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CONCEPT FOR A BALANCED INTERNAL COMBUSTION ENGINE CONFIGURATION

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Abstract: Conventional internal combustion engines (ICEs) inherently suffer from imbalances due to the reciprocating motion of their components, leading to vibrations, wear, and mechanical inefficiencies. In this paper, we propose a novel engine configuration based on four interconnected hypocycloidal straight-line mechanisms, designed to eliminate both translational force imbalances and torque fluctuations. We present the mechanical concept as a physics problem, followed by theoretical calculations showing that the proposed system results in zero net force and torque due to its symmetric design. An experimental prototype was constructed using CAD modeling and manufactured from acrylic glass. Measurements performed with an accelerometer confirm the theoretical predictions: the engine remains stable during operation, and imbalances arise only when the piston synchrony is disrupted. Our results demonstrate that such a configuration offers a mechanically balanced alternative to conventional ICE layouts, with potential applications in vibration-free piston-based engine designs.
Key words: *mechanical balance, internal combustion engine, hypocycloidal engine, piston layout, torque fluctuation, force fluctuation*

1. INTRODUCTION

Internal combustion engines (ICE as short) are a class of rotary machines that transform the reciprocating motion of pistons into rotational motion, which can then be used for various purposes (such as driving the wheels of a vehicle, generating electricity etc.). A longstanding problem in the design of such rotary machines, is the issue of dealing with imbalances that are present due to the physical layout. Ever since the last century, considerable scientific work has been dedicated to mitigation solutions of these problems [1]. The vibrations resulting from the unbalanced components of such machines performing reciprocating and rotating motion are known to put a prescribed reliability and lifetime limit on them, as these issues cannot be avoided in classical ICE designs [2]. Along other considerations, one of the sources of the diverse ICE layouts that exist can be attributed to the attempt of canceling out the action-reaction forces that are the cause of these vibrations [3]. In this regard, in-line engines are considered to be unbalanced, while the flat boxer engine is considered to be balanced from the point of view of the forces acting upon the pistons [4], but torque resonances on the crankshaft are still present [11]. Other considerations in reducing ICE vibrations is driving comfort [6, 7] and possibly manufacturing advantages due to simpler engine mounts. Interest in the problem of balancing engines and engine components are also found in the literature [8, 9].

In this article we present a simple concept of an engine layout that is balanced from the point of view of the action-reaction forces resulting from the reciprocating motion of the pistons, as well from the point of view of the sum of the resulting torques. To establish this configuration, we went back to the hypocycloidal straight-line mechanism designs from the 19th century. Using four of these mechanisms, it is possible to create a layout with the above-mentioned properties. In section 2 we present our engine layout as a physics problem, in section 3 we show with theoretical

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calculations that such a layout is balanced while in section 4 we present an experimental realization of the system along with measurements that validate our theory. In the last section we draw our conclusions with outlooks to the additional benefits of this layout.

2. THE PROBLEM OF A BALANCED ENGINE LAYOUT FROM A PHYSICS POINT OF VIEW

It can be intuitively seen that having a single piston configuration in a cylinder, along with a crankshaft, will result in inertial forces acting axially due to the reciprocating movement of the piston, and radially due to the left-right movement of the connecting rod around the crankshaft. A resultant torque countering the direction of the rotation of the crankshaft will also be present on the whole assembly of the engine (which is usually cancelled by the rotating movement of a counterweight). As we can see, such an engine will be characterized by vibrations and wear (the characteristic oval wear of the cylinders due to the radial forces [10]). Multiple piston configurations such as the flat and boxer engine may reduce a part of the resulting vibrations from the reciprocating movement [4] at the cost of increased manufacturing and engine complexity. We may note that the problem of the unpaired torques are still present in the boxer configurations which may result in critical failure [11].

Extensive research has been conducted on vibrations in internal combustion engines, with particular emphasis on vibration and noise analysis [12,13,14,15], engine balancing techniques [16,17,18,19] and design optimization principles [20,21,22].

As such in the simplest terms, the search for a balanced engine configuration may be considered a physics exercise. Different engine layouts may be considered where the resultant inertial forces cancel each other out along with the resulting torques leading to a state of balance. We found an elegant engine layout consisting of four pistons performing translational motion connected to hypocycloidal straight-line mechanisms transforming it into rotational motion. We connected these four rotating mechanisms with gears and concluded that this layout leads to a balanced state. In the next section we will present this device.

3. THE THEORETICAL CONSIDERATIONS OF AN ‘ICE’ CONFIGURATION WITH FOUR HYPOCYCLOIDAL COMPONENTS

As a diagrammatic abstraction, we are using disks rotating with perfect rolling (in the real acrylic model these are meshing gears). We consider an engine where four pistons (colored dark green in Fig. 1) are each linked to one of four distinct, smaller disks (colored blue) which, in turn, are connected with a shaft to a larger disk (colored red). In this setup the blue disks will perform a hypocycloidal motion within the stationary light green colored circle representing the internal gear (this circle does not move in relation with the engine assembly), thus transforming the linear motion to a rotational one. The larger red disks are synchronized as meshing gears as presented in Fig. 1.

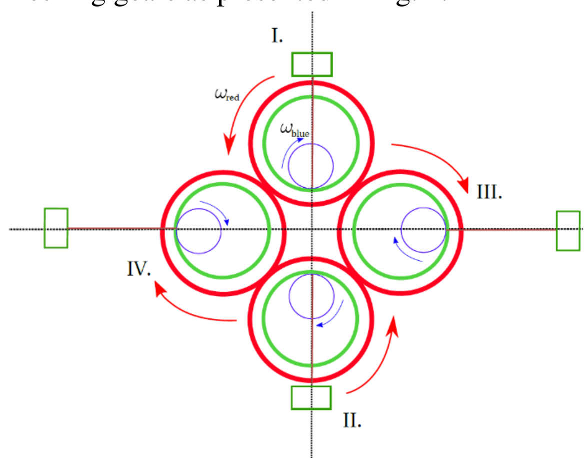

Fig. 1. A sketch of the balanced hypocycloidal engine layout, with circles that transfer the rotational motion through coupling. The dark green squares represent the pistons, linked with a brown colored rod to the blue disks. The blue disks perform the hypocycloidal motion inside the stationary light green colored circle. The blue disks are then connected with a shaft to the red disks. The red disks are synchronized as meshing gears adding up the motion of the subcomponents.

3.1 The motion of the pistons

We begin by analyzing the linear motion of the four pistons. Each piston, of identical mass m is constrained to move along its cylinder axis in harmonic motion. Denoting the displacement of piston k relative to its equilibrium position by $x_k(t)$, we can write Eq. (1)

$$\begin{aligned} x_k(t) &= A\cos(\omega_p t + \phi_k) \\ a_k(t) &= -\omega_p^2 x_k(t) \\ F_k(t) &= m a_k(t) = -m\omega_p^2 x_k(t) \end{aligned} \qquad (1)$$

Here A is the stroke amplitude, ω_p is the common angular frequency of the pistons (imposed by the gear synchronization), and ϕ_k is the phase of piston k.

The four pistons, represented by green blocks in Fig. 1., are phased with quarter-period differences described in Eq. (2):

$$\begin{aligned} I &\rightarrow \phi_I = 3\pi/2 \\ II &\rightarrow \phi_{II} = \pi/2 \\ III &\rightarrow \phi_{III} = 0 \\ IV &\rightarrow \phi_{IV} = \pi \end{aligned} \qquad (2)$$

From symmetry, pistons I and II are in opposite phases, and likewise III and IV. Summing the axial forces:

$$\begin{aligned} F_{tot} &= \sum_{k=I}^{IV} F_k(t) = \\ &= m\omega^2 (x_I(t) + x_{II}(t) + x_{III}(t) + x_{IV}(t)) \end{aligned} \qquad (3)$$

Based on phase relations in Eq. (2), the displacements of the pistons cancel each other in pairs:

$$\begin{aligned} x_I(t) + x_{II}(t) = 0 \\ x_{III}(t) + x_{IV}(t) = 0 \end{aligned} \qquad (4)$$

Hence, Eq. (3). for all t is:

$$F_{tot}(t) = 0 \qquad (5)$$

Thus, the reciprocating inertial forces cancel out completely, ensuring that the center of mass of the entire piston assembly remains fixed at its geometric center.

3.2 The resulting angular momentum and torque of the system

Each piston is connected through a hypocycloidal mechanism to a small (blue) rolling disk, which in turn drives a larger (red) gear disk. The red disks rotate with angular velocity $\omega_{red}(t)$ and angular acceleration $\alpha_{red}(t)$. By construction of the gear train, diametrically opposite red disks rotate in opposite directions, such that if disk I has ω_{red}, its opposite partner, in this case II, has $-\omega_{red}$. All red disks share the same magnitude of angular velocity because of the synchronization.

The **angular momentum** of each red disk is given in Eq. (6)

$$\vec{L}_k = I_{red}\omega_{red}(t)\sigma_k \vec{z} \qquad (6)$$

In Eq. (6). I_{red} is the moment of inertia about the spin axis, and $\sigma_k = \pm 1$ encodes the direction of rotation, and is arranged +,-,+,- around the cross layout of the engine. By symmetry, we may write the following:

$$\begin{aligned} &\sum_{k=I}^{IV} \vec{L}_k = \\ &= I_{red}\omega_{red}(t)(\sigma_I + \sigma_{II} + \sigma_{III} + \sigma_{IV})\vec{z} = \\ &= 0 \end{aligned} \qquad (7)$$

The same cancellation holds true for the smaller blue disks, whose spins are likewise paired in opposite directions, with the angular velocity $\omega_{blue} = \omega_{red}/2$. The translational (orbital) contributions of the pistons and connecting rods also cancel out due to the cross-symmetric geometry and the $\pi/2$ phase differences.

Therefore, the total angular momentum of the entire assembly relative to its geometric center is also zero:

$$\vec{L}_{tot}(t) = 0 \qquad (8)$$

Torque balance

The total external torque relative to the center is given by Eq. (9)

$$\vec{\tau}_{ext}(t) = \frac{d\vec{L}_{tot}(t)}{dt} \qquad (9)$$

Since $\boldsymbol{L}_{tot}(t) = 0$ for all values of t (in the synchronized configuration), it follows that

$$\vec{\tau}_{ext}(t) = 0 \qquad (10)$$

This implies that the engine as a whole does not transmit a net oscillatory torque to its mounting frame. It is therefore globally torque-balanced and gyroscopically neutral. If the assembly is reoriented with angular velocity $\boldsymbol{\Omega}$ the required gyroscopic torque $\boldsymbol{\Omega} \times \boldsymbol{L}_{tot}$ also cancels out.

Internal couples

It must be emphasized, however, that each individual disk still carries a nonzero angular momentum $\boldsymbol{L}_k$. During reorientation with angular velocity $\boldsymbol{\Omega}$ each unit requires a torque $\boldsymbol{\tau}_k = \boldsymbol{\Omega} \times \boldsymbol{L}_k$ applied locally at its mounting axis. These torques cancel out within the global sum, but because they act at different spatial locations, they are transmitted through the frame as internal forces. The frame must therefore be sufficiently rigid to sustain these internal loads.

4. AN EXPERIMENTAL REALIZATION OF THE BALANCED HYPOCYCLOIDAL CONCEPT

To test the balanced engine concept described in the previous chapter, we created a prototype of the engine. The individual hypocycloidal components of the engine are presented in Fig. 2.

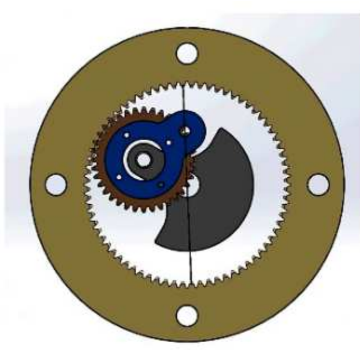

Fig. 2. The CAD model of a single hypocycloidal component from the engine block. It is represented as the green and blue circles in Fig. 1.

The whole engine is made out of four of these hypocycloidal components in a cross like layout on the top layer presented in Fig 1., while the second layer these components are connected with additional synchronization gears as presented in Fig. 3.

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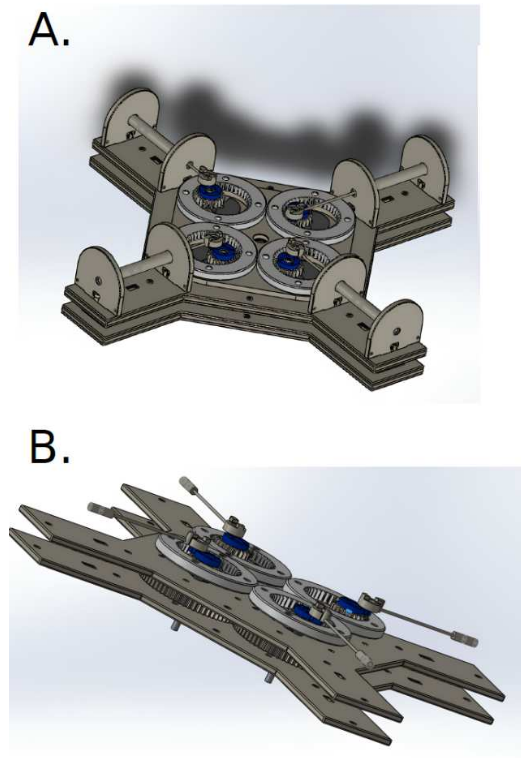

Fig. 3. A. The CAD model of the prototype engine block with four hypocycloidal components in a cross layout. **B.** The CAD model from another angle, presenting the underlying gears that connect the hypocycloidal components.

The physical model of the engine was fabricated from acrylic. The different layers of the engine were mounted together, and the hypocycloidal components were aligned and synchronized in order to ensure smooth movement. Three additional gears were added in the third lowest part of the engine that are connected to an Arduino-controlled motor which drives the whole assembly. We present pictures of the model in Fig. 4. We used this model to perform our measurements regarding the physical stability of the mechanism.

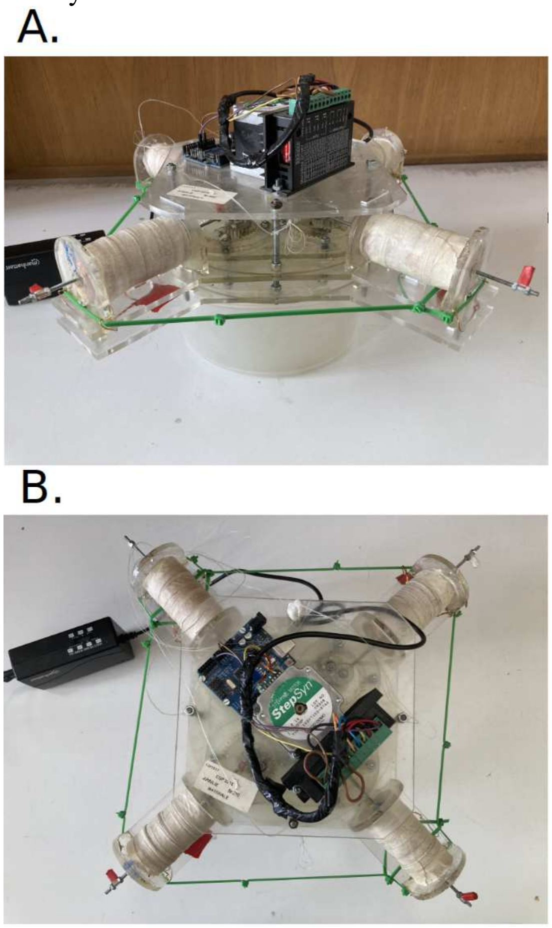

Fig. 4. **A.** Side view of the model. **B**. Top view of the model.

4.1 Experimental measurements on the concept

The motor assembly was then suspended with plastic fishing wires attached to four symmetric points on the motor assembly so it was able to freely move if any asymmetric forces or torques were present. An accelerometer was placed on the engine. Multiple tests were run with different speeds, while no motion of the engine were observed in synchronized configuration. Then one of the pistons was de-phased with 180 degrees in relation to its initial position, to break the symmetry of the mechanism. The suspended engine in this situation starts a periodic motion as anticipated. The resulting accelerations are presented in Fig. 5. As the qualitative observations shown in this figure, the vibration of the system is greatly reduced in a synchronized case compared to a desynchronized one.

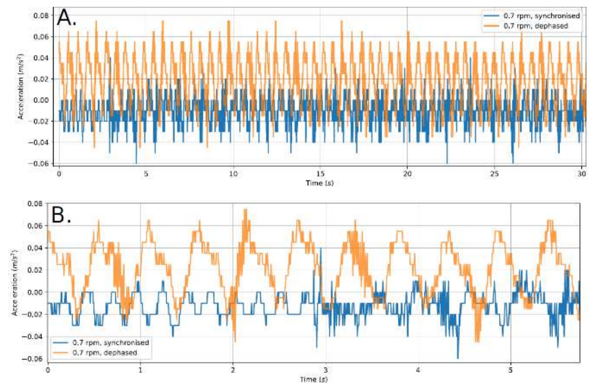

Fig. 5. The accelerations detected on the mechanism when it was rotated with 0.7 rpm, in the syncronized and de-phased cases presented on: **A.** A larger timeframe. **B.** A zoomed-in timeframe. The orange plot represents the vibrations of the system in the dephased case, while the blue plot represents the reduced vibrations in the synchronised case. This qualitative method of study shows the reduction of vibrations in the synchronised case.

5. CONCLUSIONS

In this article we present a novel approach to the problem of the conventional unbalanced internal combustion engine layout. It is known that the classical ICE designs are unbalanced, caused by the movement of the pistons and the torques present in the engine.

This in turn leads to wear, driving discomfort and other problems (ex. any unwanted vibration represents lost energy). By introducing a novel hypocycloidal based engine layout with four pistons, we proved mathematically that such a layout is completely balanced.

For an empirical validation of the concept, a model was built from acrylic. We suspended the model with wires, so it was able to freely move and we placed an accelerometer on it, to show that there is almost zero shaking compared to a state in which one of the pistons was de-phased with 180 degrees from its initial position.

Our novel approach can be applied in ICEs allowing smooth running operation, solving the problem of mechanical balance. If built as an

ICE it may allow for ceramic components to be used as there are no lateral forces to make the ceramics exceed their mechanical limits.

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All concepts, experimental results, designs, and conclusions presented herein are solely the result of the independent research and personal initiative of Ovidiu-Florin Botoș and Liviu Ancuțescu.

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Concept privind configurația echilibrată a unui motor cu ardere internă

Motoarele cu ardere internă (MAI) convenționale suferă în mod inerent de dezechilibre datorate mișcării alternative a componentelor, ceea ce conduce la vibrații, uzură și ineficiențe mecanice. În această lucrare, propunem o configurație nouă de motor, bazată pe patru mecanisme hipocicloidale în linie dreaptă, interconectate, concepute pentru a elimina atât dezechilibrele forțelor de translație, cât și fluctuațiile de cuplu. Prezentăm conceptul mecanic ca o problemă de fizică, urmat de calcule teoretice care arată că sistemul propus conduce la forță și cuplu net nule datorită designului său simetric. Un prototip experimental a fost realizat prin modelare CAD și fabricat din sticlă acrilică. Măsurătorile efectuate cu un accelerometru confirmă predicțiile teoretice: motorul rămâne stabil în timpul funcționării, iar dezechilibrele apar doar atunci când sincronizarea pistoanelor este perturbată. Rezultatele noastre demonstrează că o astfel de configurație oferă o alternativă echilibrată mecanic, pentru arhitecturile MAI convenționale, cu aplicații potențiale în proiectarea de motoare cu pistoane fără vibrații.

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