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Optimal trajectory operation of a cogging torque assisted motor driven valve actuator for internal combustion engines☆

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ABSTRACT

Cogging torque assisted motor drives (CTAMD) are a novel electromechanical valve actuation (EVA) technology for internal combustion engines that have a compact size and do not require conventional valve springs. Despite using an unoptimized position trajectory, the CTAMD was shown to produce the smallest ohmic loss at 6000 RPM when compared with other EVA systems found in literature. This paper presents a minimum-energy trajectory for a CTAMD and validates its improvements. First, an ohmic loss model for the CTAMD is formulated. Next, the optimized trajectory is generated through the use of the Nelder–Mead direct search algorithm. The optimized trajectory is then tested on a previously studied experimental CTAMD setup. Finally, the results of the experiments are analyzed to determine the performance improvements and practical advantages of the optimized trajectory. The optimized trajectory enables a further reduction of ohmic loss and reduces the number of MOSFETs required to drive the CTAMD by 75%.

1. Introduction

The robust nature and cost-effectiveness of the internal combustion (IC) engine allow it to continue to thrive despite increased interest in alternative fuel vehicles. However, increasing demand for cleaner engine technology is forcing IC engines to evolve. Variable valve actuation (VVA) is an emerging technology that promises to improve the performance and lower emissions of IC engines while decreasing fuel consumption by up to 20% [1–3].

To operate efficiently, an engine must have its air intake and exhaust stringently controlled. Unfortunately, the fixed geometry of a camshaft does not allow an engine to aspirate optimally under all operating conditions. Conventional camshafts are optimized for a single torque-speed combination and therefore suboptimal performance is obtained during transient engine operations. Electromechanical valve actuation (EVA) is a VVA method that aims to replace the camshaft in a conventional IC engine with electromagnetic actuators and allow independent control of the intake and exhaust valves. With independent valve control, fully flexible valve lift and timing can be achieved, allowing optimal engine performance to be attained for all engine speeds. Furthermore, independent valve control allows for new combustion methods to be implemented, such as homogeneous charge compression ignition [4].

For an EVA system to be considered a suitable replacement for a camshaft, it must be able to meet the minimum performance characteristics of a camshaft, such as valve transition time, seating velocity and valve lift. Furthermore, it is important that the design is compact in order to fit under the valve cover of a small engine. For an elegant and cost effective implementation, an EVA method needs to minimize its impact on surrounding vehicle subsystems such as the cooling or charging systems.

Numerous examples of EVA systems can be found in literature that use of a variety of actuators and techniques. Unfortunately, these designs are unable to meet all of the requirements for a robust and elegant EVA system. Solenoid EVA systems tend to be relatively compact, but they can only generate forces in a single direction and therefore require a return spring or a large dual-actuator pull-pull configuration [5–10]. The nonlinear force characteristics of solenoids make them hard to control and they typically have poor valve seating velocities [7]. Furthermore solenoids require large energy expenditures when holding a valve open against a valve spring [9]. Voice coils are another type of actuator investigated commonly in literature [11,12]. This type of actuator is relatively compact and has linear force characteristics, but suffers from the lowest energy efficiency among EVA actuators and

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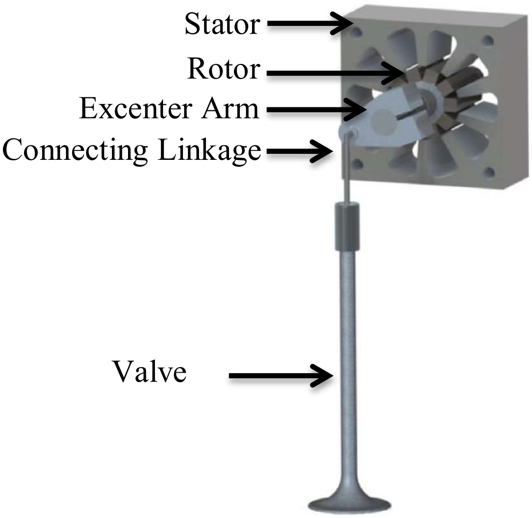

Fig. 1. A diagram of the CTAMD actuator.

exceeds the frictional loss of a conventional camshaft [11]. Voice coil EVAs cannot be easily integrated into an engine as they require active cooling and would have a substantial impact on the charging system of a vehicle [11]. Motor drives are another commonly studied EVA method [13–15]. Motor drives tend to have linear torque characteristics and are typically the most energy efficient type of actuators found in literature. However, these actuators tend to be the largest type of EVA actuator as they often require complex external spring systems to perform kinetic energy recovery of the valve. They also often use large mechanisms to couple the rotor to the valve [16]. These large external components make it infeasible to integrate motor drives under the valve cover of a small engine.

Recently a novel cogging torque assisted motor drive (CTAMD) was experimentally shown to meet the aforementioned requirements [17]. The CTAMD is a brushless DC motor that has a similar topology to permanent magnet stepper motors (PMSM) [18]. This CTAMD system differs from common PMSMs since its design is optimized for a large cogging torque by using a salient pole design with strong and thick permanent magnets and thin-tipped stator teeth with no laminate skewing [19]. These unique features of the CTAMD are shown in Fig. 1. Typically, constant or smooth sinusoidal output torque is desirable for motor applications and therefore cogging torque is minimized [20–23]. However, for EVA applications, cogging torque allows kinetic valve energy to be recovered in the form of a magnetic field which removes the need for mechanical valve springs [17]. This allows the CTAMD system to be much more compact and mechanically simple compared to other spring-assisted motor drives. Furthermore, cogging torque can be strategically utilized over 180 electrical degrees to sum with the electromagnetic torque constructively, producing large peak output torque and fast valve transition times [19]. Even though the prototype tested in [17] has a poor winding fill factor, it is still able to achieve the lowest ohmic loss when contrasted with the aforementioned EVA systems found in literature operating at a 6000 RPM benchmark speed.

When the CTAMD system was previously investigated, the energy-optimal trajectory for the three-phase BLDC motor derived in [13] was applied to the CTAMD [17]. Unlike a three-phase BLDC motor, the CTAMD has both sinusoidal electrical torque and cogging torque [24]. Naturally, a non-constant output torque indicates that the trajectories used in [17] and [19] are suboptimal and should be optimized to lower the ohmic loss of the actuator.

In literature, there are many methods to generate optimal energy trajectories for servo motor applications [25–30]. However, these methods do not account for cogging torque in their models. Since a CTAMD exhibits nonlinear behavior, an optimal trajectory cannot be obtained with simple derivative optimization techniques. One example in literature obtained an optimal energy trajectory for a nonlinear solenoid using the Nelder–Mead algorithm [31]. Naturally, the Nelder–-Mead algorithm can also be applied to the nonlinear CTAMD system.

This paper presents a minimum-energy trajectory for a CTAMD. The Nelder–Mead simplex algorithm is demonstrated as one possible technique to generate the optimal trajectory. The optimized trajectory is analyzed experimentally and the measured energy loss is contrasted with the energy loss of the unoptimized trajectory provided in [17]. Furthermore, the practical advantages enabled by the optimized trajectory are explored.

The content of this paper is divided into five sections. In Section 2 the model of the CTAMD is discussed. Section 3 describes the optimization performed and Section 4 presents the experimental results obtained by using the optimized trajectory. Finally, Section 5 draws upon the experimental findings to form a conclusion.

2. Model for the CTAMD

2.1. Actuator specifications

The same actuator that was validated in [17] is used throughout the experimentation in this paper. The details of and motivations behind the actuator design are discussed in [19]. Important actuator physical parameters and electrical parameters for the optimization problem of interest are listed in Table 1 [17].

The optimization and experimental validation discussed in this paper adhere to the same constraints mentioned in [17], which require the CTAMD system to fully emulate the operational characteristics of a typical four-cylinder, 16-valve, four-stroke IC engine with a camshaft. These operational characteristics include being able to perform 8 mm valve lifts in under 3.5 ms measured between 5% and 95% of total valve lift, which equate to a redline engine speed of 6000 RPM [13,16]. Furthermore, at redline speed, the CTAMD system needs to be able to maintain valve seating velocities under 0.3 m/s, which is common for a typical IC engine [32,33].

2.2. Performance modeling

If friction is neglected, the required input torque to accelerate the rotor and valve, T_{req}, can be defined using the mechanical model shown in (1), where $\ddot{\theta}_m$ is the angular acceleration.

$$T_{req} = (J + mr^2)\ddot{\theta}_m \tag{1}$$

The required input torque must be supplied by the cogging toque, T_c, and electrical torque, T_{elec}, of the actuator as seen below.

$$T_{req} = T_c + T_{elec} \tag{2}$$

The single-phase design of the CTAMD creates a sinusoidal electrical torque described by (3), where θ_e is the angular rotor position in electrical degrees, and I is the winding current.

$$T_{elec} = K_t I \sin(\theta_e) \tag{3}$$

Table 1
Important modeling parameters.

Symbol	Parameter	Value
J	Rotor inertia	8.75 kg/mm^2
m	Valve mass	40 g
r	Excenter arm radius	12.9 mm
p	Magnetic poles	10
K_t	Electrical torque constant	34.5 mN m/A
K_c	Cogging torque constant	1.4 N m
R	Winding resistance	67.8 mΩ
L	Inductance	129 µH