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Novel Continuous Variable Valve Lift (CVVL) Mechanisms for Throttle Free Load Control of SI Engine

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ABSTRACT

In conventional SI engines, the throttle-based air control wastes about 10% of the input energy in pumping the air. An innovating solution for throttle-free load control for spark-ignition engines is Variable Valve Actuation (VVA) system. VVA systems with continuous variable valve lift (VVL), usually combined with cam phasers, and are designed to eliminate the classical throttle mechanism.This paper present review of design aspects of Novel CVVL mechanisms with three elements including controlled shaft system. Proposed CVVL mechanism with three elements comprises of a standard roller finger follower, the cam shaft, and an intermediate rocker arm used between them. The intermediate rocker arm is equipped with a special developed contact surface, which is based on the theory of envelop curves and has a plane- parallel motion. Initially thegeneralcondition to design a mechanism for continuous VVL has been discussed which fulfills by every timing mechanism with VVL.Further contact curve equations for regular and extended curves and thekinematicanalysisofthemechanism,resultinginthe family ofthevalveliftlaws has been elaborated, output of which is further discussed in terms of valve lift, velocity and acceleration.To achieve better engine dynamic performance and lower consumption and emission CVVL is a potential variable valve actuation technology for small capacity SI engine which offers throttle free load control.

***Keywords* —** VVA - Variable Valve Actuation, VVL - Variable Valve Lift, CVVL –Continuous Variable Valve Lift, Controlled shaft angle, Contact Curve

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I. INTRODUCTION

The torque of a stoichiometric SI engine is controlled by the quantity of air/fuel mixture in the cylinder during each stroke (the quality, i.e the air/fuel ratio remains constant). Typically, the quantity is varied by changing the intake pressure and hence, the density of air/fuel mixture. Thus a throttle plate is used upstream in the intake system. This system is relatively simple and reliable, but produces substantial “pumping losses” that negatively affect the part-load efficiency of the engine. For the traditional spark-ignition engines the timing configuration represents a compromise which does not allow the best engine performance to be achieved for all regime and load. Infinitely variable inlet valve lift and timing is used to control engine load, reducing throttling losses and fuel consumption [3]. It also improves low-end torque and transient response. The chosen intake valve setting for an engine operating over a range of speeds must necessarily be a compromise between the best setting for the low speed end of the range and best setting for the high speed. One way to improve the volumetric efficiency at high speeds is to open the intake valve earlier and deeper at high speeds by variable valve timing and lift technology, which provides the possibility to control the valve events, i.e. timing, lift and duration [4].

Variable Valve Timing (VVT System, or VVA - Variable valve actuation System) allows better engine performance by reducing fuel consumption and therefore low emissions, higher efficiency, highly precise responsiveness of the power train [4]. The key parameter for petrol engine combustion, and therefore efficiency, emissions and fuel consumption is the quantity and characteristics of the fresh air charge in the cylinders. In conventional petrol engines, the throttle-based air control wastes about 10% of the input energy in pumping the air [5]. VVT systems with continuous valve lift variation, usually combined with cam phasers, are designed to eliminate the classical throttle and it’s inconvenient.

This paper present review of design aspects of Novel CVVL mechanisms with three elements including controlled shaft system..The main strategies currently used in automotive field are: timing variation, duration variation, maximum lift variation, combined but not independent variation of timing, duration and lift. The combined variation of the above parameters could enable several advantages in terms of performance, emissions and consumption.

Variable valve mechanism is responsible for the best fuel economy, improvement in volumetric efficiency, reduces NOx emission, and increase peak torque and power.

II. LITERATURE SURVEY

There are many works done in the design of cam, valve and the whole mechanical valve chain. The current methodology enables the design of the valve train systems. Some of the recent investigations are presented below:

In order to generate an entire range of valve lift laws, as shown in figure 1, it is necessary to use timing mechanism, which comprises adjustment elements to ensure this effect. A briefly state of the art is presented in the literatures [1].

The variation of the valve lift using cams with stair shape is used by Audi with AVS (Audi Valve lift System). The system achieves a discrete variation of the valve lift and is used on gasoline engines 2.8 FSI and 3.2 V6 FSI. The system consists in two cams with two profiles. At high loads, the cams lift with 11 mm, while at medium and low loads they lift with only 5.7mm and 2 mm, respectively. Honda VTEC (Variable valve Timing Electronic lift Control) ensures two stages of valve lift. The mechanism has two ‘‘small’’ cams for partial loads and a ‘‘large’’ cam for high loads. The system is electronically controlled. Toyota VVTL-i ensures: the continuity of the distribution phases, the two-step variation of the valve lift, and the time of opening for both the inlet and exhaust valves. This system is used for both valves. Similar to Honda’s system, the Toyota system also has a cam with two shapes. Delphi 2-Step Valve Lift System uses a cam with three lobes: the central one is for the maximum opening of the valve, while the other two are for the minimum opening. FIAT was the first company which patented and used (at the end of the 1960s) spatial cams on camshafts with axial displacements.

BMW Valvetronic ensures the continuous variation of the valve lift using planar cams. The system was launched in 2001 on the model 316 Ti Compact. It uses an electric motor that acts upon an eccentric control axle. Ford Motor Company achieves the variation of the valve lift by modifying the active lengths of certain arms in the kinematic chain [1].

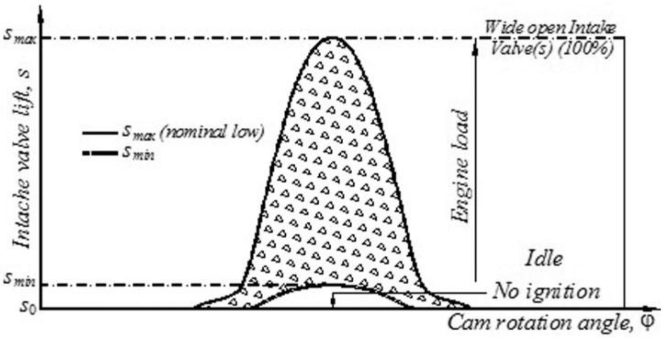


Figure.1 Engine load control by variation of intake valve lift

S. Mihalcea, N. Stanescu and D.popa (2015) have presented a new type of continuously variable valve lift (VVL) system. When the rotation angle of the adjustment shaft is controlled, the valve lift height is also controlled. The profile of the contact surface is analytically determined using the theory of the envelope curves. Using a certain cam profile, the kinematic analysis of the mechanism proceeds, resulting in the family of the valve lift laws. This paper also establishes the general conditions to design a variable valve timing (VVT) mechanism with continuous VVL and mechanical actuation.

S. B. Trimbake, Dr. D. N. Malkhede (2015) have presented a flexible and practical approach to achieving SI and CAI combustion in a four stroke gasoline engine has been developed by making use of mechanical variable valve lift. In this paper Valvetronic system which offers the phenomenon of continuous Variable Valve Lift is discussed.

S. Mihalcea (2010**)**has introduced an analytic method for kinematic analysis of the valve timing mechanism with three elements, which mainly includes the camshaft, the roller rocker finger and an intermediate rocker arm. This type of mechanism ensures a continuous valve lift (VVL System) between two extreme valve heights. It is also presented the numerical example for the variable valve lift mechanism’s motion.

S. Mihalcea and N. Pandrea(2010)have presented an innovating solution for throttle-free load control for spark-ignition engines is variable valve timing system. In this paper is presented a kinematic analysis, using the analytic method, of the valve timing mechanism with three elements and continuous valve lift variation. It is also presented the numerical algorithm for the mechanism’s motion.

P. K. Wong and K.W. Mok (2008)have introduced a novel design named dual-mode electro-hydraulic fully variable valve train for both engine intake and exhaust valves. Experimental and simulation results showed that the dual-mode electro-hydraulic variable valve train can achieve fully VVT and lift control, and has the potential to eliminate the traditional throttle valve in the gasoline engines. As claimed the engine performance at various speeds and loads can be significantly improved. Methods for cam motion synthesis have become increasingly sophisticated and many alternatives are continuously proposed.

Yasukazu Sato, Yukinori Nishimoto, Yoshitomo Fukushima and Takuya Nagataki(2008) presented a highly reliable VVL mechanism controlled by a hydraulic 3-step rotary actuator. 3-step VVL with high-, middle- and low-valve lift, is realized by the pivot shifting of an intermediate cam placed between a camshaft and valve tappet.

III.VARIABLE VALVE ACTUATION(VVA) MECHANISM

According to the controlled object, VVA is roughly divided into three types; variable valve timing (VVT) varying the phase of valve actuation, variable valve lift (VVL) varying the stroke of the valve, and variable valve event (VVE) varying the duration in which the valve is opening.

A. Variable Valve Timing (VVT)

VVT system is one of the simplest ways for the valve actuations in 4 stroke engine. In thissystem, only the valve timings are varied without changing valve lift profiles and durations. As represented in Fig. 2-a, the VVT pulley installed at the front of the intake and exhaust camshaft provides a timing difference between the camshaft and the crankshaft via a hydraulic actuator. This hydraulic actuator is activated by the oil control valve (denoted as OCV) which controls oil pressure supplied to the VVT pulley based on the ECU command. The entire system is capable of phasing the intake and exhaust cam within 40° of crank angle (CA)[10].

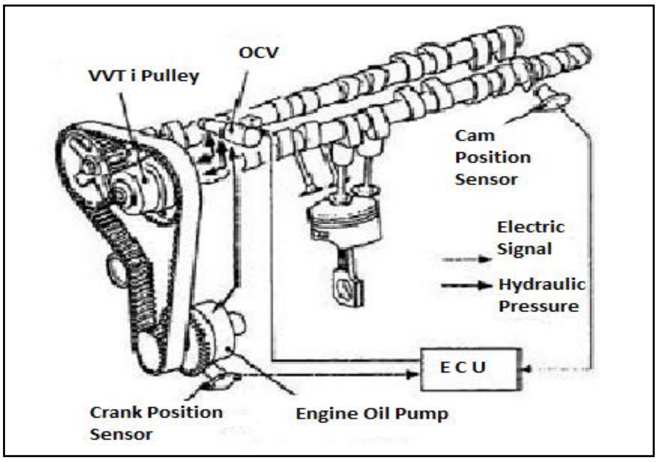


Figure.2-a: VVT Overall System [10]

Such VVT was utilized first time by Zhao et al., in 2002to achieved CAI combustion through residual gas trapping with NVO in a Ford 1.7 LitreZetec gasoline engine over a range of speed and load. This retrofitting was done by replacing the standard intake and exhaust cam shafts with a set of low lift camshaft with two independent VVT altering valve timing by 40° crank angles [10].

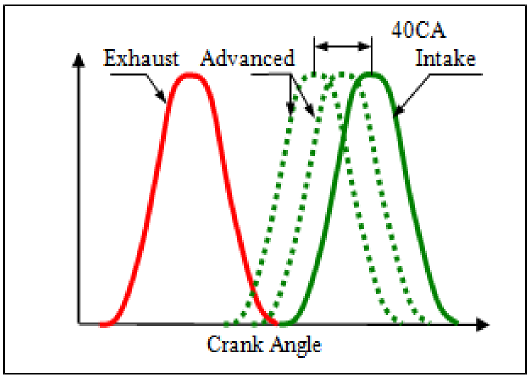


Figure 2-b: VVT Cam Phasing Range [10]

3.2 Variable valve Lift (VVL)

The mechanism shown in Figure3, shows the evolution of the concept of VVL mechanism. In this mechanism the adjustment is done by rotating the control element 0 about the fixed point O3, leading to a circular path travelled by the point O2. The dependence between the valve maximum height Smax and the α angle is obvious, namely for $0 \leq \alpha \leq \pi$, Smax increases when the angle α decreases [1].

The VVL (Variable valve Lift)mechanisms are classified into two categories:

1. Discrete Variable Valve Lift
2. Continuous Variable Valve Lift

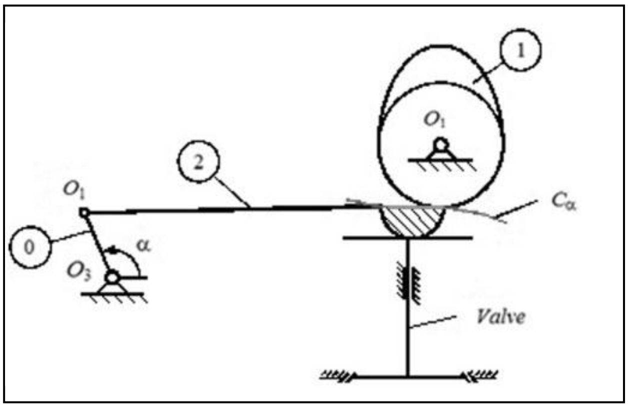


Figure 3: VVL mechanism with one intermediate element

with rotational motion-controlled intermediate element [1]

3.2.1 DISCRETE VARIABLE VALVE LIFT

In Discrete Variable valve lift mechanism, here two mechanisms taken into consideration-

A. VTEC Mechanism

A. VTEC MECHANISM

The basic mechanism used by the VTEC technology is a simple hydraulically actuated pin. This pin is hydraulically pushed horizontally to link up adjacent rocker arms. A spring mechanism is used to return the pin back to its original position.

As shown in fig. 4 it comprises a camshaft with two cam-lobes side-by- side. These lobes drive two side-by-side valve rocker arms [10].

The two cam/rocker pairs operate independently of each other. One of the two cam-lobes is intentionally drawn to be different. The one on the left has a "wilder" profile, it will open its valve earlier, open it more, and close it later, compared to the one on the right. Under normal operation, each pair of cam-lobe/rocker-arm assembly will work independently of each other.

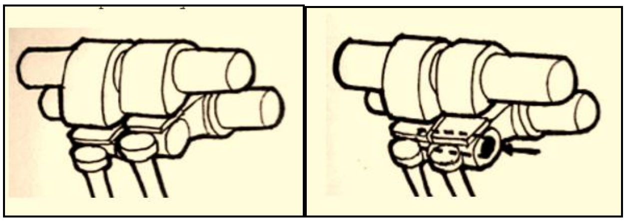


Figure 4: VTEC mechanism [10]

VTEC uses the pin actuation mechanism to link the mild-cam rocker arm to the wild-cam rocker arm. This effectively makes the two rocker arms operate as one. This "composite" rocker arm(s) now clearly follows the wild-cam profile of the left rocker arm. This in essence is the basic working principle of all of Honda's VTEC engines.

3.2.2Continuous Variable Valve Lift

In Continuous Variable valve lift mechanism, here three mechanisms taken into consideration-

A. VVL mechanism with three elements with sliding system
B. VVL mechanism with three elements with Gear system
C. VVL mechanism with three elements with controlled shaftsystem

A. VVL MECHANISM WITH 3 ELEMENTS SLIDING SYSTEM

The proposed mechanism is defined as a “3 elements-sliding system”, because of its working: it enables the valve lift variation thanks to a sliding element (this first system has been designed to be applied on intake valve) and because it is a mechanical VVA system that consists of three elements: cam, main rocker arm with fixed fulcrum and secondary rocker arm with mobile fulcrum.

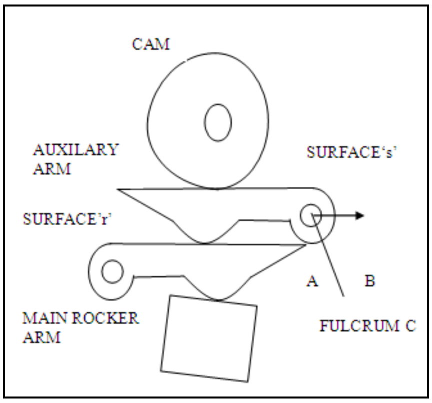


Figure 5: Proposed Mechanism [5]

This system enables valve lift variation through a simple sliding of one of the three elements (the secondary rocker arm). In this system (fig. 5), fulcrum C of the auxiliary arm can slide from point A (maximum valve lift) to point B (minimum valve lift) along the segment AB.

The studied system presents a peculiarity: when valve is closed, fulcrum C sliding direction is parallel to the upper surface of the main rocker arm. The output of the mechanism i.e Variable Valve Lift Profiles for Sliding system is shown in Figure 6.

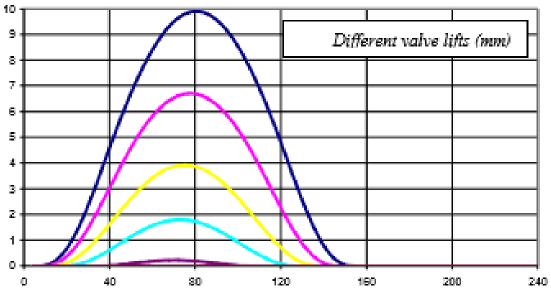


Figure 6: Variable Valve Lift Profiles for Sliding system

B. VVL MECHANISM WITH 3 ELEMENTS GEAR SYSTEM -

The mechanism (Figure 7) comprise the housing (9), the intake cam (1), the rocker arm (2), the hydraulic lash adjuster (3), the valve spring (4),the intake valve (5), the link element (6), valve lift control gear (7), intermediary rocker arm (8). The valve’s motion is provided from intake cam (1) via the rocker arm (2) which is hinged connected with the intermediary rocker arm (8). The link element (6) and intermediary rocker arm (8) are contact jointed, the contact surface being composed from two tangent circles R, R’

The valve lift is controlled by the link element’s position, which is controlled with gear 7. Maximum valve lift (α has a maximum value) is achieved when the joint contact C2 coincides with the tangency point between circles R, R’ and the joint contact C1 is between circles r2, r1.

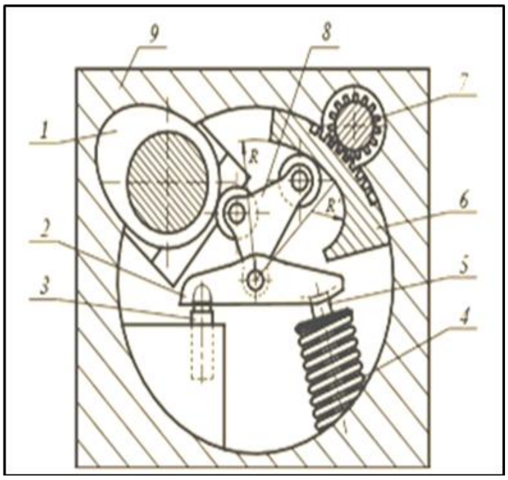


Figure 7Mechanism with gear system [3]

Therefore, when the cam performs a complete rotation, C2 is only on the R’ circle. Intermediate valve lift is obtained by decreasing angle α, and C2 runs both on R and R’. No valve lift is obtained when C2 runs only on R circle.

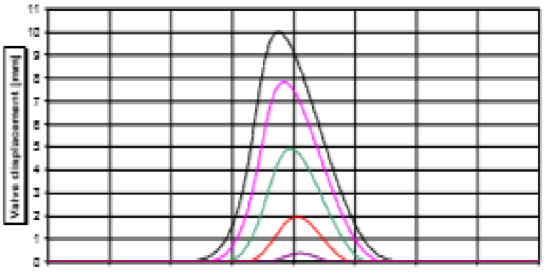


Figure 8. Variab for VVL gear system [3]

C. VVL MECHANISM WITH THREE ELEMENTS WITH CONTROLLED SHAFT SYSTEM (VALVETRONIC MECHANISM)

The mechanical structure of the system is illustrated in Fig.9. It mainly consists of the following components: stepper motor actuated eccentric shaft, intermediate lever, roller rocker arm, and cam operated by camshaft.

The upper end of intermediate lever acts as the pivot point, which is in contact with the eccentric shaft. The eccentricity of shaft controls the position of pivot point, which ultimately controls the valve lift.

The intermediate lever has a roller at the center which is in direct contact with the cam, whereas the lower curved end is in contact with the roller rocker arm.

The motion of the cam is transferred to the roller rocker arm through the pair of cam and intermediate lever roller andpair of lower curved end of intermediate lever and roller of rocker arm for activation of valve motion [11].

Low Lift Operation

In the case of low or no lift the stepper motor turns the eccentric shaft in such a way that the eccentricity is minimum and the upper end of the intermediate lever is in backward position.

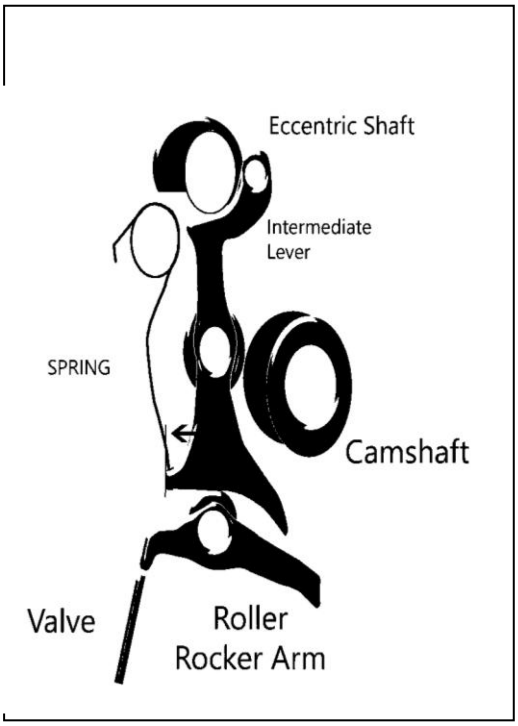


Figure 9-a: Low Lift [11]

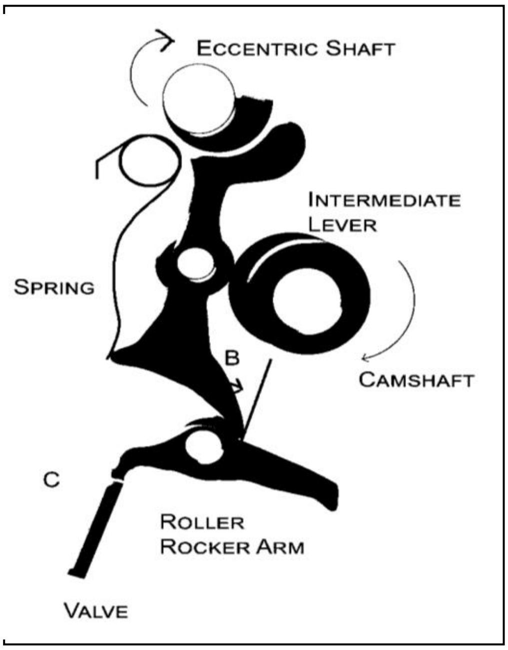


Figure 9-b: High Lift [11]

This ensures that the contact surface between the lower curved end of the intermediate lever and the roller of valve rocker arm remains almost flat (surface A) as described in Fig. 9-a. In this case, roller of rocker arm moves only along the flat surface A, so that the rotation of cam provides no or very small valve lift as intended [11].

High Lift Operation

In the case of high lift, the stepper motor turns the eccentric shaft in such a way that the eccentricity ismaximum and the upper end of the intermediate lever is in the forward position. This ensures that the contact surface between the lower curved end of intermediate lever and the roller of rocker arm becomes more round such as the surface *B* depicted in Fig. 9-b.

The roller rocker arm then moves along the rounded surface *B* so that the rotation of camshaft now results in a high lift of the valve [11].

Based on above operating principle, the Valvetronic system can generate the valve lift profile, as shown in Fig. 9-c.

The valve lifts of the both intake and exhaust valves can be adjusted continuously from less than 1 mm to 9 mm. In combination with two independent cam phasers, the timing and duration of intake and exhaust valves can be altered and optimized for different engine operating conditions.

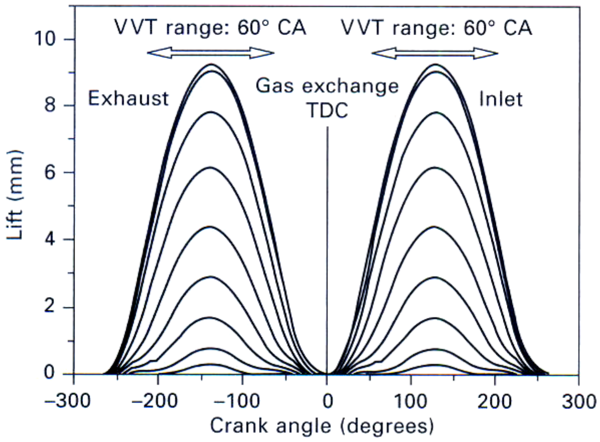
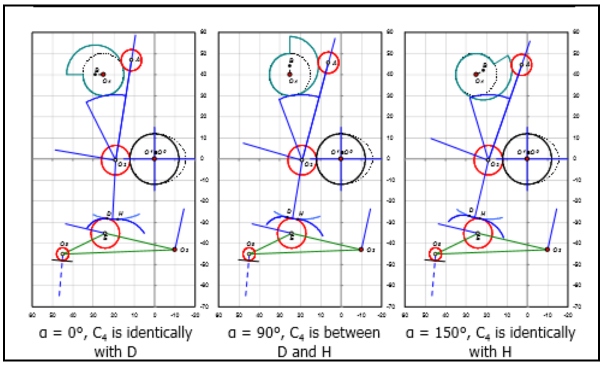


Figure 9-c: Variable Valve Lift Profiles in Valvetronic Mechanism [11]



α = 0°, C_4 is identically with D

α = 90°, C_4 is between D and H

α = 150°, C_4 is identically with H

Figure10.Mechanisms different positions for command angle α [4]

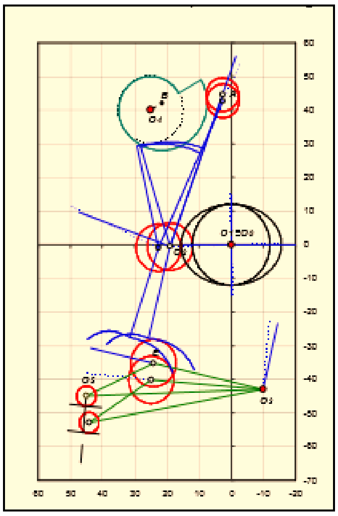


Figure 11. Mechanisms kinematic overlapped position at φ=0^o, φ=178^o and α=150^o[4]

Figure 10 shows the mechanisms different positions for different command angles i.e α=0^o α=90^o α=150^o and the position of contact point C_4 i.e the contact between ntermediate lever and Roller rocker arm.

Figure 11 shows the two extreme positions of the mechanism i.e at φ=0^o, φ=178^o and α=150^o for the VVL mechanism with three element with controlled shaft system.

IV.KINEMATIC ANALYSIS

To obtain the desired results, it is very important to identify the issues regarding the correct adjustment of the valve lift prior to the Kinematic analysis of the mechanism[1].

The condition to achieve the required maximum valve lift.

Achievement of maximum lifting height of the valves is a problem which may be reduced to[1]:

- Determination of the general configuration of the VVL mechanism
- Choice of a position of the element(s) of adjustment, called the maximum adjustment position,
- Achievement of the cam synthesis starting from the valve lift law with the maximum valves height (nominal law).
- For a given mechanism, the condition required to achieve maximum lifting height of the valves is therefore reduced to a problem of cam synthesis.

Thecondition to achieve the required minimum valve lift.

For a given VVL mechanism characterized by the nominal valve lift law and an adjustment range defined by successive positions occupied by the adjustment element(s), the achievement of minimum lift height of the valves is a problem that is reduced to[1]:

- Choice of a position of the element(s) of adjustment, called the minimum adjustment position, by modifying the maximum adjustment position, so that the valve lift reaches the required value,
- If the adjustment range does not contain a position of the adjustment element(s) which leads to a

minimum required valve lift, then the problem requires a mechanism optimization procedure.

- For a given VVL mechanism, the condition to achieve the required minimum valve lift is therefore
- Reduced to the finding of the minimum adjustment; otherwise, a dimensional reconfiguration of the
- Mechanism by an optimization procedure is necessary.

In order to proceed on the kinematic analysis with respect to the proposed mechanism as shown in fig.no. 12, we need to establish the equations for the contact curve[1].

- ⦿ C_α Contact curve parametric equation

- ⦿ Equations for the extended Contact curve

- ⦿ The contact with tangency equations with **C1** point
- ⦿ The contact with tangency equations with **C2** point

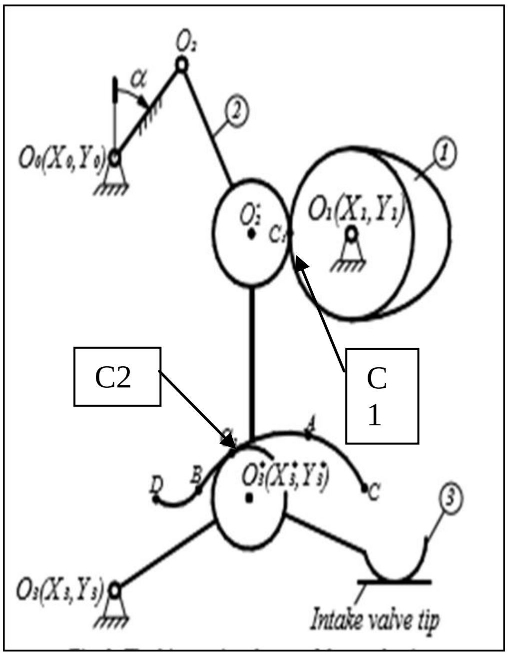


Figure 12 Kinematic schema of the mechanism[1]

- ⦿ C_α Contact curve equation

Let usconsider that the general coordinates system is *OXY* (fig. 12) and the rocker arm local coordinates system is *O*2 *x*2 *y*2.. Considering that the *C*2 contact point's coordinates, in *O*2 x2 *y*2, are $\tilde{x}_2, \tilde{y}_2$ from the permanent contact between *Cα*curve results in,

$$\tilde{x}_2 = -X_2 \cos\theta - Y_2 \sin\theta + X_3^{*} \cos\theta + Y_3^{*} \sin\theta + r_3^{*} \cos(\theta - \xi) \tag{1}$$

$$\tilde{y}_2 = X_2 \sin\theta - Y_2 \cos\theta + X_3^{*} \sin\theta + Y_3^{*} \cos\theta + r_3^{*} \sin(\theta - \xi) \tag{2}$$

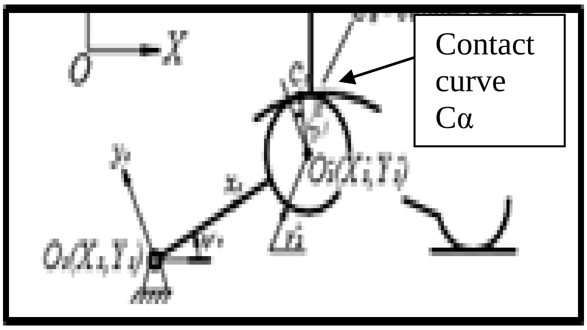


Figure 12-a Regular contact curve Ca [1]

- ⦿ Equations for the extended Contact curve

There is the possibility that the length of the contact curve arch to be deficient when the camshaft rotates, and therefore we have to consider the extended contact curve, Γ, which is obtained from *C*α by tangent-connecting, in points *A* and *B* , two circle arches of r_A and r_B radii (fig. 12-b)

$$\begin{aligned} x_\Gamma &= xo_A - r_A \sin(-\gamma_A - \alpha_{min} + \eta)\,, if \eta < \alpha_{min} \\ &= \tilde{x}_2, if\, \alpha_{min} \le \eta \le \alpha_m \\ &= xo_B + r_B \sin(-\gamma_B + \alpha_{max} - \eta)\,, if \eta > \alpha_{min} \end{aligned} \tag{3}$$

$$\begin{aligned} y_\Gamma &= yo_A - r_A \cos(-\gamma_A - \alpha_{min} + \eta)\,, if \eta < \alpha_{min} \\ &= \tilde{y}_2, if\, \alpha_{min} \le \eta \le \alpha_m \\ &= yo_B + r_B \cos(-\gamma_B + \alpha_{max} - \eta)\,, if \eta > \alpha_{min} \end{aligned} \tag{4}$$

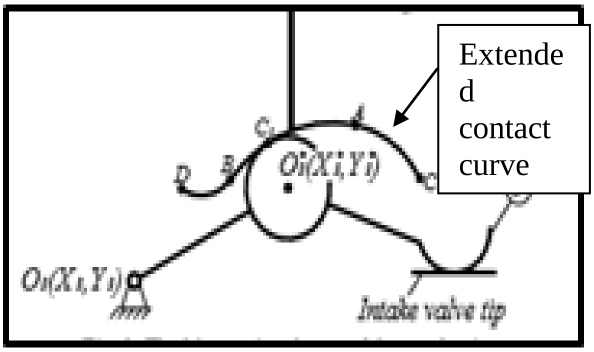


Figure 12-a Extended contact curve Ca [1]

- ⦿ The contact with tangency equations with **C1** point can be obtained as

$$X_2 + x_2 cos\theta - y_2 sin\theta$$
$$-X_1 - x_1 cos\varphi + y_1 sin\varphi = 0,$$
$$Y_2 + x_2 sin\theta + y_2 cos\theta$$
$$-Y_1 - x_1 sin\varphi - y_1 cos\varphi =$$

(5)

$$(x_{1p}x_{2p} + y_{1p}y_{2p})\sin(\varphi - \theta) - (x_{1p}y_{2p} - y_{1p}x_{2p})\cos(\varphi - \theta) = 0$$

- The contact with tangency equations with C2 point can be obtained as,

$$X_2 + x_T\cos\theta - y_T\sin$$
$$-X_3 - x_3\cos\psi + y_3\sin\psi = 0,$$
$$Y_2 + x_T\sin\theta + y_T\cos\theta$$
$$-Y_3 - x_3\sin\psi - y_3\cos\psi =$$

(6)

$$(x_{Tp}x_{3p} + y_{Tp}y_{3p})\sin(\theta - \varphi) - (x_{Tp}y_{3p} - y_{Tp}x_{3p})\cos(\theta - \varphi) = 0$$

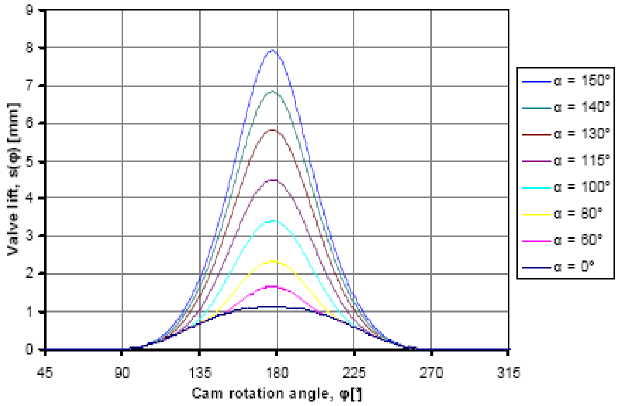


Figure 13. The evolution of valve lift for various command angle α

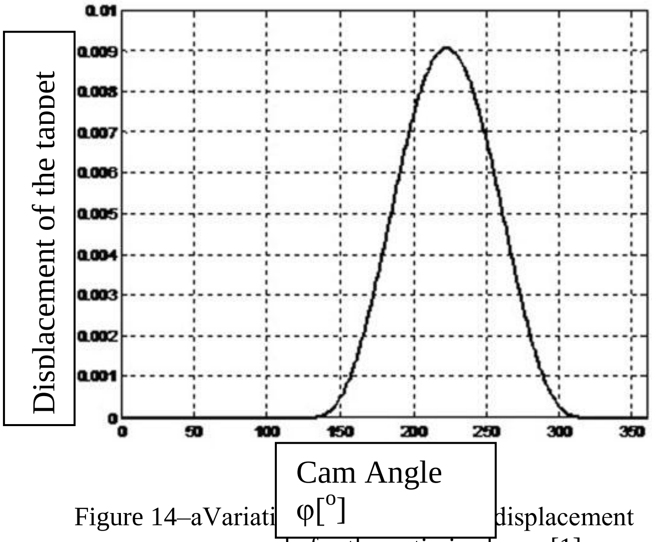


Figure 14–aVariati displacement versus cam angle for the optimized cam [1].

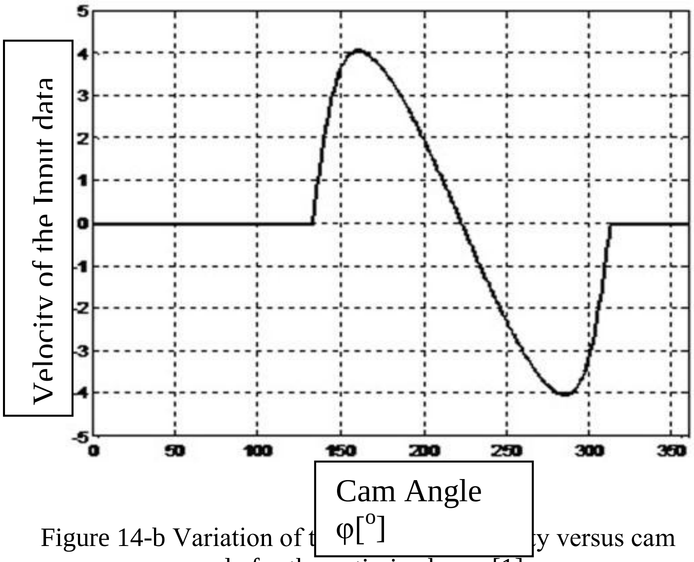


Figure 14-b Variation of t y versus cam angle for the optimized cam [1].

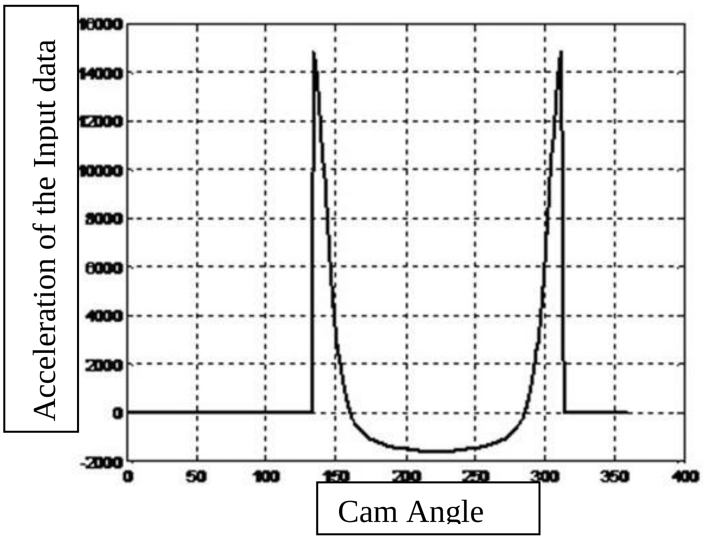


Figure 14-c Variation of the follower's acceleration versus cam angle for the optimized cam [1].

By increasing the adjustment angle from 100° (Maximum valve lift) up to 155°, it results the valve lift family laws (figure 13).After kinematic analysis results are obtained in terms of valve lift, velocity and acceleration as shown in figure 14-a, 14-b, 14-c.

V. CONCLUSION

- Variable valve mechanism having combination of variable valve lift (VVL) and variable valve timing (cam phasers), are generally designed to eliminate the conventional throttling losses.
- Discrete Variable valve lift mechanism, where the valve lift is in two steps (Low and High lift) or three steps (Low, medium and High lift) improves the performance at part load but cannot cover the whole range of speed and load.
- The variable valve lift mechanism with three elements with controlled shaft system offers a continuous variation of the valve lift, with valve

displacement starting from around 1 mm lift to a maximum lift around 8 mm.

- In CVVL mechanism with three elements with controlled shaft system, the intermediaterockerarmisequipped withaspecialdevelopedcontactsurface, which is based on the theory of envelop curves and has a plane- parallel motion.
- The general conditions such as correct adjustment of valve lift, minimum valve lift and maximum valve lift in design criteria needs to be considered for CVVL mechanism to ensure the valve opening according to requirement of the thermal regime of engine. These conditions are fulfilled by every timing mechanism with VVL.
- A correct valve lift adjustment is achieved when the following two conditions are simultaneously fulfilled: the valve remains closed, and the contact joints are maintained.
- By increasing the controlled shaft angle, the eccentricity of controlled shaft varies from minimum to maximum which results the valve lift family laws.
- The kinematic analysis shows that the mechanism offer a continuous variation of the valve lift, with valve displacement starting from around 1 mm lift to a maximum lift around 8 mm, without changing the valve opening and closing points.
- The variable valve lift mechanism with three elements with controlled shaft system stands superior in comparison with other VVL mechanisms and hence it is used for high end sedan car engine, as it cover the whole range of speed and load.
- CVVL is also a potential variable valve actuation technology for small capacity SI engine which offers throttle free load control and ensures better engine dynamic performance and lower consumption and emission.

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