

Electric Water Cooling Pump Sensitivity Based Adaptive Control

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ABSTRACT

With the trending electrification of vehicle accessory drives brings new control concepts useful in many cases to optimize energy management within the powertrain system. Considering that direct engine drives do not have as much flexibility as independent electric drives, it is apparent that several advantages are to be expected from electric drives. New developed high efficient electric drives can be implemented when considering many vehicle sub-systems. Combinations of continuous varying and discrete flow control devices offer thermal management opportunities across several vehicle attributes including fuel economy, drivability, performance, and cabin comfort. Often new technologies are integrated with legacy systems to deliver maximum value. Leveraging both electrical and mechanical actuators in some cases presents control challenges in optimizing energy management while delivering robust system operation. In this paper Electrification of Water Cooling Pump has been considered where Sensitivity Based Adaptive Control has been investigated because of the simplicity of this methodology resulting in lower computational burdens and its applicability to many engineering projects. Sensitivity Based Adaptive Control has lead us to opinion that Renaissance of this method may soon come.

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I. INTRODUCTION

Automotive Thermal Management system has high potential to be optimized for better: Fuel Economy, Climate, Packaging, as well as Vehicle Performance. Thermal Management is complex interdisciplinary trade-offs between mechanical, thermal, fluid dynamics, and control systems technologies. Low fidelity plant dynamic model results in large uncertainties and time delays leading to the reliance of vehicle data for correlation under different operating conditions. Hardware in the Loop (HIL) simulation offers a low cost alternative to vehicle testing for control and hardware development. A powertrain cooling system incorporating an electrically driven coolant pump has been investigated. As belt driven mechanical coolant pumps are relatively low consumers of parasitic power, they over deliver coolant flow at nominal conditions keeping the powertrain from operating at its most efficient thermal state.

Electric motor control is required to emulate the mechanical coolant pump's operation. To bring realistic operation with the use hardware in the loop lab system, Coolant pump speed has been recorded during various vehicle driving events. To mitigate as many as possible uncertainties some of the associated with thermostat and thermal delays the need for simple engineering application oriented method for adaptive tuning has resulted in the Sensitivity Based Adaptive Controller (SBAC) investigation. Frequency domain analysis and fixed parameter controller design for plants without uncertainties may need to be the first step of the SBAC design process.

This first step can be used for appropriate pole zeros placement, for the order, relative degree of the transfer function, and low frequency phase delays adjustments. Plant parameters variation, and uncertainties analysis seems to be next step of the design. In some more complex design solutions, inner control loop can be used to provide possibility for simple PI adaptive controller implementation. If this systematic approach is used, it may results in the need for just one or two controller parameters adjustments, while providing compensation for a majority of the plant parameters variation. In this systematic design approach (SBAC) can produce excellent results for a wide range of engineering applications.

SBAC was used in Electro-Hydraulic Power Assist Control System as presented during an SAE conference [3]. Electronic Throttle Control was also investigated with the SBAC control methodology [4]. An Electro-Magnetic Actuator for a Cam-less Engine, controlled with the SBAC methodology, augmented with some nonlinear control features, has performed outstanding levitation control to achieve soft landing objective within non-linear magnetic field resulting in better performance than with feedback linearization method [5].

In this paper, SBAC method is used to control of a water coolant pump for engine thermal management system. This cooling system is briefly explained in [section 2](#) along with the consideration behind the derivation of Control Design Objective. In [section 3](#) a simple linear control oriented plant model is derived from basic principles with the simplification of high order plant model including only dominant plant dynamics. The sensitivity method background is briefly

presented in section 4 where the Sensitivity Filter is derived and SBAC controller is developed. Simulation results are shown in section 5 while section 6 presents experimental results.

The conclusion of this paper, in section 7, includes discussion of obtained results and some selected examples where SBAC is implemented often with combination with some other control methods.

II. BREF DESCRIPTION OF ENGINE COOLING SYSTEM

A lab's HIL cooling system layout is represented in Figure 1. External to the pump, multiple coolant loops Figure 1 use electric flow valves to source hot coolant during engine warm-up and cool coolant for transmission cooling. In addition to these valves, the wax-motor thermostat also introduces varying loads to the flow circuit (Figure 2) the pump must take into account when targeting a desired flowrate through pump speed control.

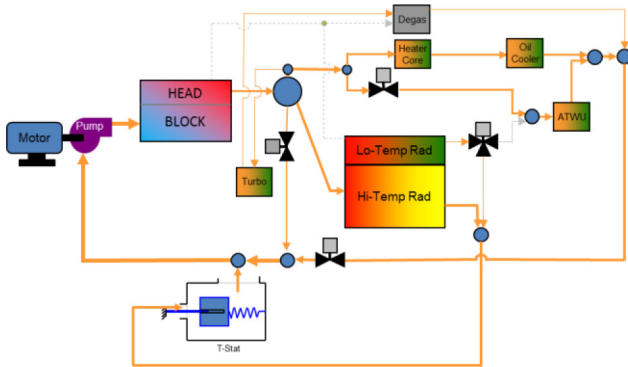


Figure 1. Hardware in the loop cooling system lab set up

The pump non-linear characteristic (Figure 2) and motor assembly (Figure 3) also exhibits a dead zone and challenges with fluid properties entrained with vapor bubbles. Two phase fluid has an effect on fluid bulk modulus adversely influencing cooling efficiency. Pump/Motor friction torque inversely scales with temperature of the assembly. High temperatures reduce the damping coefficient and result in increasing mechanical tolerance, consequently steady state pressure value is changing during operation.

Furthermore, pump characteristic shows that this is not positive displacement pump. To provide the required flow for cooling system, a flow demand setpoint is required. For the hardware in the loop lab development set up, it has been decided to provide this by emulating vehicle driving event recording some selected data during the specific drive events and duplicating these conditions in the lab environment.

Resolving precise duplication of these events with the use of appropriately controlled hardware in the loop in presence of all noise factors is the goal of this project. So the project is divided in two parts. The first part addresses the development of in lab hardware in the loop cooling system where engine is not available, while second part focuses on closed loop control system. This publication is focusing on the emulation of a driving event (engine speed) for a HIL lab system.

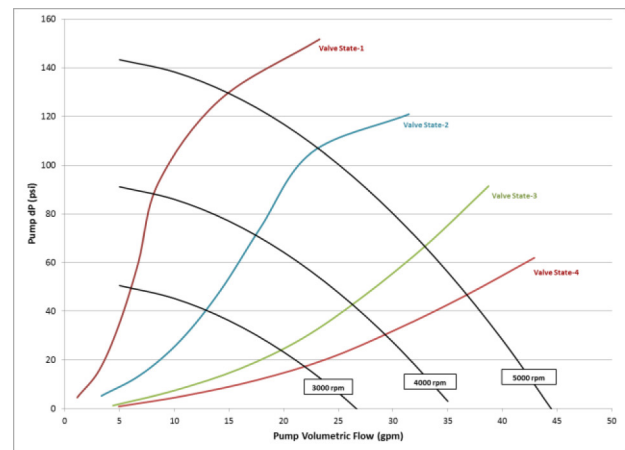


Figure 2. Cooling water pump Flow/Pressure characteristic

To ensure the lab environment delivers the most accurate emulation of in-vehicle operation, appropriate selection of power electronics has been conducted for electric driven cooling pump for lab set up.

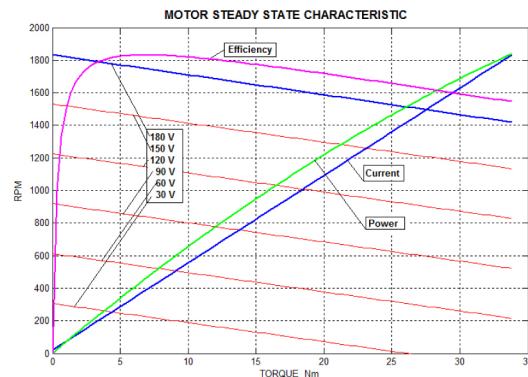


Figure 3. Electric motor Static Characteristic

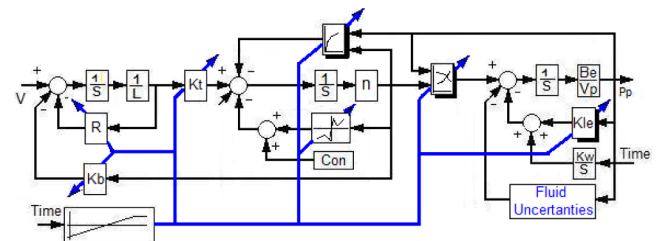


Figure 4. Electric driven cooling pump simplified model presentation

The emulation of recorded driving event engine speed needed to be duplicated for hardware in the loop system in the lab. Selection of the motor drive is important here for control bandwidth achievement, needed to track down recorded speed event. For this reason motor speed measurement was available for closed loop control. Plant parameters variation and some noise factors have been represented in Figure 4 by slanted lines across the corresponding blocks. In spite of presence of many described uncertainties SBAC performance is investigated with following goals.

Control Design Objectives

Pump speed control system has to provide good tracking and disturbance rejection properties in spite of unknown disturbances, non-linear plant nature, and all changes associated with temperature, friction, torque variations,... resulted in demands listed below:

- The engine speed profile from a vehicle drive cycle to be duplicated on the test bench reproducing coolant flow transients of the mechanical water pump in a lab environment.
- Direct coupled motor and pump drives is required to have pump speed accuracy within $\pm 3\%$.
- The control system needs to be self-calibrating in order to reduce calibration effort (Figure 5).

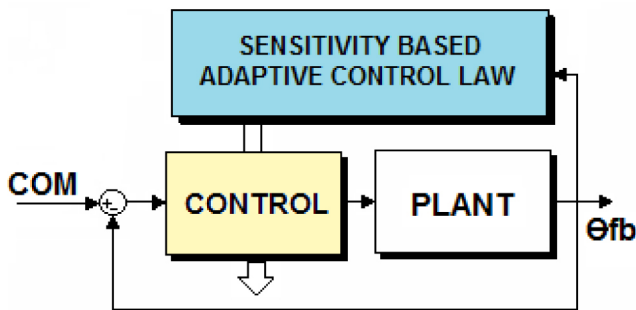


Figure 5. Self calibration control system block diagram

On the other hand for in vehicle application the control system needs to guarantee performance over the life of the system through on-line adjustment (adaptation) of controller parameters. In addition to these basic functions the diagnostic system should be able to detect abnormal events and to send warning signal in the event that service is needed.

III. CONTROL ORIENTED MODEL

A simplified control oriented linear model of system dynamics is represented in Figure 6. In the example, a non-positive displacement pump is driven by electric motor.

Simplified control oriented system model in Figure 6 is obtained with description of cooling system as a volume, with pump flowing in, disturbance flow flowing out of the volume as it is formulated bellow. This model considers only the dominant system dynamics determined by investigation of effective fluid bulk modulus, system compliance, pump's leakage and friction linearization.

$$L \frac{di}{dt} + R \cdot i = V_{in} - K_b \cdot \omega \quad (8)$$

$$J_m \cdot \frac{d\omega}{dt} = T_m - T_L - T_{FR} \quad (9)$$

$$T_m = K_t \cdot i \quad (10)$$

$$T_L = D_p \cdot P_p \quad (11)$$

$$Q_p - Q_{INJ} - Q_{le} = \frac{V_p}{\beta_e} \cdot \frac{dP_p}{dt} \quad (12)$$

Where:

L Is motor inductance

R Motor resistance

i Motor Current

V_{in} Input Voltage

K_b Back EMF coefficient

ω Motor / pump speed

J_m Motor and pump inertia

$T_m = K_t \cdot i$ Motor generated torque

K_t Torque constant

$T_L = D_p \cdot P_p$ Torque load

D_p Pump displacement

P_p Feedback pressure

$Q_p = D_p \cdot \omega$ Pump flow; D_p (m^3/rad) pump displacement

Q_{INJ} Injector flow emulated with solenoid valve.

$$Q_{le} = K_{le} \cdot P_p + \frac{K_w}{s}$$

Leakage flow where:

K_{le} Leakage coefficient

K_w Wear flow coefficient

V_p Equivalent DI volume

β_e Fuel effective bulk modulus

In Figure 6 the disturbance flow is not directly included although the final Matlab model and hardware set up do have a disturbance flow emulating the rest of the Cooling system represented in Figure 1.