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Precise piston trajectory control for a free piston engine

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ABSTRACT

A free piston engine removes the mechanical constraint on the piston motion by eliminating the crankshaft. The extra degree of freedom offers many advantages for reducing fuel consumption and emissions. Nevertheless, stability and robustness of the engine operation has been affected in the meantime. To ensure smooth engine operation, an active motion controller, which utilizes robust repetitive control, was developed previously to regulate the piston motion of a hydraulic free piston engine to track pre-defined trajectories. However, the long piston stroke length, high operating frequency and system nonlinearity impose challenges to precise piston motion control. Therefore, feedforward controllers are investigated in this paper to complement the repetitive control to further improve the tracking performance. The first feedforward design involves the inversion of a linear plant model that describes the dynamics of the engine operation, and the second design is based on the flatness approach, which involves the inversion of a nonlinear model of the system. The two feedforward controllers are designed and implemented on the free piston engine. The experimental and simulation results demonstrate the effectiveness of the proposed control under various operating conditions and reference piston trajectories.

1. Introduction

As an alternative of the conventional internal combustion engine, the free piston engine (FPE) offers the ultimate engine operation flexibility by eliminating the crankshaft. Instead of mechanical power output, the engine can be combined with linear alternators or linear hydraulic pumps to produce electricity or fluid power. The FPE design drastically reduces the complexity of the machine as well as the frictional loss. Most importantly, the design allows us to alter the compression ratio during the engine operation. This unique feature enables multi-fuel operation, as well as the implementation of advanced combustion strategies, such as homogeneous charge compression ignition (HCCI), that improves the engine efficiency and reduces emissions. Nevertheless, the extra degree of freedom reduces the robustness of the engine operation. By removing the crankshaft, the mechanism that ensures consistent piston motion is dismissed as well. Therefore, difficulty in achieving robust engine operation has been the major technical barrier for mass production of this technology.

Several FPE motion control strategies have been published in the literature. Among them is the pulse pause modulation (PPM) control which has been implemented by a number of researchers on single-piston and opposed-piston FPEs (Achten, Van Den Oever, Potma, & Vael, 2000; Hibi & Ito, 2004; Zhao, Zhang, Huang, Zhao, & Guo, 2012). The main idea is to utilize hydraulic circuits as a bounce chamber which holds the piston at its bottom dead center (BDC) to achieve identical piston motion of each engine cycle. A flow control valve is used to adjust the waiting period between the consecutive cycles. Therefore, the output flow rate of the engine can be changed in real time by adjusting the timing of the flow control valve. Due to the identical engine cycles, the PPM control produces nearly constant efficiencies across the engine power output range. However, this approach is only applicable to the single-chamber FPE architectures where continuous operation is not required. Johansen, Egeland, Johannessen, and Kvamsdal (2002) developed a control system for a FPE powered turbine with air bounce chamber. The control system utilizes PID controllers to regulate the location of the top dead center (TDC) by adjusting the air mass in the bounce chamber, while the location of the BDC is controlled by adjusting the fuel injection quantity. Stable engine operation was achieved at a specific operating condition with the proposed control. Mikalsen and Roskilly (2010) investigated the motion control of a FPE linear generator with air bounce chamber. A pseudo-derivative feedback (PDF) control maintains the TDC and BDC at the reference by adjusting the fuel injection quantity and air mass of the bounce chamber. In addition, a feedforward control modifies the fuel quantity and air mass according to the load. Simulation results show that the PDF

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plus feedforward control have a better transient performance than PID control when handling load change. Researchers from Toyota Central R&D Laboratory (Goto et al., 2014; Kosaka et al., 2014) have developed a piston motion control for a FPE linear generator. The motion control consists of a PID control and a gain scheduling map to alter the load. The experimental results demonstrate stable engine operation at a specific operating point with the control scheme. An energy-balance based feedback control strategy, which adjusts the fuel injection quantity each cycle by calculating the energy flows in and out from the combustion chamber, was proposed by Tikkanen and Vilenius (2006) for a dual-chamber FPE. Simulation results showed that the control strategy was able to produce stable energy operation at various operation points, but it does not address the engine stall issue of the FPE in the case of a misfire.

Besides the limitation of being applicable to only a specific FPE architecture, many of the existing control strategies rely on calibration to be effective. However, the complex interactions between the gas dynamics and the load in real time make the calibration a tedious task, and the resulting controllers are sensitive to variation of the operating conditions and disturbances. To address the challenge, an active piston motion controller, which seamlessly coordinates the combustion and the load so that piston follows prescribed reference trajectories, was designed (Li, Sadighi, & Sun, 2014). Since the controller acts as a crankshaft but not an actual mechanism, it was named the virtual crankshaft which is implemented digitally on the FPE. Optimal trajectories can be designed for the FPE under various operating conditions, so that not only does the virtual crankshaft guarantee a stable operation, but it also regulates the engine to run at maximum efficiency. Due to the periodic nature of the piston motion, the virtual crankshaft design employs robust repetitive control which is capable of tracking any periodic reference signals. The virtual crankshaft has been successfully implemented on a hydraulic FPE system for engine motoring and firing tests.

It is obvious that precise motion control is necessary in order to control compression ratio and optimize engine operation in real time. While most of the electrohydraulic actuation systems are capable of tracking references less than 10 Hz with relatively small stroke length (Mohanty & Yao, 2011; Sohl & Bobrow, 1999; Sirouspour & Salcudean, 2001; Yao, Bu, Reedy, & Chiu, 2000), the operating frequency of the FPE is 25 Hz with 50 mm piston displacement. The nonlinearity of the FPE system is more prominent compared to a typical hydraulic system due to the nonlinear dynamics of the hydraulic system and the combustion chamber, which is caused by the compression and expansion of the in-cylinder gas mixture. Furthermore, to achieve precise tracking in most of the applications, the actuation force is generally much larger than the resisting force. However, in our case, the resisting force caused by piston inertia and combustion chamber pressure is on the same level with the hydraulic actuation force, which is limited by the maximum operating pressure of the hydraulic components. These combined factors mentioned above make the precise motion control of the FPE a challenging task even with the robust repetitive control. To assist the existing motion control and further improve the tracking performance, two feedforward control designs are proposed in this paper. The first feedforward design involves the inversion of a linear model that describes the dynamic of the engine operation. The second design is based on the flatness approach, which involves the inversion of a nonlinear model of the hydraulic FPE system.

The most important procedure in a linear model inversion, besides inverting the stable poles and zeros, is the inversion of the unstable zeros. A number of techniques have been developed to minimize the effect of unstable zeros on the linear model inversion. Among these is the zero phase error tracking (ZPET) scheme (Shi & Stelson, 1990; Tomizuka, 1987, 1989) which is a noncausal feedforward compensation that has the effect of completely eliminating any phase error. However, with the plant model of the hydraulic FPE, employing the ZPET scheme induces high gains in the frequency range of the engine operation. Therefore another scheme which utilizes series expansion for the model inversion (Gross, Tomizuka, & Messner, 1994) is investigated in this paper.

The nonlinear feedforward control in this paper is designed based on the flatness approach. The property of flatness of a system can be extremely useful when tracking trajectories: from the reference trajectories, states and control inputs can be calculated directly, without integrating any differential equation, in terms of the reference and a finite number of its derivatives (Fliess, Levine, Martin, & Rouchon, 1995). Therefore, flatness-based control is widely used from motion planning to stabilization of reference trajectories. Many of the realistic models are flat, such as aircrafts (Martin, 1996), motors (Chelouah, Delaleau, Martin & Rouchon, 1996) and clutch systems (Horn, Bamberger, Michau, & Pindl, 2003). Kock and Ferrari (2011) proposed a flatness-based feedforward plus feedback (PID and PD repetitive) control of a hydraulic actuator, which is utilized for a FPE test stand, to track high frequency and high amplitude signals. However, the gas dynamics was treated as an external input and the experimental validation was conducted in the absence of combustion chamber.

The two feedforward controls are implemented on the hydraulic FPE together with the robust repetitive control. The tracking results of various piston trajectories are compared and discussed. The rest of the paper is organized as follows: Section 2 describes the hydraulic FPE system. Section 3 presents the feedforward control design procedure. In Sections 4 and 5, respectively the experimental and simulation results of the controllers are compared and discussed. Section 6 concludes the paper with a summary and topics of future work.

2. System description

The hydraulic FPE has an opposed-piston opposed-cylinder (OPOC) design which offers the highest power density and scavenging efficiency among the FPE architectures. This is a 1.2 L engine with 50 kW (67 HP) maximum power output and it is designed for mobile applications such as hydraulic hybrid vehicles and excavators. The engine is equipped with direct fuel injection system and is targeted for advance combustion strategies such as the homogeneous charge compression ignition (HCCI). Since there is no mechanical output, the FPE can be designed in a modular fashion. Specifically, we can combine several FPE modules which do not need to operate at the same time or locate at the same space. They can be turned on and off according to the power demand so that the overall cycle efficiency can be significantly improved.

A photograph of the hydraulic FPE and its schematic diagram are shown in Fig. 1. The two combustion chambers, that are located on the left and right sides of the engine, are connected by two piston pairs. The two piston heads reciprocate inside the combustion chambers in opposite direction while generating fluid power via the hydraulic block in the middle of the engine. Three hydraulic chambers are embedded in the hydraulic block with two small chambers connected with the outer piston pair and a larger chamber connected with the inner piston pair. A four-way three-position servo valve is installed on top of the hydraulic block for piston position control. Left side of the hydraulic chambers are connected to the high pressure (HP) or low pressure (LP) accumulators through the servo valve and two pairs of check valves, whereas right side of the hydraulic chambers are all interconnected through hydraulic passages. To compensate the position