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Automotive drive by wire controller design by multi-objective techniques

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Abstract

The presence of flexibility in automotive drivelines, coupled with nonlinear elements such as gear lash leads to the presence of an undesirable oscillatory acceleration response to step changes in throttle input. This oscillation is generally low frequency (approximately 2–5 kHz) and can be of sufficient amplitude to cause driver discomfort and subjective disappointment with the driveability of the vehicle. A pole placement controller is developed for a "drive-by-wire" (electronically operated throttle) system, with the objective of reducing or eliminating the oscillatory response. The results of an existing factorial study are used to calculate the required number of poles. Due to the inherent nonlinearities present in the system and the various constraints which must be applied to the controller design, the polynomial values for the pole placement controller are selected by the application of multi-objective optimisation. The controller is shown to achieve excellent performance and robustness to parameter variations and operating conditions.

Keywords: Pole placement; Drive by wire; Multi-objective optimisation; Automotive; Driveability

1. Introduction

This paper describes the development of a longitudinal oscillation controller via a low-cost electronic throttle actuator and microcontroller. A feasibility study had been carried out on a vehicle fitted with the electronic throttle system (Stewart & Fleming, 2001, 2002) to confirm the performance potential of such a system. Drive by wire applications for the replacement of the conventional cable link between the throttle pedal and the throttle body are now the focus of development by many major automotive manufacturers. Direct fitting of a stepper or permanent magnet servo motor to the spindle of the throttle butterfly plate allows electronic throttle pedal (fitted with a potentiometer) control via a microcontroller or DSP. High-performance current control algorithms can be implemented around the throttle actuator (Stewart & Kadirkamanathan, 2001) to facilitate a fast acting mechanical response. Other control systems have been designed (Rossi, Tilli, & Tonielli, 2000) to ensure fast and accurate tracking of the pedal demand signal, and have been shown to possess robust operational characteristics. Currently, electronic throttle control and variable valve timing are the most powerful tools in the pursuit of "driveability" (the difference between the driver's perceived required performance and the actual performance of the vehicle), (Azzoni, Moro, Ponti, & Rizzoni, 1998; Stefanopolou, Cook, & Grizzle, 1995). A torque controller is designed and implemented in this paper to shape the vehicle response to the first torsional mode of the driveline. The initial requirement is to damp the oscillations generated by throttle "tip-in" (step throttle input). The control system acts as a dynamic mapping between the accelerator pedal and the throttle butterfly angle, allowing the amount of torque developed by the engine to be closely controlled to improve the driveability of the vehicle. The design problem in this case is multivariable, being described by a five component objective function:

- minimise rise time,
- minimise overshoot,

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- minimise settling time,
- minimise steady-state error,
- minimise delay.

Control analysis and design for this automotive system is complicated by a various factors. There are a number of nonlinearities present, such as backlash in the gearbox, a tyre model which varies nonlinearly with load, and a nonlinear clutch response. Also, a significant time varying lag is present between throttle actuation and torque production due to manifold fill delay. Finally, a nonlinear engine torque-speed mapping exists (Kienke & Nielsen, 2000). It has been found (Stewart & Fleming, 2001), that a set of throttle angle trajectories exist which successfully suppress the vehicle longitudinal acceleration oscillations. The application of the response surface methodology derived a second-order approximation surface of the acceleration response in order to design a simple feedforward controller. In this manner, it was verified that the oscillatory response can be adequately controlled by electronic throttle, however a closed-loop control system was still to be designed. Experimental open-loop data was available from a test car which was fitted with a data acquisition system including a longitudinal axis accelerometer. A V6 engined saloon vehicle was loaned for the purpose of analysis, design and testing. A systematic excitation of the driveline was made experimentally on the vehicle by performing step demands in all gears at discrete points throughout the effective engine speed range of the vehicle, allowing the validation of a dynamic model which had been developed in *Matlab and Simulink*. A representative experimental response is shown in Fig. 1. Particular note should be taken of the time delay between step demand acceleration response. Open-loop study (Stewart & Fleming, 2001) indicates that the control action necessary to reduce the oscillation has a time period similar to the response lag, rendering the delay a significant one. Also the under-damped acceleration profile which can lead to driver dissatisfaction with the perceived smoothness of the overall vehicle response.

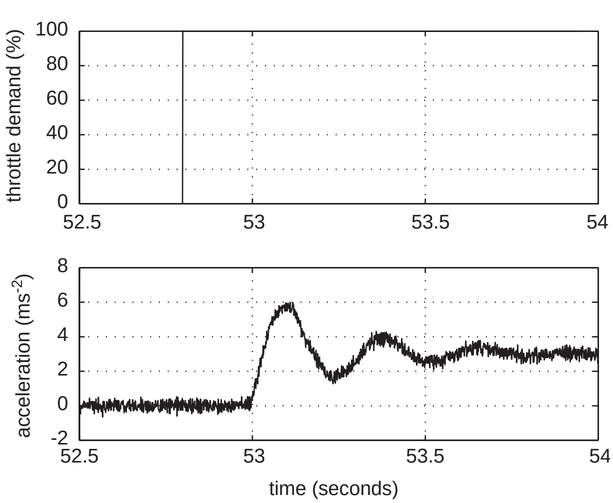

Fig. 1. Vehicle acceleration step response in second gear at 10 ms^{-1}.

Cancellation of driveline oscillations has been studied using several methods. Generalised optimal control theory has been applied (Best, 1998), however, the oscillation in the controlled acceleration response was found to be still significant because of the presence of lash nonlinearities. Fuzzy control has been proposed (Willey, 1999), yet stability was found to be a major concern. Pole placement strategies have been used (Richard, Chevrel, de Larminat, & Marguerie, 1999), but acceleration response still remained open to considerable improvement, due to the difficulty of ascertaining the controller polynomial values. This does suggest that progress might be made if the correct controller values could somehow be chosen.

The objectives of the controller design will be to reduce or eliminate both the overshoot and subsequent oscillation of the vehicle acceleration during throttle step demand, while attempting to maintain the open-loop acceleration rise time. The controller design can be best assessed in 2nd gear as this gear demonstrates the worst-case oscillations. The pole placement approach will be further developed by using a multi objective approach to choose the controller polynomial values. There are a number of novel aspects associated with this work. The results of a factorial experimental study are analysed and an approximation derived, to determine the number of poles which it is necessary to place to achieve successful control. A closed-loop controller with performance which fulfills a demanding cost function has been designed, which compares favorably with previous designs described in the literature. A method of varying the system parameters such as lash and loading has been introduced during the iterative design process to derive a robust controller.

2. Pole-placement design

The objective of the pole-placement design method is to design a closed-loop system with specified poles and thus the required dynamic response. The measured variable for feedback considered here is provided by a longitudinal accelerometer, as the manufacturer concerned will make such a sensor available in production should the derivation of acceleration from the velocity signal prove inaccurate or too noisy. The resulting characteristic equation will determine the features of the system, such as rise time, overshoot and settling time. The system model and its linear controller can be expressed, respectively, as

$$A(s)y(s) = B(s)u(s), \tag{1}$$