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Gear Drive Mechanism for Continuous Variable Valve Timing of IC Engines

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ABSTRACT

Continuous variable valve actuating (CVVA) technology provides high potential in achieving high performance, low fuel consumption and pollutant reduction. To get full benefits from (CVVT) various types of mechanisms have been proposed and designed. Some of these mechanisms are in production and have shown significant benefits in improving engine performance. In this investigation a newly designed gear drive mechanism that controls the intake valve opening (IVO) and closing (IVC) angles is studied. The control scheme is based on maximizing the engine brake power (P) and specific fuel consumption (BSFC) at any engine speed by continuously varying the phase between the cam shaft angle and the crank shaft angle. A single-cylinder engine is simulated by the "LOTUS" software to find out the optimum phase angle for maximum power and minimum fuel consumption at a given engine speed. The mechanism is a planetary gear drive designed for precise and continuous control. This mechanism has a simple design and operation conditions which can change the phase angle without limitation.

Keywords: Mechanism Design; Planetary Gear; Variable Valve Timing; Spark Ignition Engines; Performance

1. Introduction

In internal combustion engines, variable valve timing (VVT), also known as variable valve actuation (VVA), is a generalized term used to describe any mechanism or method that can alter the shape or timing of a valve lift event within an internal combustion engine [1-6]. The (VVT) system allows the lift, duration or timing (in various combinations) of the intake and/or exhaust valves to be changed while the engine is in operation, which have a significant impact on engine performance and emissions. In a standard engine, the valve events are fixed, so performance at different loads and speeds is always a compromise between drivability (power and torque), fuel economy and emissions. An engine equipped with a variable valve actuation system is freed from this constraint, allowing performance to be improved over the engine operating range [7-10].

Some types of variable valve control systems optimize power and torque by varying valve opening times and/or duration. Some of these valve control systems optimize performance at low and mid-range engine speeds. Others focus on enhancing only high-rpm power. Other systems provide both of these benefits by controlling valve timing and lift. There are many ways in which this can be achieved, ranging from mechanical devices to hydraulic, pneumatic and camless systems [11-14]. Hydraulic system suffer from many problems including viscosity change of the hydraulic medium due to the temperature change, the liquid tends to act like a solid at high speed, and hydraulic systems must be carefully controlled, which require the use of powerful computers and very precise sensors. Pneumatic system utilizing pneumatics to drive the engine valves would in all probability not be feasible because of their complexity and the very large amount of energy required for compressing the air. Camless system (or, free valve engine) uses electromagnetic, hydraulic, or pneumatic actuators to open the poppet valves instead. Common problems include high power consumption, accuracy at high speed, temperature sensitivity, weight and packaging issues, high noise, high cost, and unsafe operation in case of electrical problems. Multiair system (or Uniair) is an electro-hydraulic variable valve actuation technology controlling air intake (without a throttle valve) in petrol or diesel engines. The system allows optimum intake valve opening schedules, which gives full control over valve lift and timing.

2. Continuous Variable Valve Timing (CVVT)

First, the (CVVT) system offers a unique ability to have independent control of the intake and exhaust valves in an internal combustion engine [15-17]. For any engine load criteria, the timing of intake and exhaust can be independently programmed and the engine's performance could be optimized under all conditions. However, if valve timing could be controlled independent of crankshaft rotation, then a near infinite number of valve timing scenarios could be accommodated which would dramatically improve fuel economy and emission levels of an automobile. These systems are used in several automobiles with gasoline engine like Toyota, Nissan, Honda, and others. In 2010, Mitsubishi developed and started mass production of its 4N13 1.8 L DOHC I4 world's first passenger car diesel engine that features a variable valve timing system.

One of the high effective mechanisms proposed for controlling variable valve timing is planetary gear mechanism. The planetary gearbox arrangement is an engineering design that offers many advantages. One advantage is its unique combination of both compactness and outstanding power transmission efficiencies. A typical efficiency loss in a planetary gearbox arrangement is only 3% per stage. This type of efficiency ensures that a high proportion of the energy being input is transmitted through the gearbox, rather than being wasted on mechanical losses inside the gearbox. Another advantage of the planetary gearbox arrangement is load distribution. Because the load being transmitted is shared between multiple planets, torque capability is greatly increased. The more planets in the system the greater load ability and the higher the torque density. The planetary gearbox arrangement also creates greater stability due to the even distribution of mass and increased rotational stiffness. Hence, in this work we will present a new design of planetary gear drive mechanism for Continuous variable valve timing IC engine.

3. The Gear Drive Mechanism Design

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3.1. A Description

The proposed gear drive mechanism is designed by Prof. M. Dado from mechanical engineering department at the University of Jordan. This mechanism guarantees a precise and continuous camshaft phasing for intake and exhaust valves in internal combustion engine. The phase angle between the camshaft and crankshaft changes related to engine's speed, which improve engine's performance and emissions.

The mechanism shown in **Figure 1** is a planetary gear train system consisting from an external sun gear (3), planetary gears (2) carried by two planet arms (1), and an internal ring gear (4) with external worm teeth meshing with a worm gear (5) which is connected to a stepper motor interfaced to the engine computer control system. When the stepper motor shaft is stationary, which is the prevailing case, the ring gear is also stationary. This yields a constant speed ratio between the crank shaft and the camshaft. A rotation of the stepper motor shaft leads to the rotation of the ring gear resulting in additional rotation for the planetary gears and the external sun gear and the camshaft. This additional rotation results in phase change between the crank shaft and the cam shaft.

3.2. Mechanism Installation

The mechanism is operated by planetary gear train to continuously and precisely change the phase angle between camshaft and crank shaft. The internal ring gear has an external worm tooth so it can acts like a worm wheel. It trains with the worm. The mechanism is operated by planetary gear train to continuously and precisely change the phase angle between camshaft and gear. The four identically planetary gears are meshing with the ring gear and the sun gear and they are carried by the two arms.

The mechanism (**Figure 2**) is installed to the internal combustion engine as follows: the mechanism is carried by bearing in such way that the camshaft (6) and the sun gear shaft are coaxial and then shafts are connected by the

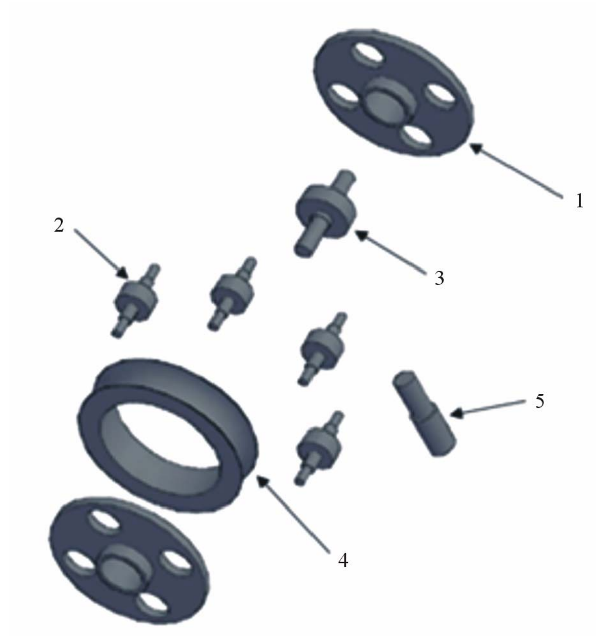


Figure 1. The components of the mechanism.

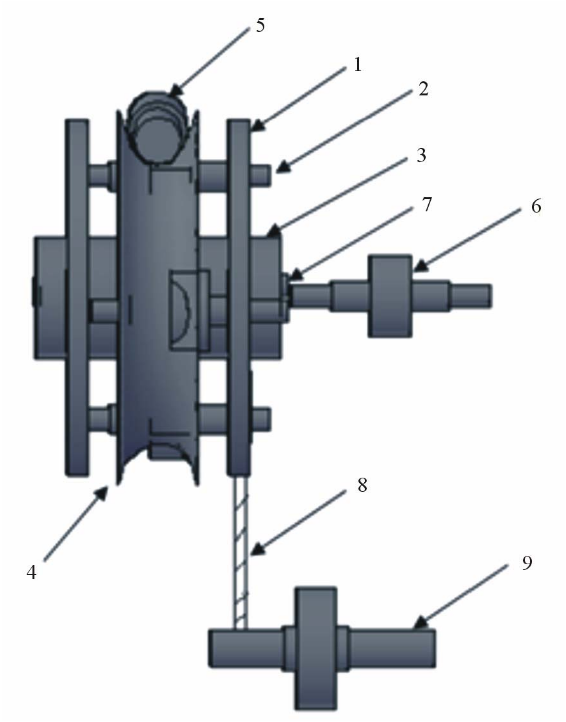


Figure 2. The mechanism installation.

spline coupling (7). One of the planet arms (1) is connected with the crank shaft (9) by chain or timing belt (8). The worm gear shaft is connected mechanically with a stepper motor. The stepper motor is equipped with sensors and power supply, which are connected to the CPU to control the motion of the worm gear.

3.3. The Method of Operation

The method of the mechanism operation is easy and simple and it's described below:

1) When the stepper motor shaft is stationary, which is the prevailing case, the ring gear is also stationary. The rotation of the arm by the crank shaft causes the rotation of the ring according to the equation:

$$\omega_3 = \left(\frac{T_4}{T_1} + 1\right)\omega_1 \tag{1}$$

where:

ω_3—the speed of the sun gear (3), which is also the speed of the camshaft;

ω_1—the speed of the arm (1).

T_1 and T_4 are the number of teeth of the sun gear and the number of internal teeth for the ring gear, respectively.

The relationship between the number of teeth for the sun gear, planetary gears, and internal ring gear is:

$$T_4 = T_3 + 2T_2 \tag{2}$$

where:

T_2—the number of teeth for the planetary gears (2).

2) When the stepper motor have a signal from the CPU it will rotate according to the required shift angle resulting in the rotation of the worm gear (5), which will cause the rotation of the ring gear and consequently an additional rotation of the planetary gears.

3) This rotation resulting in additional rotation for the sun gear, which is connected with the camshaft, according to the following equation

$$\Delta\theta_3 = -\frac{T_3}{T_4}\frac{T_5}{T_6}\Delta\theta_5 \tag{3}$$

where:

$\Delta\theta_3$—the shift angle for the camshaft;

$\Delta\theta_5$—the angle of rotation for the worm gear;

T_5, T_6—the number of teeth for worm gear and external teeth for the ring gear, respectively.

4) The arm will not be affected by this rotation, because it is coupled to the crankshaft.

5) The additional rotation for the sun gear which is connected to the camshaft results in phase change between camshaft and crank shaft of value $\Delta\theta_1$.

3.4. The Advantages of the Mechanism

The main advantages of the above mechanism over other mechanisms can be summarized as follows:

1) The change in the phase angle is constrained to the motion of the stepper motor, which can be controlled with accuracy up to 1.8 degrees for each step with zero overshoot. This value will be smaller for the camshaft depending on the gear teeth numbers.

2) The worm gear, which is connected to the stepper motor and meshing with ring gear, offers a self-locking mechanism for ring gear. That will guarantee a constant speed ratio between the camshaft and crank shaft for specific phase angle, which is necessary for good engine operation.

3) In this mechanism there is no limitation for phase angle changing value, except the limitation imposed by the engine's performance envelop.

4. Cam Phasing Optimization—Maximizing Power Output

In this work, the optimum values for intake and exhaust valve timing have been calculated to maximize brake power. These values were used to calculate and compromise the brake power and fuel consumption for different engine's speeds and compression ratios. For the purpose of analyzing the engine characteristics the dimensions were considered with Lotus Engineering Software. The Lotus Engine Simulation and analysis program is an in-house code developed by LOTUS ENGINEERING Company since the late 1980's. Validation of global performance parameters of power, volumetric efficiency and fuel consumption has been performed on a wide range of current production engines.

The simulation model of 4-cylinder engine (**Figure 3**) has been built to find out the optimum phase angle for maximum power. The engine geometry data and valve timings are as shown in **Table 1**. Input data such as inlet pressure, temperature, equivalence ratio are also introduced for all runs. Also the required exit data such as the back pressure are given. The calculations were carried out for the default and optimum values of valve timing which are given in **Table 2**. The optimization engine variable is to find the maximum brake power output. The speed is varied from 1000 - 6000 rpm. The effects of optimum valve timings values and default values on the brake power and for different compression ratio (CR) are illustrated in **Table 3** and **Figure 4** through **6**.

5. The Application of the Mechanism (Example)

The data given in **Table 2** were used to calculate the required values of shift angle for worm gear. To illustrate the work of the above mentioned mechanism we have made the following assumptions:

$$T_3 = 20, T_2 = 20, T_5 = 2, T_6 = 45 \tag{4}$$

From Equations (1) and (2) we get:

$$T_4 = 20 + (2 \times 20) = 60$$
$$\text{and} \tag{5}$$
$$\omega_3 = 4\omega_1$$

which means that one revolution of the arm results in 4 revolutions of the camshaft (and the sun gear). This requires keeping the velocity ratio between crankshaft and the arm equals two to obtain the velocity ratio between the camshaft and the crankshaft equals two, which is necessary for four stroke IC engine operation.

On the other hand, the relationship between the stepper motor angle and camshaft angle is obtain from Equation (3)

$$\Delta\theta_3 = -\frac{N_3}{N_4}\frac{N_5}{N_6}\Delta\theta_5 \Rightarrow \Delta\theta_3 = -\frac{\Delta\theta_5}{7.5} \tag{6}$$

That mean when the stepper motor (and worm gear) rotates 7.5 degrees, the camshaft rotates one additional degree.

The dimensions of the mechanism can be found as following: we assume that planetary gear, sun gear, and ring gear are helical gears with helical angle ψ = 30˚ and module m = 1 [mm] and the face width f = 20 [mm]. In addition, the worm teeth has lead angle χ = 10˚ and axial pitch p = 2 [mm]. From these assumptions we find out that the diameter of the mechanism are not more than 150 × 150 × 50 [mm], so it can be installed in engine room easily.

6. Conclusion

A planetary gear drive mechanism is designed and implemented to optimize the performance of a four stroke single-cylinder engine. The mechanism precisely and continuously changes the phase angle between the cam shaft and crank shaft angles. The effect of optimizing the phase angle at a given speed on the brake power is

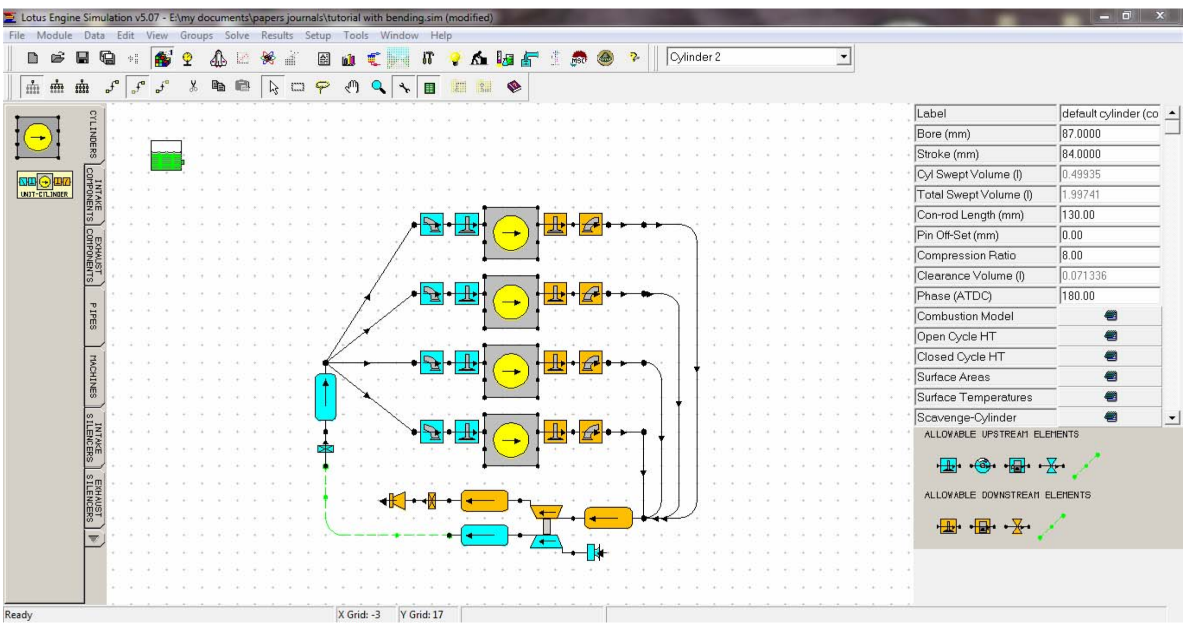


Figure 3. The simulation model of IC engine.

Table 1. Base engine geometry, fuel is gasoline (C_8H_{18}).

Type of engine	4-stroke
Bore	82 mm
Stroke	80 mm
No. of cylinders	4
Compression ratio	8 - 14
Inlet throat dia.	26.5 mm
Exhaust throat dia.	22.5 mm
Max. valve lift	8 mm
IVO angle bTDC	10 deg
IVC angle aBDC	66 deg
EVO angle bBDC	38 deg
EVC angle bTDC	38 deg
Speed	1000 - 6000 rpm

Table 2. Optimum values of valve timing for maximum power and different speeds.

Valve timings	Inlet valve timing		Exhaust valve timing	
Speed, rpm	Open, bTDC	Close, aBDC	Open, bBDC	Close, aTDC
1000	25°	30°	55°	32°
2000	33°	37°	65°	39°
3000	44°	43°	70°	45°
4000	49°	47°	70°	51°
5000	51°	50°	70°	53°
6000	57°	60°	70°	57°

Table 3. (a) Brake power for optimum and default values of valve timing for different speeds; (b) Brake power for optimum and default values of valve timing for different speeds.

(a)

	CR 8			CR 10		
Speed rpm	Opti	Def	% incre	Opti	Def	% incre
1000	3.73	2.78	34	4.1	2.98	37
2000	7.8	6.09	28	8.35	6.52	28
3000	11.7	9.37	25	12.56	10.05	25
4000	15.31	12.4	23	16.47	13.38	23
5000	18.56	15.2	22	20.07	16.43	22
6000	21.39	17.7	21	23.22	19.13	21

(b)

	CR 12			CR 14		
Speed, rpm	Opti	Def	% incre	Opti	Def	% incre
1000	4.21	3.11	35	4.3	3.24	33
2000	8.76	6.8	29	9.07	7.06	28
3000	13.1	10.5	25	13.69	10.91	25
4000	17.3	14.0	23	18.01	14.58	24
5000	21.1	17.3	22	22.02	17.97	23
6000	24.5	20.2	22	25.62	21.03	22

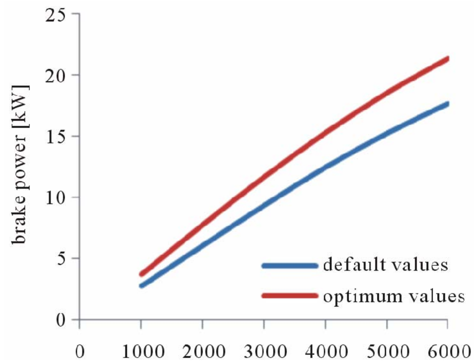
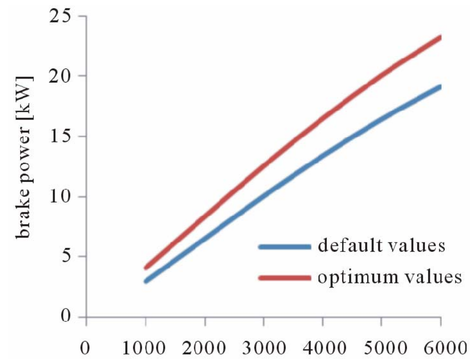
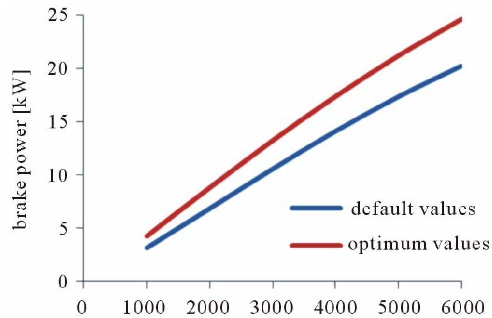


Figure 4. The effect of optimum valve values and default values on brake power (CR 8).



(a)



(b)

Figure 5. (a) The effect of optimum valve values and default values on brake power (CR 10); (b) The effect of optimum valve values and default values on brake power (CR 12).

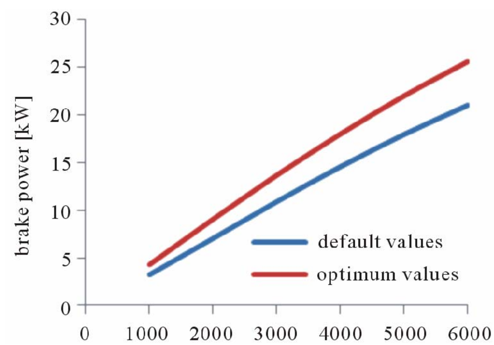


Figure 6. The effect of optimum valve values and default values on brake power (CR 14).

appreciable. The increase of the brake power ranges between 21% and 35% depending on the engine speed and compression ratio as indicated in **Table 3**. This increase is large at low engine speed and drops as the engine speed increases. It could be concluded that the implementation of the proposed mechanism in four stroke engines improves the engine performance and efficiency.

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