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Research paper

A balancing cam mechanism for minimizing the torque fluctuation of engine camshafts

Deng-Ying Lin, Bo-Jiun Hou, Chao-Chieh Lan*

Department of Mechanical Engineering, National Cheng Kung University, No. 1, University Road, Tainan City 701, Taiwan

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ABSTRACT

This paper presents the design and experiment of a balancing cam mechanism to minimize the torque fluctuation of engine camshafts. Torque fluctuation of rotary machines causes unwanted vibration that would impair their performance and reliability. The combination of inertia, driving, and resistive torque fluctuations on engine crankshafts and camshafts is the major source of vehicle vibration. For camshafts, the magnitude of resistive torque fluctuation is more substantial than that of inertia torque fluctuation at low to medium speeds. While previous methods focused on suppressing or isolating vibration motion from engine to chassis, the proposed method seeks to directly reduce the torque fluctuation on engine shafts. The balancing mechanism consists of a cam, rocker, and spring. Given a resistive torque curve of a camshaft, the cam profile can be synthesized such that the output balancing torque cancels with the original resistive camshaft torque. Thus the camshaft will statically generate zero output torque. Based on a derived camshaft torque model, a design process of the cam profile is presented. The effect of inertia torque at various speeds is compared with the balancing torque. Finally, a prototype and its associated experiments are presented to demonstrate the torque balancing performance.

1. Introduction

Vibration of rotary machines causes increased wear, unpleasant noise, and imprecise motion that would reduce their performance and reliability. Rotary machine vibration is primarily due to the oscillating rotational speeds that are created by periodic torque fluctuations on rotating shafts. As shown in Fig. 1, torque fluctuation can be categorized into three major types based on the source of fluctuation. The first type is due to the non-negligible inertia force from the acceleration of imbalanced mass connected to a rotating shaft [1]. The magnitude of torque fluctuation is in general proportional to the square of shaft speed. Hence the induced speed fluctuation is less a problem at low speeds and becomes more severe at high speeds. The second type is originated from the uneven input driving actuation on a shaft within one full rotation. For example, the ignition of an internal combustion engine results in highly uneven gas torque on its crankshaft. Switched reluctance motors [2] produce non-constant torque for each phase due to their nonlinear magnetic characteristics. Similarly, air vane motors [3] produce fluctuating torques due to their unmatched vane torques. Unlike the first type, the magnitude of torque fluctuation of the second type is independent of shaft speed. It only depends on the shaft angle and input power (P_{in}). The third type is caused by the fluctuating resistive load on a shaft. For example, an engine valve system [4] reacts with fluctuating resistive torque to a camshaft. Similar to the second type, this type of fluctuation only depends on the shaft angle and is independent of shaft speed.

* Corresponding author.
E-mail addresses: dennis14989@gmail.com (D.-Y. Lin), hobo920609@gmail.com (B.-J. Hou), cclan@mail.ncku.edu.tw (C.-C. Lan).

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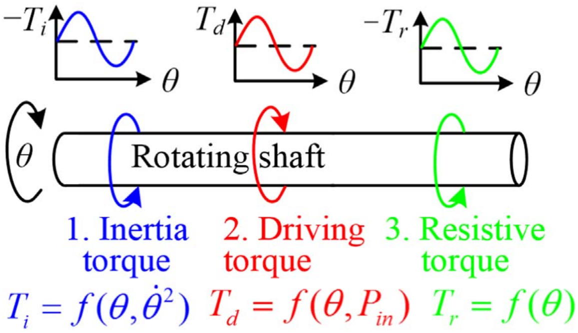

Fig. 1. Three types of torque fluctuation.

Passive techniques such as flywheels (e.g., Ref. [5]) or torsional vibration dampers provide ready solutions to reduce speed fluctuation of the three types in Fig. 1. Flywheels can reduce speed fluctuation by storing and releasing kinetic energy. The required large inertia makes flywheels bulky. Flywheels are less preferable for low speed applications because they offer only minor speed fluctuation reduction. Vibration dampers are applicable for various speeds at the cost of energy loss. To be more energy efficient, torsional pendulum vibration absorbers or centrifugal pendulum vibration absorbers [6] have been used. Another centrifugal pendulum based on cam mechanisms [7] has been proposed to completely remove the torque fluctuation of the first type. In addition to the previous passive techniques, active control techniques (e.g., Refs. [8,9]) were also developed to provide an opposing force or torque to cancel with the source of torque fluctuation.

Internal combustion engines exhibit significant vibration from two sources: the speed fluctuation of the crankshaft and the camshaft. The crankshaft speed fluctuation is due to the unsmooth torque from the combination of slider-crank inertia (first type) and piston gas force (second type). The camshaft speed fluctuation is primarily due to the fluctuating resistive torque required to compress and release the valve springs (third type). Except for very high speed, the inertia torque fluctuation of the camshaft is much smaller than the resistive torque fluctuation and hence can be ignored. Engine-mount systems with active or passive vibration control methods [10,11] have been developed to reduce the effect of engine vibration. However, these methods primarily focused on suppressing or isolating the vibration from engine to chassis. The vibration inside engines remains unsolved. It is still a challenge to directly remove the torque fluctuation on crankshafts or camshafts without including extra complexity and cost.

This paper aims at designing a passive balancing mechanism to perfectly compensate the fluctuating resistive torque (third type) of an engine camshaft. The proposed method is based on a cam mechanism to generate a torque that cancels with the resistive camshaft torque at any position. Cam mechanisms can ideally generate arbitrary force or torque output by synthesizing the cam profiles and follower geometries (e.g., Ref. [12]). They have been used to reduce the speed and torque fluctuation in rotary machines [3,7,13–22]. Unlike most of previous cam mechanisms that were used to reduce the inertia [7,14–22] or driving [3,13] torque fluctuation (first or second type), this paper explores a new area by specifically focusing on a cam mechanism that can eliminate the resistive torque fluctuation of an engine camshaft. The cam mechanism reduces vibration inside the engine rather than outside. Hence extra complexity and cost could be avoided. As far as we know, we are the first to present a balancing method for the resistive torque fluctuation of engine camshafts. In what follows, a camshaft torque analysis is presented in Section 2. Based on the fluctuating resistive torque curve obtained in Section 2, the design procedure of a balancing mechanism is proposed in Section 3. Section 4 studies the effect of inertia torque (first type) on the balancing performance at various speeds. Finally, a prototype of the balancing mechanism and its associated dynamic experiments are presented in Section 5 to demonstrate the performance of torque fluctuation minimization.

2. Camshaft torque analysis

Without loss of generality, we consider a valve mechanism as shown in Fig. 2(a). This type of valve mechanism is commonly used in single-piston or multi-piston vehicle engines to control proper opening and closing of valves. The valve mechanism consists of a camshaft as shown in Fig. 2(b). The camshaft has an exhaust cam and an inlet cam. The exhaust cam is connected to an exhaust rocker, exhaust valve, and exhaust spring. Similarly, the inlet cam is connected to an inlet rocker, inlet valve, and inlet spring. Fig. 3 shows the schematic front view of the valve mechanism. Given input rotation θ from the camshaft, the exhaust cam causes the exhaust rocker to rotate with angle ϕ_e whereas the inlet cam causes the inlet rocker to rotate with angle ϕ_i. The rotation of the rockers opens and closes their respective valves. The displacements of the inlet and exhaust valves are denoted as δ_i and δ_e, respectively. The opening of the valves will compress the springs, whereas the closing of the valves will release the springs. The magnitudes of inlet and exhaust spring forces are denoted as $|\mathbf{F}_{si}|$ and $|\mathbf{F}_{se}|$, respectively. The clearance between the valve and rocker is very small and thus ignored.

A driving torque on the camshaft is required to compress and release the springs. Fig. 4 shows a sequence of four snapshots as the camshaft completes one full rotation. In Fig. 4(a) and (c), positive (clockwise) torques are required to compress the exhaust and inlet springs, respectively. In Fig. 4(b) and (d), negative (counterclockwise) torques are required to release the exhaust and inlet springs, respectively. To study the torque fluctuation, we consider the inlet spring as an example. The magnitude of inlet spring force