Design of an Effective Timing System for ICE

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***Abstract*—The present paper describes the design and the prototype realization process of a new effective timing system for ICE (internal combustion engine). In particular, the present paper outlines the dynamic behavior and related performance of the innovative timing system applied to a two cylinder engine. The procedure to validate the prototype, based on experimental tests carried out on a test bench, is presented and discussed. The traditional finite elements method and computational fluid dynamics (CFD) analysis are used to estimate the dynamic performance of the engine with the new timing system. The comparison with the data reported in bibliography shows the effectiveness of the new timing system. The study indicates that the proposed system is of great significance for the development of timing system in an automotive engine.**

***Keywords*-Specific power; Computational dynamic analysis; 3D modeling; CFD analysis; Reliability.**

I. Introduction

The idea of a new timing system originated from the passion for combustion engines of Mr Giuseppe Serra, with whom the authors of the present paper collaborated in the design and implementation of a virtual environment using 3D modeling software and 3D CFD computational code. The new timing system was built in the first prototype and today is functional and effective in an ICE (Internal combustion engine). Technical characteristics of the original internal combustion engine, for the purposes of which the new timing system was designed and fabricated, are illustrated in Table I below.

TABLE I
ENGINE TECHNICAL SPECIFICATIONS

Engine configuration	Air-cooled vertical 2-cylinder in-line engine, aluminium cylinder head and crankcase
Fuel	Gasoline
Carburettor	Weber 28 IMB
Cubic capacity	(Cylinder bore x stroke = 74 x 70 mm), $594cm^3$
Power	16 kW (23 CV) at 4800 revolutions
Maximum torque	41 Nm
Valve train	Overhead valves, parallel to pushrods and rocker arms. Chain driven lateral camshaft
Compression ratio	9

II. A Brief Overview of the existing Timing System

Valve train is a complex mechanical system which involves the components responsible for regulating intake and exhaust ports whose synchronised operation contributes to the implementation and timing of the phases of the theoretical cycle. In a four-stroke engine, generally conical valves are employed; they open under the action of cams, fitted on the camshaft parallel to and activated by the crankshaft, subsequently closing at the position due to the push by appropriate calibrated coil springs [1], [2], [3], [4], [5].

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A. The main timing elements

The main elements of a timing system are:

- Camshaft
- Valves (guides, seals and springs)
- Tappets
- Pushrods
- Rocker arms

The most common valve train system involves pushrods and rocker arms; however, there are other valve train systems available, offering such solutions as single or double camshaft. The cam does not act directly on the valve spindle, thus a cylinder-shaped steel component is inserted between the cam and the valve. It operates on the even surface of the tappet. The opposite far end of the tappet is hollow, thus, depending on the configuration of the valve train system, it bears a position in which a shaft (in case of shaft and rocker arms) or a valve stem (in case of single or double camshaft with cams at the top) is situated.

B. Timing typology

1) *OHV (Overhead Valves)*: valves are situated in overhead position. Camshaft is located in the crankcase. Such arrangement enhances engine performance and reduces fuel consumption due to higher compression ratio, optimized intake and exhaust strokes, considering minor obstructions and more suitable positioning of transmission links; moreover, the arrangement requires less maintenance, taking into account that cams are surrounded by cooler wall sections and thus are subjected to lower stresses.
2) *DOHC (Double Overhead Camshaft)*: consists of two camshafts (intake and exhaust) located at the top of the cylinder head. Such arrangement improves the output power and engine life span due to reduced energy losses to adjust the motion of the valves as the tappet includes less moving parts if compared to engines with pushrods and rocker arms, the arrangement requires less maintenance due to the fact that cams are in direct contact with valves or a finger follower is installed to reduce lateral forces on the tappets.

3) *SOHC (Single Overhead Camshaft)*: camshaft is situated at the top of the cylinder head. This arrangement is characterized by a single camshaft, which can be:
   - direct acting, featuring two cams and two valves per cylinder;
   - with rocker arms, featuring two additional support shafts to ensure the rotary motion of the rocker arms which operate the valves;
   - combined or Unicam design, where camshaft is situated in a decentralized position to directly operate valves located on one side of the cylinder, whereas rocker arms are employed to operate the valves located on the other side of the cylinder.

4) *Desmodromic valve train system*: type of valve train, which can be either SOHC or DOHC, its essential feature being regulating opening and closing stroke of air/fuel intake valves and discharge of exhaust gas from the cylinders. There are no springs to push valves back to the closing position, but a direct mechanical system consisting of two rocker arms connected to the camshaft, which apart from the common egg-shaped cam provides an additional cam, operating the valve both opening and closing it. Desmodromic valve train ensures excellent reliability and ability to reach higher revolutions and thus generate substantially more power.

C. Different Architecture of Variable Valve Trains

The most well-known and employed architecture of variable valve train systems are the following: The dimension of the impression surface once the load is removed is calculated as follows:

- CAMSHAFT PHASING UNIT;
- VTEC valve train;
- VANOS valve train;
- VALVETRONIC valve train;
- UNIAIR valve train.

These types of architecture allow for variation in timing of valve opening and closing angles, monitoring the intersection angle.

III. The Proposed Effective Timing System

The new valve train system is of desmodromic type as closing of the valves is not ensured by the return springs, but rather by the kinematic motion of rod-crank. The proposed system does not employ valves, eccentric elements (cams), rocker arms; these components are entirely substituted by a rod-crank system, i.e. the classic mechanism consisting of pistons and rods actuated by a crankshaft which in the present system is the camshaft as opposed to the original crankshaft. The main parts of the proposed system are:

- Cylinder shell assembly, alluminium 6061;
- Alloy steel camshaft;
- Four pistons, two for each cylinder, one for air-fuel intake and one for exhaust gas discharge, alluminium 6061;
- Four alloy steel rods, one for each piston valve, with a removable rod cap;

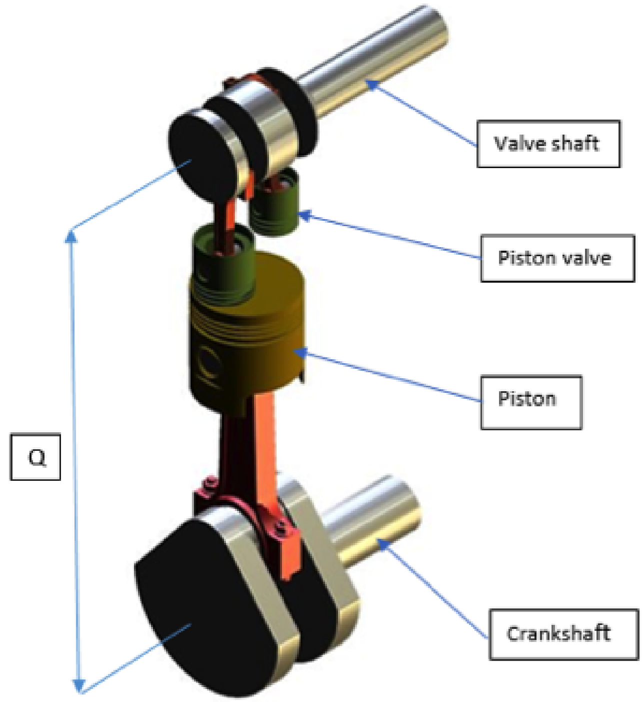

Fig. 1. Geometric model of the system.

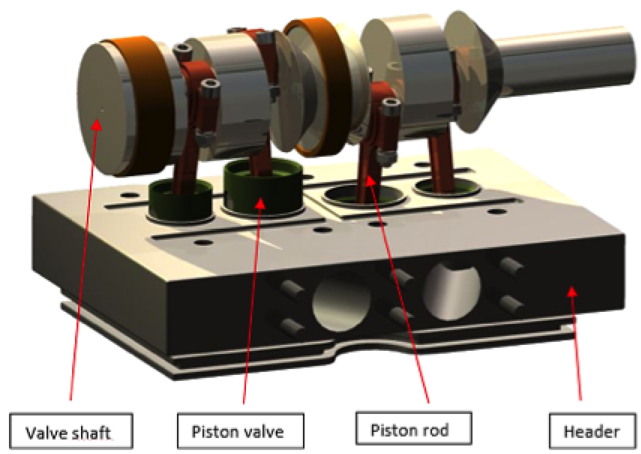

Fig. 2. Model of the new timing system.

- Shaft bearing, alluminium 6061.

Fig. 1 shows the geometric model with a single cylinder to compute numerical models.

In Fig. 2 is shown the dynamic multibody model that outlines the kinematic prototype with a single cylinder. The development of the prototype gives the possibility to evaluate the exact timing, defining the optimal time limit for piston valve intake and exhaust [6], [7].

Numerical simulations allowed determining the best camshaft position by adjusting the camshaft frame with respect to the position of the cylinder head [8], [9], [10], [11].

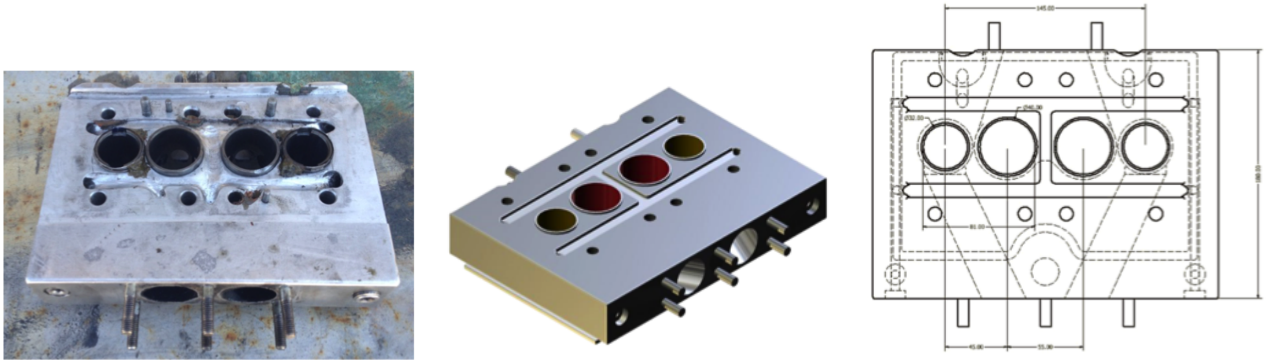

Fig. 3. Cylinder head: (left) Real; 3D model (center); drawing with dimensions (right).

This arrangement provides a major cubic capacity, greater power, finer performance with equal fuel consumption. Fig. 3 illustrates the comprehensive model of the new power distribution system without the camshaft housing.

A. The cylinder head

Cylinder head prototype is made of alluminium EN AW 6061, an alloy mostly used in structural applications where it has enormous potential due to medium-high resistance achieved after thermal hardening (tempering and artificial aging).

It can be defined as the core of the proposed system, where the air-fuel intake and exhaust gas discharge is regulated by the piston valves.

We can see the four piston sleeves, those of intake and exhaust pistons, and the corresponding ducts. The opening of a piston valve is approximately at 330^o with a raise of 14 mm [12], [13], [14].

B. The new Camshaft

In the proposed system, the camshaft has an additional function of serving as the second crankshaft, which, as previously mentioned, is opposed to the original crankshaft. It is actuated as a general camshaft, i.e. via chain drive operated by a crankshaft, but, in this case, the rotary motion around its own axis together with the connecting rods generates the reciprocating motion of the pistons, thus opening and closing intake and exhaust valves. Considering that it is the second crankshaft, it rotates around the bearings located in the main fixtures, and it is inevitably subjected to different stresses, such as twisting force, bending and shear. The material used for this component has to comply with the following requirements: high resistance, excellent elastic modulus, core toughness and surface hardness. The only material that satisfies the previously mentioned demands is steel, i.e. carbon case hardening steel (mainly selected for two-stroke engines) and alloy steel. The camshaft provides a bearing clearance for lubricating oil to cool the components [15], [16], [17], [18], [19].

C. Valve Piston and Connecting Rods

It is essential to make pistons of materials with good mechanical characteristics, high thermal resistance[20], [21] low values of thermal expansion and light weight. The pistons employed are made of alluminium by shell-mould casting and cold-pressing. As previously mentioned, two pairs of pistons are made, one pair bearing a larger diameter of 40 mm for intake, whereas the second pair bearing a smaller diameter of 32 mm for exhaust [22], [23].

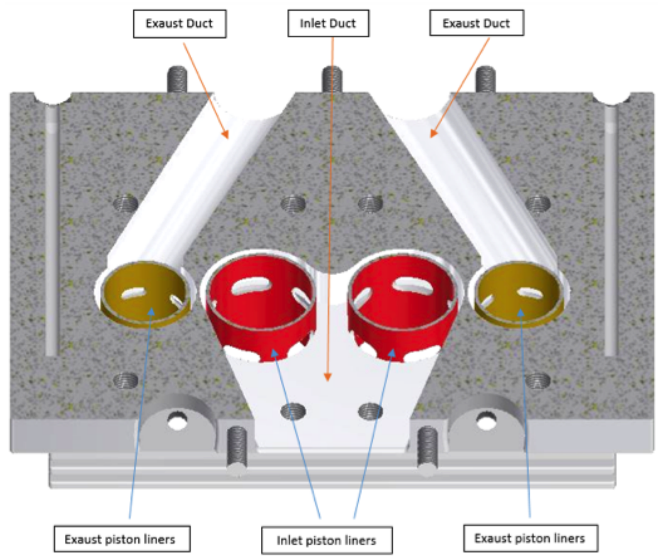

Fig. 4. Section of a cylinder head

The connecting rods employed have a removable rod cap; they are made of spheroid cast iron by melting. In addition to being easy to use, they have good mechanical characteristics able to satisfy the first signs of the sportiness of engines fitted on small road vehicles [24], [25].

D. Camshaft Frame

Made of alluminium 6061, camshaft frame is a very important component of the present system and serves two functions. It is the housing, the shell that covers and protects the moving mechanical components ensuring appropriate lubrication in connections with oil. Seats are allocated for the main bearings to support the camshaft. Camshaft support is the main function that characterizes the whole system. Piston valves are opposed

Fig. 5. Camshaft (left) ; 3D model (center); drawing with dimensions (right).

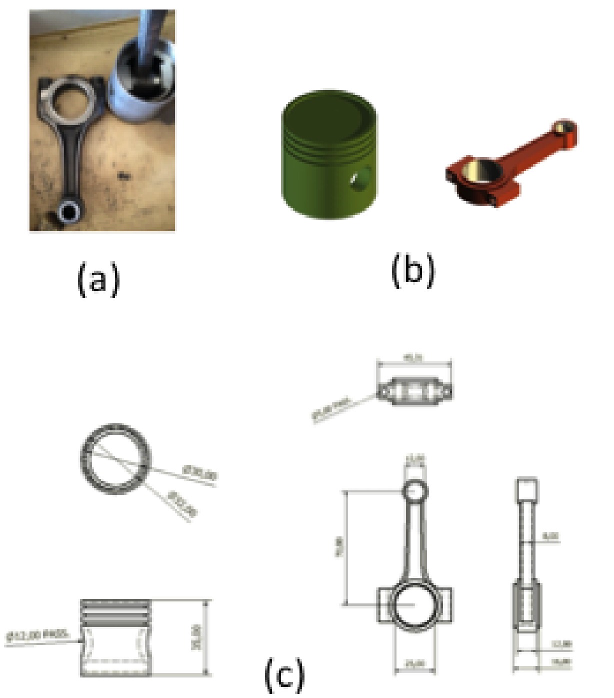

Fig. 6. Valve piston and related connecting rods: (a) Real; (b) 3D model; (c) drawing with dimensions.

to the original engine pistons and connected to the camshaft via corresponding connecting rods, thus defining a fixed rate crank drive between piston valve and connecting rod; the obtained result is the variable combustion chamber, partly created by pistons and piston valves. During the power stroke both piston valves are situated 12 mm from the piston. It must be highlighted, however, that at the end of the stroke piston valve is situated 3 mm from the cylinder head. It offers numerous solutions from the point of view of the performance, as proper modification of the height of the camshaft via camshaft frame, i.e. interaxle spacing between the two shafts, will change the dimensions of the combustion chamber, thus outlining other transmitted power values, definitely offering more advantageous values than the original ones.

Figg. 8, 9, 10, 11 show the real system:

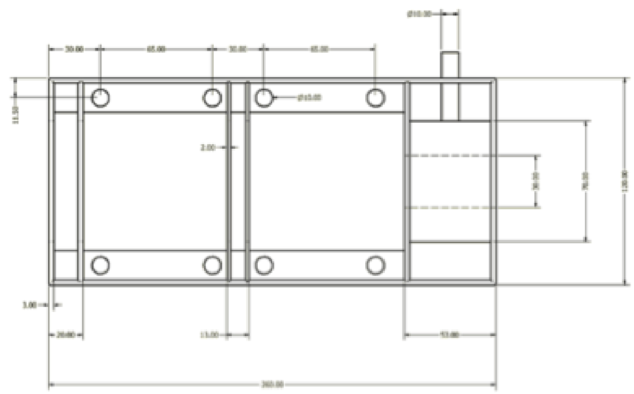

Fig. 7. Headframe.

Fig. 8. Front view with transmission belt.

IV. Experimental and Simulation Results

The system under analysis highlights strong reliability and safety of the components. Camshaft is actuated by the crankshaft via a chain drive, common arrangement employed in many valve train systems. In case drive is interrupted, which can be due to an excessive use of the chain drive causing it to break, other main valve train system components will not suffer any damage. It helps to safeguard the life span of the engine, not affecting its overall performance. This feature is

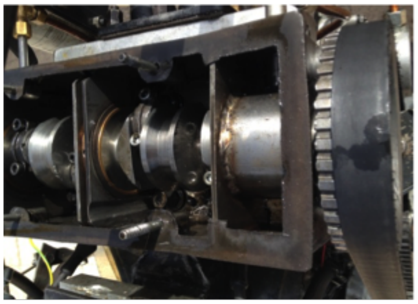

Fig. 9. Prototype of the timing system.

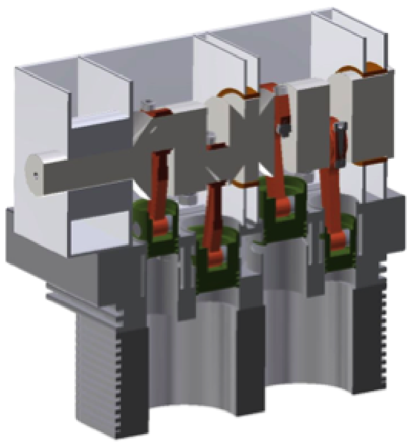

Fig. 10. 3D view of the internal system.

one the main characteristics of the proposed system, opposite to what usually occurs in traditional valve train systems where the break in valve train control system causes irreparable damage to the other components of the engine (camshaft, valves, cams, rocker arms, connecting rods and pistons).

The partly ensured variability in the opening and closing of valves which, as previously mentioned, are characterized by the kinematic motion of rod-piston valve, whose position in the piston sleeve determines the end of the stroke, depends on the interaxle spacing between the two shafts, i.e. camshaft and crankshaft. This variability in rate is regulated mechanically by the camshaft frame. The partly-variable timing allows for the adjustment in opening and closing of intake and exhaust valves with the additional goal being monitoring the generated load with the same valve timing, eliminating the throttle body. The formulation of the optimal engine load control strategy is not vague as it is essential to state the exact limits for the piston valves to ensure optimal synchronization. In the particular case, the limit of the intake piston valve has been observed at 38 mm from the internal profile of the piston sleeve. It enabled the increase in the original cylinder capacity by 15%, thus accounting for the cylinder capacity of 680 cm3 with the compression ratio 12 and considerable reduction in fuel consumption. The cylinder capacity is roughly linear according to the trend illustrated in the figure below, outlining the height at the end of the stroke.

Fig. 11. Internal view with inlet and exhaust duct.

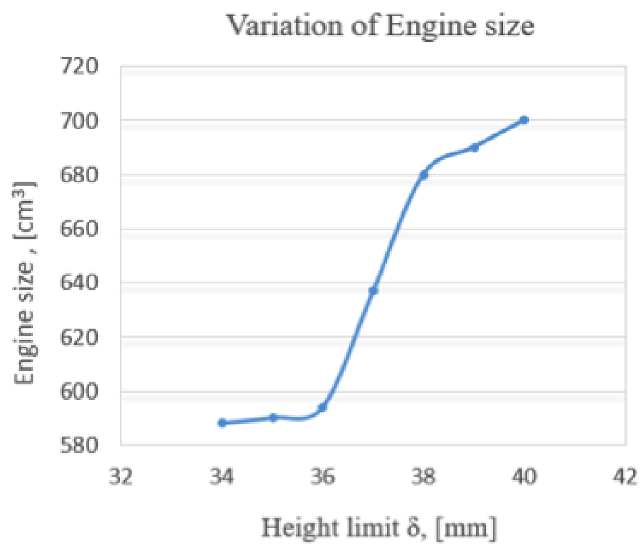

Fig. 12. Cylinder capacity.

Changes in power are shown below in relation to the height at the end of the stroke.

V. Conclusion

The paper presents a new effective timing system for ICE. In particular, the present study discusses the dynamic behaviour and the related performance of the innovative timing system applied to a two cylinder engine. The comparison with the data reported in bibliography shows the effectiveness of the new timing system. The study indicates that the proposed system is of great significance for the development of timing system in an automotive engine. Therefore, the proposed architecture can be proficiently used to improve engine performance.

It will be possible, in a further study, to perform an in-depth CFD analysis to evaluate the precision of the performance of the new system. Ordinary and differential thermography are full-field experimental techniques which could allow to

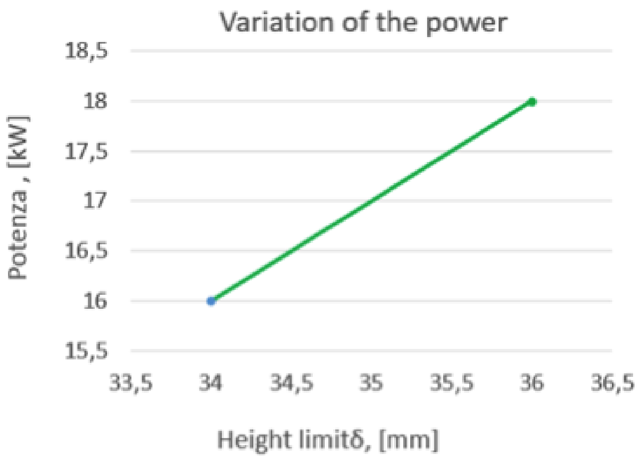

Fig. 13. Power versus heigth stroke.

validate numerical results with reference to stress and temperature distributions. In such further studies we might introduce advanced neural network based models, since they have been shown as effective in several previous works, such as e.g. in [26], [27], [28].

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