

DigitalAir™ Camless FVVA System - Part 2, Gasoline Engine Performance Opportunities

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ABSTRACT

The paper describes a completely new approach to fully variable valve actuation (FVVA), which allows almost unlimited continuously variable control of intake and exhaust valve opening and closing events, and duration without the use of a camshaft.

DigitalAir replaces conventional poppet valves with horizontally actuated valves located directly above the combustion deck of the cylinder head, which open and close a number of slots connecting the cylinder with the intake and exhaust ports, [Figure 1](#). The stroke of the valves to provide the full flow area is approximately 25% of the stroke of the equivalent poppet valve, thus allowing direct electrical actuation with very low power consumption. This design arrangement also avoids the risk of poppet valve to piston collision, or the need for cut-outs in the piston crown, since the valves do not open into the cylinder.

The paper will present analytical and experimental data which confirms that the proposed FVVA system can meet the basic performance requirements of modern GDI engines with respect to breathing characteristics across the speed range, throttleless operation at and above idle, opening and closing event optimization, cylinder deactivation, control of residual gas fraction / scavenging and exhaust thermal management.

Analytical results were developed using GT-POWER Cycle Simulation and CONVERGE computational fluid dynamics (CFD). Cycle simulation was used to study the system level performance, such as full load capability and transient response, and in particular to quantify the fuel consumption benefits of throttleless operation. CFD was used to better understand the opportunities for in-cylinder charge motion - tumble, swirl and turbulence.

JP SCOPE Inc. has been running experimental engines with DigitalAir for several years and has successfully completed performance and durability tests. The mechanical and thermal design of the cylinder head, and the design of the actuator will be covered in Part 1 of this paper [1].

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INTRODUCTION

The benefits of FVVA for gasoline engines are well understood and well documented, for example by Schechter and Levin of Ford Motor Company [2]. With the development of turbocharged GDI technology, combined with downsizing, the opportunities for FVVA are perhaps even greater, especially given the regulatory pressure to reduce CO₂ emissions.

Fully variable valvetrain actuation may be defined as the complete freedom to command engine valve events directly from an engine control unit (ECU), for example as occurred with the development of common rail fuel systems. This would include the freedom to command the timing of intake and exhaust opening and closing

events, and hence the duration. The definition of FVVA should also include fast response such that the valves may be commanded within one engine cycle.

The most significant impediment to achieving FVVA is the camshaft, which ultimately restricts the range of valve events that can be achieved, since the driving force for valve operation is provided by the cam lobe. Several hundred mechanical and hydraulic mechanisms have been proposed as a means to modify the physical connection between the cam lobe and the poppet valve in order to provide some degree of control over intake and exhaust valves [3,4]. Some of these are available today in production vehicles, for example the Schaeffler UniAir [5,6], Audi AVS [7,8] and BMW Valvetronic [9]. Cam phasing systems (VCP) are widely available and often combined with variable valve systems (VVA) to provide a range of timing, lift and duration flexibility.

The documented studies of FVVA have, almost without exception, involved the development of fast response electro-hydraulic actuators which act upon conventional poppet valves [2,10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. With the possible exception of Koenigsegg [20], such systems have failed to progress beyond the research stage despite intensive efforts to move them forward. Perhaps the most significant impediment to successful commercial application is the poppet valve itself, which requires a relatively long stroke, high opening forces (at least on the exhaust valve), and carries the risk of valve to piston contact. Overcoming these factors ultimately drives cost, complexity, high energy consumption and packaging challenges into the electro-hydraulic actuator which thus far have restricted their application to the engine research laboratory.

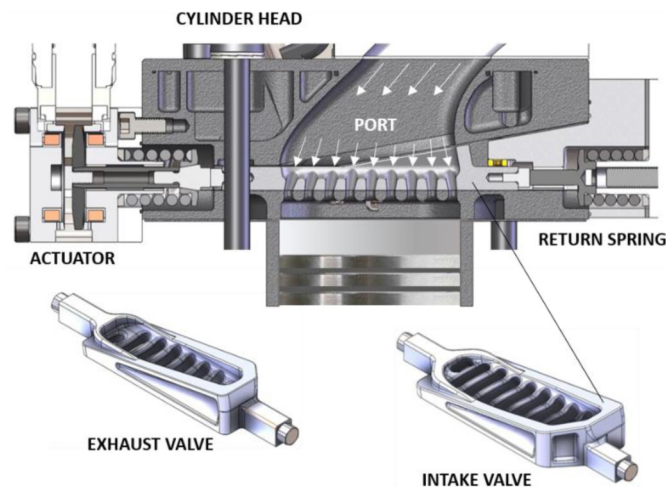


Figure 1. Horizontally acting intake and exhaust valves with direct electrical actuation

DigitalAir addresses the limitations to FVVA posed by the poppet valve, and at the same time eliminates the need for electro-hydraulic actuation. Figure 1 shows a cross-section through the cylinder and cylinder head of the DigitalAir system. Also shown are intake and exhaust valves. The important performance features will be discussed in a later section, supported by analytical results from cycle simulation and CFD and experimental results from single cylinder engine testing.

BRIEF REVIEW OF CAMLESS AND CAM-DRIVEN VVA SYSTEMS

Camless Valve Systems

There have been several notable attempts to develop cost-effective and efficient camless valve systems. Without exception, these have retained the poppet valve and sought to drive the intake and exhaust valves directly using electrical or electro-hydraulic actuation. Perhaps the first of these developments was that by Richman and Reynolds [10]. They developed a hydraulic actuator controlled by a fast acting servovalve. The system is shown in Figure 2.

The performance of this system was successfully demonstrated at engine speeds up to 1000 r/min. This system was used as a research tool to explore the benefits of valve control on engine performance and emissions.

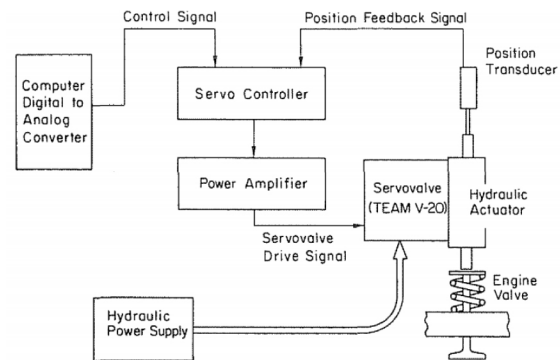


Figure 2. Valve-actuator system block diagram [10]

Ford engineers Schechter and Levin [2] developed a camless engine, again using poppet valves and an electro-hydraulic actuation system. The authors referred to the system as an electro-hydraulic camless valvetrain (ECV). The design used a novel hydraulic pendulum, shown in Figure 3. In Part I of their paper, they outlined the potential benefits of a camless engine, for example:

- Freedom to independently schedule valve lift, duration and placement,
- Reduced throttling,
- Improved fuel consumption,
- Improved volumetric efficiency,
- Improved torque at low and high engine speeds,
- Lower idle speeds and idle stability - by better control of residuals,
- Ability to deactivate cylinders for variable displacement,
- Improved packaging,
- Influence over charge motion and turbulence,
- Control of effective compression and expansion ratios, and
- Ability to create and control internal EGR.

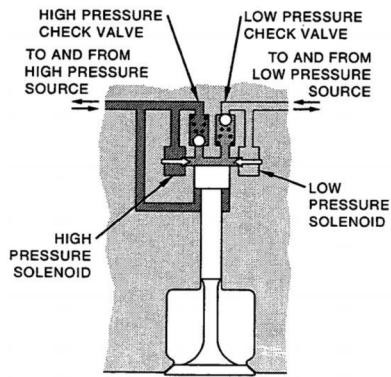


Figure 3. Hydraulic pendulum used in the Ford camless engine [2]

Turner et al [11] (Lotus Engineering), and Turner, Kenchington (Lotus Engineering) and Stretch (Eaton Corporation) [12] have developed an electrohydraulic valve train (AVT), shown in Figure 4.

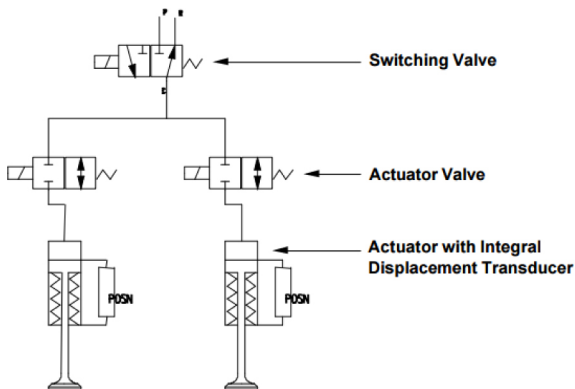


Figure 4. Hydraulic circuit of the Lotus / Eaton camless valve train [11,12]

The authors claimed the system to be capable of

- Throttleless operation,
- Controlled auto-ignition (HCCI),
- Fast start,
- Variable firing order,
- Differential cylinder loading, and
- Ultimately air hybridization.

The targets for the system development included: up to 15 mm lift, unrestricted event timing and phasing, maximum engine speed 7000 r/min with a timing repeatability of 1 degCA.

The analytical results presented from a Simulink model indicated power consumption for the AVT system would be of the order of 5.5 kW at 6000 r/min for a European 2L 16V engine operating at full valve lift.

Turner and Babbitt et al [13] at Sturman Industries developed a two-stage electro-hydraulic valve actuation system, shown in Figure 5. They had previously developed a single stage electro-hydraulic actuator and found limitations in the ability to control seating velocity over a wide range of engine speed and oil temperature / viscosity. The two-stage system was developed as a means to provide variable

geometry that could respond to inputs such as engine speed and oil temperature to better control seating velocity in a wide speed range gasoline engine.

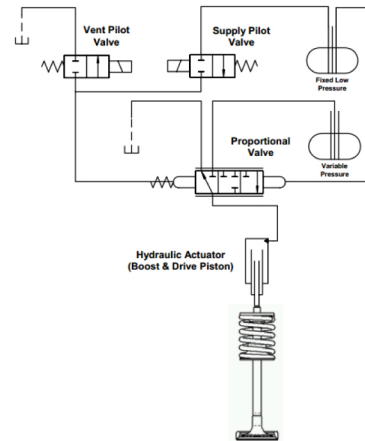


Figure 5. Two-stage electro-hydraulic valve actuation system [13]

Cam Driven Variable Valve Systems

Many mechanical and hydro-mechanical variable valve systems have been proposed. The most complete reviews by Dresner and Barkan [3,4], while dated, provide a useful classification system. They concluded that the 800 or so patents and technical papers they reviewed could be reduced to only 15 basic concepts. Here we will briefly review a selection of those systems in current production engines.

UniAir [5,6]

Figure 6 shows the design of the UniAir VVA system for the intake side of a 4 cylinder engine [5,6]. Figure 7 shows the General layout of the UniAir variable valve train system.

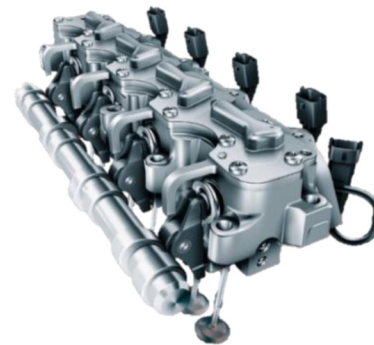


Figure 6. Design of the UniAir VVT system for the intake side of a four cylinder engine [5,6]

UniAir is a cam driven electro-hydraulic variable valve timing and lift system, first developed by Fiat as the *MultiAir* system, later licensed by Schaeffler. The major components of the UniAir system are shown in Figure 7, and comprise a fast acting solenoid valve, a high pressure reservoir and a piston pump operated by a roller finger follower and output cylinders that act directly on the engine valves. The available valve lift profiles are shown in Figure 8. Essentially this device is an electro-hydraulic lost motion device, which allows a

range of lift profiles within the envelope of the cam lobe. The primary application of the UniAir system is to reduce or eliminate throttling as a means of load control in gasoline engines.

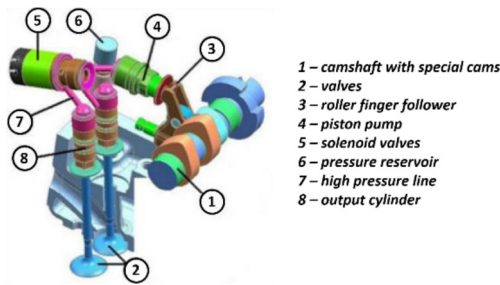


Figure 7. General layout of UniAir variable valve train system [5,6]

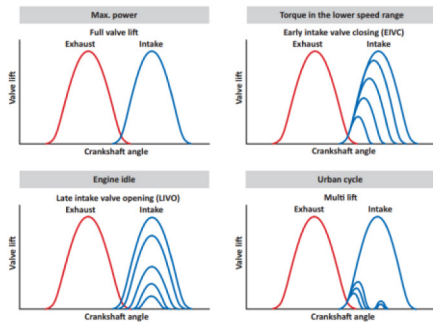


Figure 8. UniAir valve lift modes for the intake side [5,6]

Audi Valvelift System (AVS) [7,8]

The Audi AVS system is essentially a cam profile switching system (CPS) combined with a hydraulic cam phasing system [7,8]. The cam profiles are designed to better optimize performance across the engine speed range. When combined with cam phasing AVS provides a means to significantly reduce throttling and to provide optimum torque and power. In some applications AVS is applied to both intake and exhaust valves. Figure 9 shows two operating modes of the Audi AVS system.

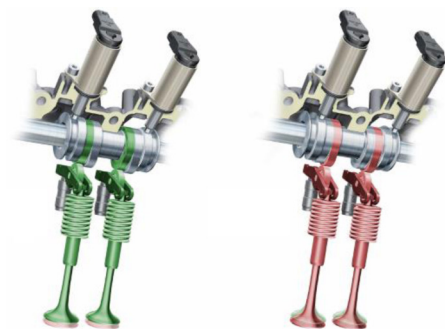


Figure 9. Audi valvelift system for the 2.0 L TFSI engine [7,8]. At left is the 'small cam' for low engine speeds, and at right is the 'large cam' for high engine speeds.

BMW Valvetronic [9]

Figure 10 shows the BMW Valvetronic variable valve timing system, which provides variable intake lift and duration. It is typically combined with cam phasing. Valvetronic controls valve lift by modulating the fulcrum of a roller finger follower by means of an

eccentric shaft, thereby delaying the engagement of the cam lobe with the follower and allowing control of valve lift. Valvetronic is combined with a cam phasing system to allow control of both lift and timing [9]. The wide range of valve lift control (0.18mm to 9.9mm) combined with cam phasing allows throttleless operation over a significant portion of the operating range of the engine.

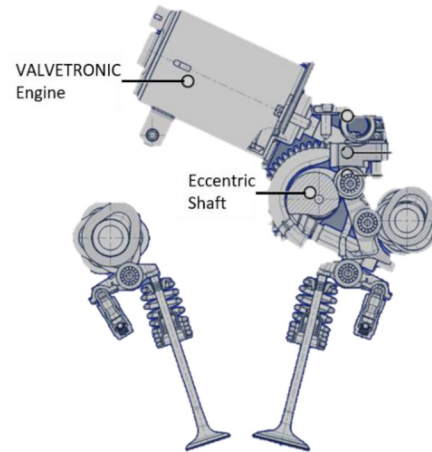


Figure 10. BMW Valvetronic variable valve timing system [9], which provides variable intake lift and duration. It is typically combined with cam phasing.

THE DIGITALAIR CONCEPT

Figure 1 shows a cross-section of the DigitalAir system developed by JP SCOPE Inc. DigitalAir replaces the poppet valve with horizontally acting slotted valves, which provide the full flow area with a very short stroke compared with a poppet valve [21, 22, 23, 24, 25]. This approach provides advantages over electro-hydraulic camless poppet valve systems, such as:

- Short stroke from fully closed to fully open
- Direct solenoid actuation
- Fast opening - 2 ms
- High integrated effective flow area $\dots \int_{Open}^{Close} A \cdot Cd$
- No possibility of valve-to-piston contact
- Low opening forces
- Low power consumption
- Control of seating velocity

As with any new technology, this approach does raise some obvious questions, which are being addressed and will be discussed further in this paper and in the companion paper [1], for example:

- Volume of slots added to the combustion chamber
- Sealing between cylinder and ports
- Surface area, heat transfer and cooling of the valve bridges
- Potential for quenching and hydrocarbons in the slots
- Wear on the mating faces due to debris

In this paper analytical and experimental results are presented from a variety of engines, Table 1.

Table 1. Engine platforms included in this study.

Displacement	Bore x Stroke mm	Study	Comments
0.5 L	92 x 75	Performance, Durability	Single Cylinder Test platform
2.0 L	87.5 x 83.1	Cycle Simulation	Four Cylinder GTDI with VVA
0.57 L	87.5 x 94	CFD	Single Cylinder 4V & DigitalAir

Breathing Capability

Figure 11 shows the geometry of the intake and exhaust slots controlled by the movement of the valves placed above the combustion deck of the cylinder head as shown in Figure 1. Although the fully open geometric area of the DigitalAir valves is less than the typical 4V intake fully open geometric area, this is offset by a combination of rapid opening (2 ms), favorable discharge coefficient (>0.90) and the freedom to optimize event timing. As will be shown in a later section, this geometry is capable of delivering volumetric efficiency comparable with a conventional 4V poppet head.

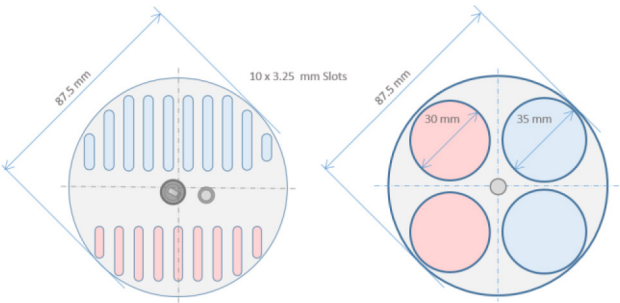


Figure 11. Plan view of the prototype head based on the Mazda 2.3L engine. At left is the DigitalAir head showing the intake and exhaust slots. At right is the production head showing intake and exhaust poppet valves.

Figure 12 shows a sample of the flow bench fixtures used to quantify the discharge coefficient of intake and exhaust slots under steady flow conditions. A range of slot geometric parameters were studied as illustrated in Figure 13.

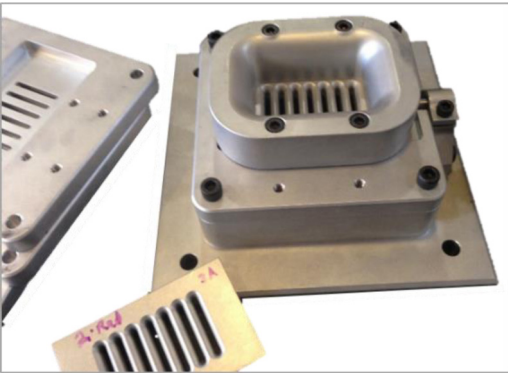


Figure 12. Flow bench fixtures used to assess slot discharge coefficients.

The CFD study considered 38 different slot geometries at 3 pressure drops: 70 mbar, 172 mbar and 6.9 bar, with inlet pressures of 1.07 bar, 1.17 bar and 7.9 bar respectively. The fluid was assumed to be air at 300K. Figure 14 shows a sample of the CFD study where slot

geometries were being screened for performance. The CFD and flow bench results correlated quite well with discharge coefficients exceeding 0.90.

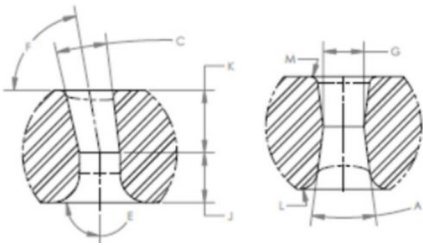


Figure 13. Slot parameters studied on a flow bench and with CFD analysis.

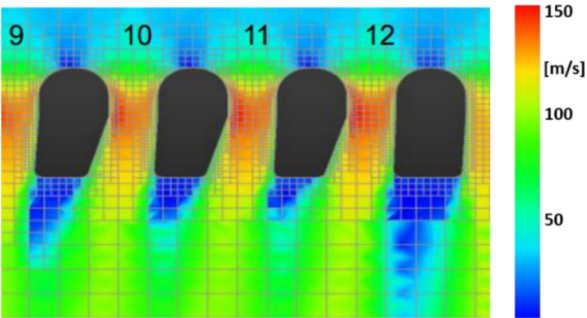


Figure 14. A large number of slot geometry variations were studied using CFD to narrow the options for intake and exhaust valve design. The figure shows velocity contours for four variations - with 70 mbar pressure drop, 1070 mbar inlet pressure.

Range of Operation

The DigitalAir system allows intake and exhaust valves to be commanded open and closed almost without limitation. With 2 ms opening and closing ramps, valves can be opened fully in less than 20 degCA at 1000 r/min, and 84 degCA at 7000 r/min, see Figure 15.

Figure 16 illustrates the freedom to command valve events provided by the DigitalAir system. Since the valves can be opened in 2 ms, the valve profile resembles a square wave at low engine speeds and a trapezoid at higher engine speeds.

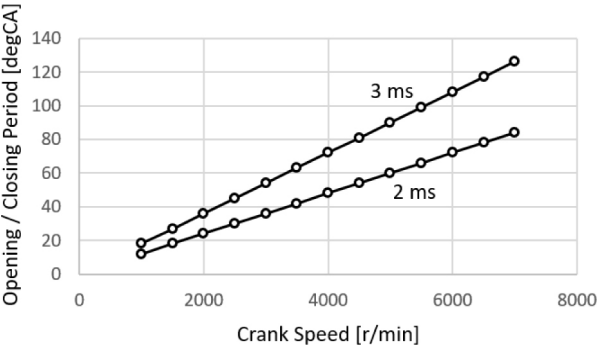


Figure 15. Valve opening / closing period versus engine speed for 2 ms and 3 ms actuation rates. The system has been designed for, and achieves, 2 ms opening and closing periods.