations [29]: