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Production AVT Development: Lotus and Eaton's Electrohydraulic Closed-Loop Fully Variable Valve Train System

Entwicklung eines Serien-AVT-Systems: Lotus' und Eatons elektrohydraulischer voll variabler Ventiltrieb (AVT)

1. Introduction

Lotus and Eaton are collaborating to bring a production closed loop control Fully Variable Valve Timing system, known as Active Valve Train (AVT), to market in the 2008-9 timeframe. The system uses electrohydraulic operation, movement of the engine poppet valves being initiated by oil flow into and out of a hydraulic chamber which is controlled by fast acting electrohydraulic servo valves developed by the two companies. This in turn allows infinitely variable timing, duration and lift.

The system, which is currently being engineered in prototype form for an OEM, will allow ready application of many advanced engine control strategies, such as throttleless operation, Controlled Auto Ignition (or Homogeneous Charge Compression Ignition), fast start, variable firing order, differential cylinder loading and ultimately air hybridisation. However, to gain acceptance in the marketplace, the two partners understand that productionisation must not come at the expense of high Bill Of Materials cost, and in controlling that requirement, the performance of the system must not be allowed to suffer.

This paper relates the present developmental status of the system from a valve control standpoint and describes some of the design features which have been adopted to fulfil the above requirements. An estimate of BOM costs for a typical light duty automotive application is also given.

1. Vorwort

Lotus und Eaton entwickeln zusammen einen voll variablen Ventiltrieb, auch 'active valve train' oder AVT genannt, der etwa 2008 / 2009 Serienreife haben wird. Das System verfügt über einen 'closed loop Controller' und benutzt eine Elektrohydraulik, die die Bewegung der Ventile durch Ölfluss steuert. Der Ölfluss in und aus der Hydraulikkammer wird durch schnell schaltende elektrohydraulische Servoventile kontrolliert, die Lotus und Eaton miteinander entwickelt haben. Hierdurch werden ein variabler Ventilhub sowie variable Öffnungszeiten ermöglicht.

Das System, das sich derzeit im Prototypenstadium befindet und für einen großen Fahrzeughersteller entwickelt wird, wird die Applikation von vielen unterschiedlichen Steuerungsstrategien wie Motoren ohne Drosselklappe, HCCI, CAI, variable Zündfolge, gesteuerter zylinderspezifischer Mitteldruck und Luftdruck-Hybridisation ermöglichen. Um jedoch eine hohe Marktakzeptanz zu erreichen, muss das System nicht nur technisch, sondern auch wirtschaftlich machbar sein. Beide Entwicklungspartner verstehen diesen Zielkonflikt und entwickeln ein System, dass beide Seiten gleichermaßen berücksichtigt.

In diesem Paper werden der derzeitige Entwicklungsstatus des AVT Systems, die Strategie der Ventilkontrolle sowie einige Entwicklungsmerkmale dargestellt, die dazu dienen, die oben genannten Forderungen zu erfüllen. Eine Abschätzung der Kosten des Systems am Beispiel eines kleinen Nutzfahrzeugdieselmotors beschließen die Präsentation.

2. The Benefits and Drivers leading to the Choice of a Fully Variable Valve Train System

There are many theoretical advantages to having continuous control over the three basic dimensions governing intake and exhaust valve events in poppet valve four-stroke engines. Variation of valve opening point, valve closing point and valve lift directly effects the gas exchange process, so that the pumping losses and, in some circumstances, the combustion timing of the engine are affected [1,2]. Together with a variable intake system, the correct intake valve closing point (IVC) can lead to significant increases in full load torque in addition to the part load improvements which have been observed [3]. Optimising exhaust valve opening (EVO) can lead to increased expansion and therefore improved efficiency, and varying exhaust valve closure (EVC) directly controls the amount of exhaust gas trapped inside the cylinder and can therefore have a major effect on NOx emissions.

At present, the only variable valve train capable of varying the intake valve opening duration continuously between limits is BMW's "Valvetronic" mechanism, which also requires an inlet cam phasing device to realise the full benefits of Miller Cycle Early Inlet Valve Closure operation (EIVC). Other cam switching mechanisms exist which provide a degree of these EIVC benefits, such as the INA switching tappet [5], manufactured under licence from Lotus, and Honda's V-Tec mechanisms [6].

One common trait shared by all of these Mechanically Variable Valve Trains is that, for each extra level of flexibility, another degree of complication is unavoidable. This is illustrated in Figure 1, which shows an oscillating cam mechanism with the same functionality as Valvetronic, but which is clearly far more complicated than the simple direct acting cam profile switching tappet arrangement embodied by the Lotus-INA mechanism also shown. Both of these devices also need intake cam phasing to realise part load reductions in pumping losses.

Given that completely flexible control of valve events is a very desirable concept from a thermodynamic and engine control standpoint, and that a purely mechanical system would be inordinately complex (if indeed possible to arrange), one has to look to other actuating media to obtain the desired functionality. Coupled to this, the cost of development and manufacture of purely-mechanical systems is likely to increase for diminishing returns, whereas a Fully Variable Valve Train is likely to become cheaper as take-up is increased. Hence Lotus and Eaton, in the production AVT project, have set out to develop a practical, cost-effective FVVT system.

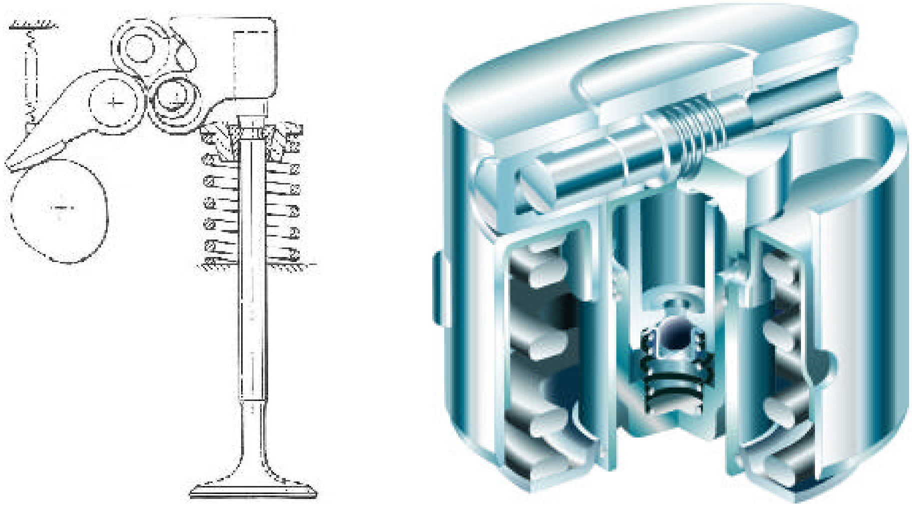

Fig. 1: Lotus "Oscillating Cam" Early Inlet Valve Closure Mechanism (left) and Lotus-INA "Cam Profile Switching" Coaxial Tappet (right) [Courtesy INA-Schaeffler KG]
Bild 1: Lotus "Schwenknocken" frihe einlass Ventil schliessen Einrichtung (Links) und Lotus-INA "Nocken Profil Schaltend" koaxialen Nocke (Rechts) [Bedankum zum INA-Schaeffler KG]

2.1 Production AVT System Selection Considerations

Lotus is a pioneer in the engineering of fast-acting electrohydraulic systems and has over 25 years experience of developing them. It was the first manufacturer in Formula 1 racing to win a race with an Active Suspension car (Figure 2). Since then, Lotus' Control Systems department has engineered many "Active" systems, including Anti-Noise and Active Rear-Wheel Steer. Where high force authority is required, hydraulics have generally been the preferred actuating medium, but the selection of actuation power source for a Fully Variable Valve Train system was not automatically made favouring hydraulics.

Fig. 2: Lotus Active Suspension F1 Car
Bild 2: Lotus ablauffährig Aufhängung F1 Auto

Investigations and calculations were carried out into both electromagnetic and electrohydraulic systems and, for simple electromagnetic operation, the benefits arising from low power consumption weighed against the combustion disadvantages enforced by fixed lift operation. Following this, a table of performance targets was drawn up, determining that for optimum engine control any system chosen should be capable of meeting the following criteria:

Table 1: Production AVT Performance Targets
Table 1: Die functionen Ziel für Serienreifen voll variable Ventiltrieb

Variable	**Performance**
Lift	0-15mm, Continuously Variable
Valve Opening / Closing Timing	Unrestricted
Phasing of Event	Unrestricted
Maximum Velocity	5m/s
Valve Operation	Individual
Maximum Engine Speed	7000rpm (Gasoline/HSDI) 2400rpm (Heavy Duty Diesel)
Residual Cylinder Pressure	20bar (70bar for Exhaust Braking)
Lift Repeatability	1%
Timing Repeatability	1° Crank Angle

The investigation of electromagnetic systems showed that the major issues would be those relating to the method of actuation, specifically the lack of easily-controlled soft touchdown and variable lift facilities. Control of the force with respect to the displacement of the valve would also be an engineering challenge.

It was also felt that there would be packaging issues, particularly with the commonly-imagined arrangement of electromagnets acting along the line of the valve stem, though it was accepted that oscillating arrangements might be better in this respect. The failure mode of these systems was also considered a problem as a latching mechanism would have to be provided to allow engine operation without excessive cut-outs in the piston crown. A related concern was that any lack of real-time positional feedback control would make them virtually impossible to apply to diesels; since one of the primary targeted benefits for such a system was a mechanism readily to control HCCI, this was considered a major drawback, as it virtually halves the prospective marketplace for such a Fully Variable Valve Train system.

From these investigations, it was concluded that the production AVT system should be electrohydraulic, and employ a real-time feedback system for valve motion control. Serendipitously, the production programme could also draw heavily on work already conducted in the engineering of the commercially-available Lotus Research AVT system. This in turn would also ensure that the Powertrain Research Group would not be constrained by the development process for the valve gear in the investigation of control parameters and methodologies applicable to it, and therefore that a simultaneous engineering approach for both mechanism and combustion control could be adopted throughout.

3. Production AVT System Philosophy and Design

3.1 Research AVT Baseline

Photographs of an engine fitted with the Research AVT system, which Lotus has been providing to clients for 13 years, are shown in Figure 3.

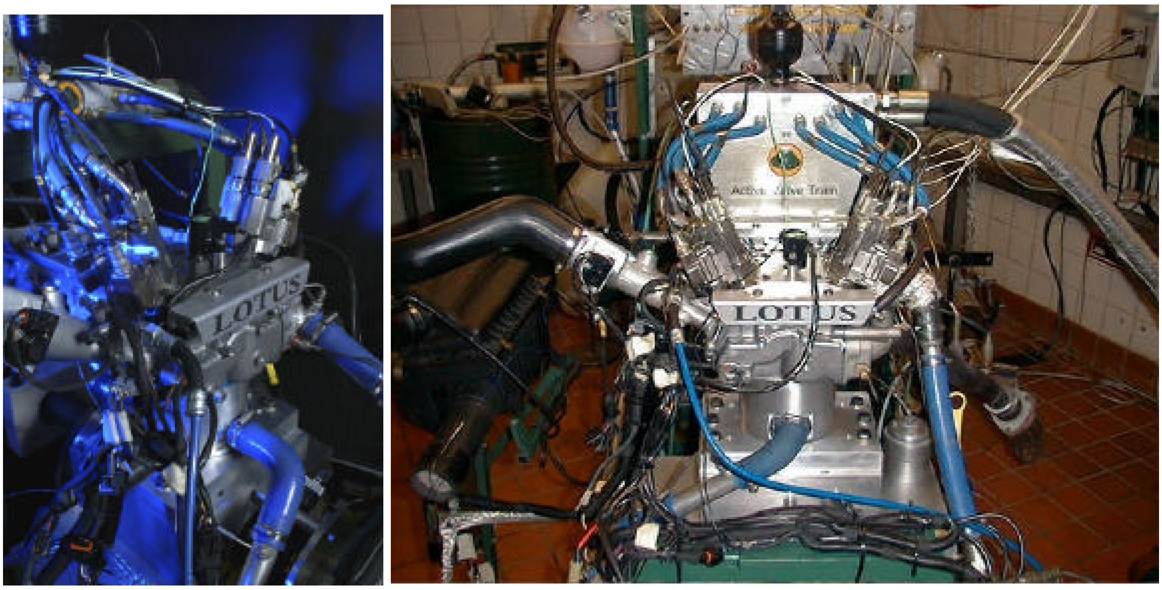

Fig. 3: Photographs of Research AVT System fitted to a Single Cylinder Engine
Bild 3: Bilde vom Forschungs AVT System auf ein einzel Zylinder Motor

The valves are hydraulically opened and closed in a desmodromic fashion; there is no return spring in this system. The actuator valve block with its hydraulic drillings used to achieve this is shown fitted with the 4-way servo valve in Figure 4.

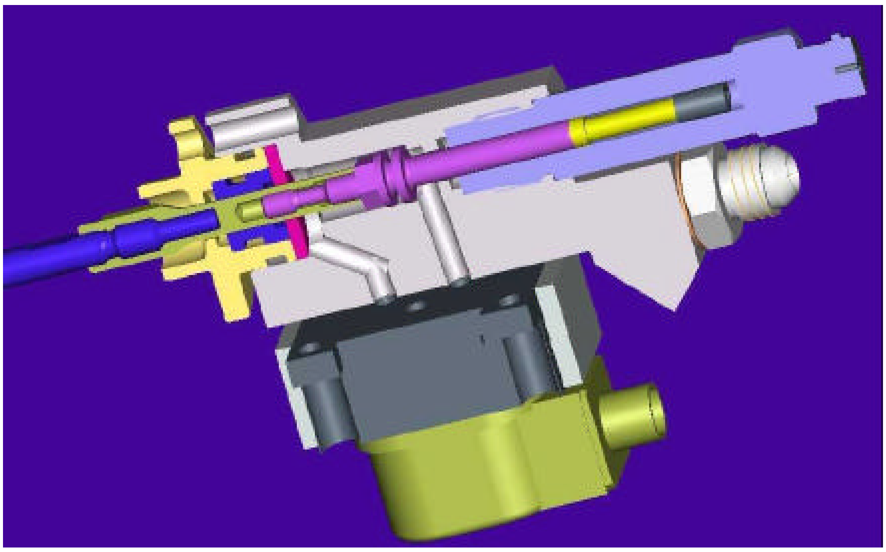

Fig. 4: Valve Block of Research AVT Actuator (4-Way EHSV at Bottom, Displacement Transducer at Top Right)
Bild 4: Ventil Block vom den Forschungs AVT Bedienteil (4 Weg EHSV untern, Ablösung Sensor oben)

The 4-way electrohydraulic servo valve switches pressure to either the top or the bottom chamber (depending upon whether the valve is being commanded to open or close, respectively), simultaneously venting fluid from the bottom or top chamber. Figure 4 also shows the position sensor fitted to the top of the actuator rod which feeds back in real time to the valve control computer, allowing it in turn to alter the position of the 4-way valve to achieve the desired valve displacement for any given crank angle.

The 4-way electrohydraulic servo valve is extremely expensive, being developed for controlling the flow of fuel and oxidant systems in rocket engines, and so is not a viable option for any production system. Furthermore, it does not offer sufficient speed for accuracy at engine speeds above 4000rpm. A new approach was required which would simultaneously minimise cost and markedly improve performance.

3.2 Production AVT Actuator Layout

For the production AVT programme, the hydraulic system determined to offer the functionality targeted in Table 1 is shown schematically in Figure 5. Immediately one can see that the hydraulic complexity of Research AVT has been halved by the use of a return spring. The remaining functionality of the Research AVT system's 4-way valve is then split into two. A 'switching valve' is used to direct flow either to or from 'actuator valves' (one per engine poppet valve) depending upon whether the poppet valve is to be commanded to move open or closed.

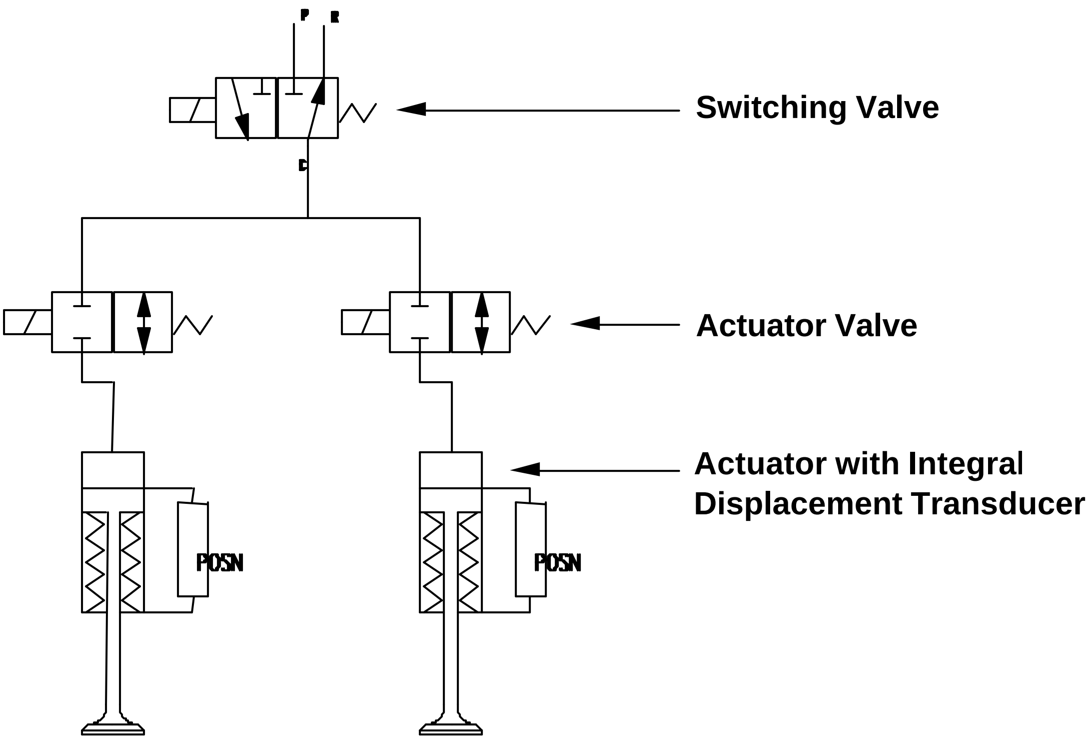

Fig. 5: Schematic of Hydraulic Circuit of Production AVT System
Bild 5: Schema von hydraulischen AVT Kreislauf den serienreife AVT System

A typical sequence of operation from a closed position would occur thus (see also Figure 6): the switching valve would move to "pressure", the actuator valves remaining closed. Some controlled leakage through the actuator valves would lift the valve from the seat. The actuator valve would then positively open to enable a faster opening rate, and then close near to peak lift. The valve would continue to open slowly because of the controlled leakage mentioned above. At approximately half way through the valve event the switching valve would move to "return" and the controlled leakage would start to allow the valve slowly to close due to the strain energy stored in the spring during the opening event. Positive opening of the actuator valve now allows the valve to close faster. Near to the seat the actuator valve closes, and the controlled leak and reduced spring load now gives soft touch down and with it the facility to tailor valve overlap.

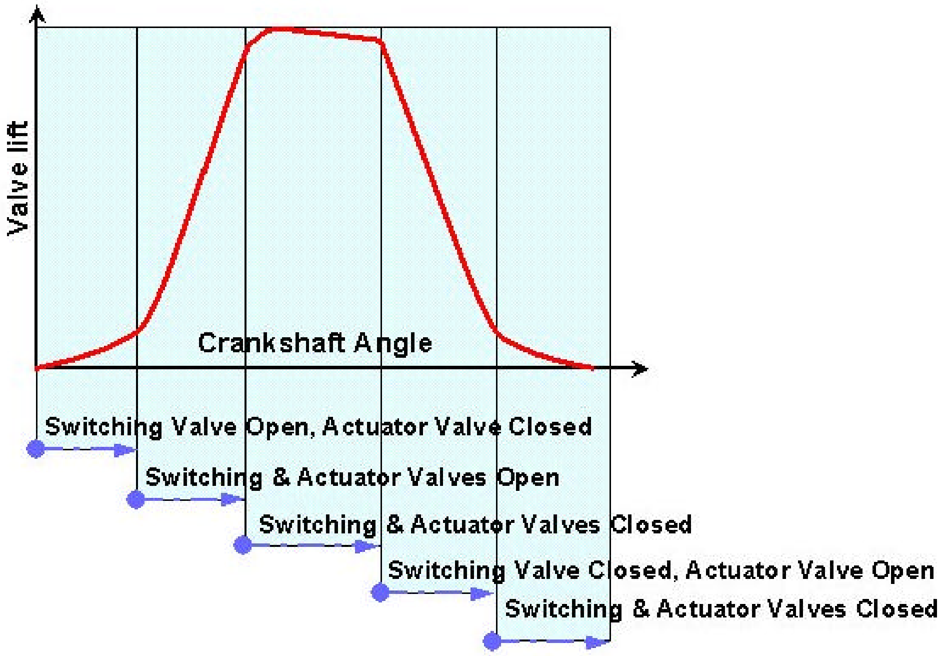

Fig. 6: Production AVT Control Valve Sequencing versus Crank Angle
Bild 6: Die Ablaufsteuerung den serienreife AVT kontrol ventil gegen den Kurbelwinkel

Valve position is controlled via a closed loop, with the position sensor being inside the actuator body: it is wrapped around the hydraulic chamber, with the target for the sensor being the hydraulic piston. The piston itself is not rigidly attached to the valve; instead it butts up against the valve tip, and the whole AVT cassette can be mounted in one unit to the top of what is a cylinder head of largely conventional architecture, albeit one without the complication of cams and tappets and their associated components.

The return spring brings other significant advantages, as well as providing a conventional cylinder head arrangement and assembly procedure. When the engine is switched off, setting all of the control valves to "return" ensures that the poppet valves park on their seats (cf. the electromagnetic systems needing an additional locking mechanism to achieve this, otherwise having to park half-open). This means that at start up the system automatically has a baseline, and during start procedures the valves can be held closed if required to allow the crankshaft to spin to a higher speed before allowing the admission of air. Parking closed also means that SHED test results are likely to improve, there now being no leakage path from intake to exhaust system for backflow of uncatalysed exhaust gases. Finally, the reduction in closing force near to the seat means that soft seating is easier to arrange.

It was decided very early on in the programme that the system would not be engineered to attempt to reproduce polynomial valve profiles, as these are only a function of the limitations of a spring system being operated by a mechanical cam. Instead it was intended to provide trapezoidal profiles with an opening and closing ramp of minimum fixed rate, and opening and closing flanks of variable velocity up to the target maximum of 5m/s. Clearly, the amount of valve lift is variable as well. All of this will allow control of touchdown, overlap, duration and time-area to suit an engine's mechanical and airflow requirements within the limitations of the system.

3.3 Balance of System

A complete AVT system is shown schematically in Figure 7, which represents the hydraulic circuit of a 4-cylinder, 16 valve engine.

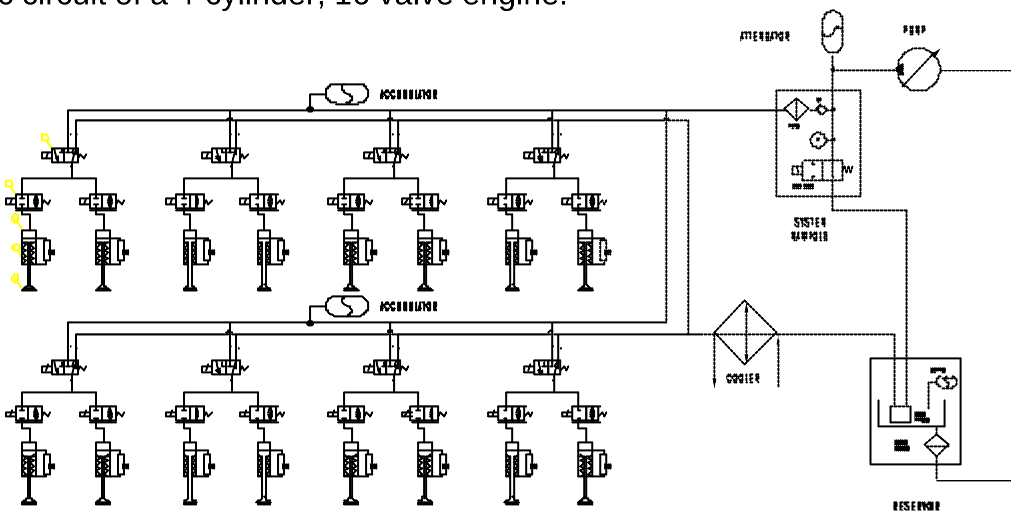

Fig. 7: Hydraulic System Schematic for 4-Cylinder, 16 Valve Engine
Bild 7: Das Schema den hydraulische System für 4 Zylinder, 16 Ventile Motor

The pump is a variable displacement unit supplied by Eaton-Vickers, a subsidiary of Eaton Automotive, and is shown in Figure 8. Since (to a first degree of approximation) the power necessary to drive the valves is linearly proportional to the lift demanded, and the pump will never pressurise more fluid than required to a pressure greater than required, substantial savings in hydraulic drive power can be expected at light load. This is discussed in more detail later in this paper.

Fig. 8: Variable Displacement Pump supplied by Eaton-Vickers
Bild 8: Variable Verschiebepumpe von Eaton-Vickers

The remaining hardware comprises flow lines, accumulators and attenuators, together with a cooler and possibly a heater for low temperature operation. This may or may not be necessary as, firstly, flowing hydraulic fluid through orifices, even at low rates, generates significant heat, and, secondly, the coils in the control valves could briefly be used as heaters to enable a better start.

The cassette-type construction of the hydraulic valve drive mechanism (which will be bolted to the cylinder head and could possibly be provided as an assembly with it), means that the number of potential leakage paths has been minimised. The only moving seal is that running against the actuating piston, because, unlike the research system, there is no need to have the positional feedback sensor on the *end* of the valve (Figure 4).

Mock-ups of the system suggest that the package of an engine with Production AVT could be reduced in size; additionally, the valves could be placed at an angle so that lowering the overall engine height, and with it increasing the clearance to the bonnet, is also a possibility.

Currently the actuators are at an advanced state of prototype development, ready for fitment to a cylinder head for rig and engine testing for an OEM.

The hydraulic oil system is designed to be completely separate from the crankcase lubrication system, but the oil is compatible with existing engine oil should any crossover occur. In the long term it is envisaged that the formulation of crankcase oils for engines with this type of valve gear could be modified, as there will no longer be any need to have friction modifiers commonly associated with cam-to-tappet pressure resistance, etc. present in current oil blends.

3.4 Modelling for Performance and Power Consumption

In order to develop the control strategy, and to assess the impact of design changes on system performance, a Simulink model was built utilising control algorithms developed and used on the Research AVT system. In addition to establishing whether the system would meet its target performance, this modelling work allowed estimates to be made of the degree of phase advance necessary for the switching and actuator valves to obtain the desired valve motion.

The Simulink model allowed initial estimates of power consumption to be made. This was found to be in the order of 5.5kW at 6000rpm crankshaft speed for a conventional European-type 2 litre 16 valve engine, running full-lift valve events for maximum power. This is obviously a high amount (piston friction might be expected to be about 6.5kW here), and would be expected to reduce for the lower lift values needed at part load. Further reductions in power consumption can be expected with reduced system pressure at low engine speed and valve lift rates, and valve deactivation (on the inlet or exhaust) or skip-firing operation in some areas of the operating map. Further benefits would accrue on pressure charged downsized engines, which would seek to reduce the number of cylinders for a given power output, and hence the number of engine poppet valves and the total hydraulic flow rate.

For the typical range of valve lifts and number of cycles per second of the engine types targeted for this technology, oil flow rates of 20 litres per minute for the actuator valve and 40 litres per minute for the switching valve will be required.

3.5 Control Valve Detail Design

With the philosophy decided upon and the initial control valve modelling complete, detail design of the control valves could begin.

Lotus' initial intention was not to perform the detail design of the hydraulic control valves itself. However, a study of available products from existing manufacturers, and discussions with most of them, revealed that nothing was commercially available that met the demanding requirements in terms of overall flow capacity and frequency response. Consequently Lotus has had to carry out initial design and testing itself.

A CAD representation and photograph of a sub-module for the inlet or exhaust valve is shown in Figure 9. The switching valve can be seen to the left in each picture and the two actuator valves are above the actuator pistons which would in turn be above the valve stems. The feed and return galleries are visible in the right-hand CAD representation, communicating with the switching valve.

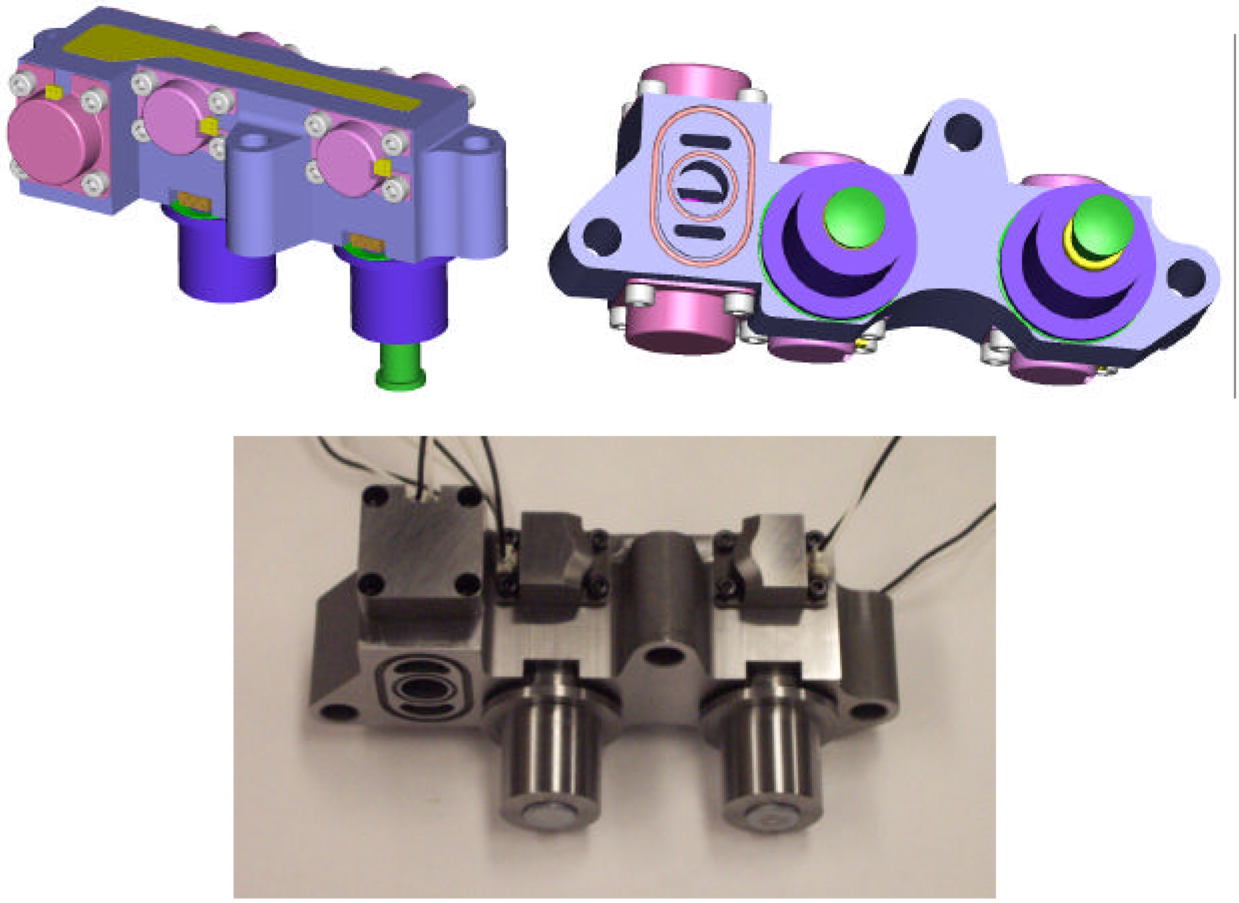

Fig. 9: CAD Models and Photograph of AVT Sub-Module for Inlet or Exhaust Valves of a Single Cylinder
Bild 9: CAD Modelle und ein Bild den AVT Baugruppe für Einlass oder Auslaß Ventile vom ein Zylinder

These modules are in the final stages of prototype development prior to fitment to an OEM's engine cylinder head for rig testing and then on an engine for fired testing.

4. Rig Testing and System Power Consumption

4.1 Actuator Rig Testing

Rig testing has been conducted throughout the actuator development programme to gauge the actuators' response to input commands [7]. This has been carried out on a dedicated rig. The current performance of the latest level of development is shown in Figure 10.

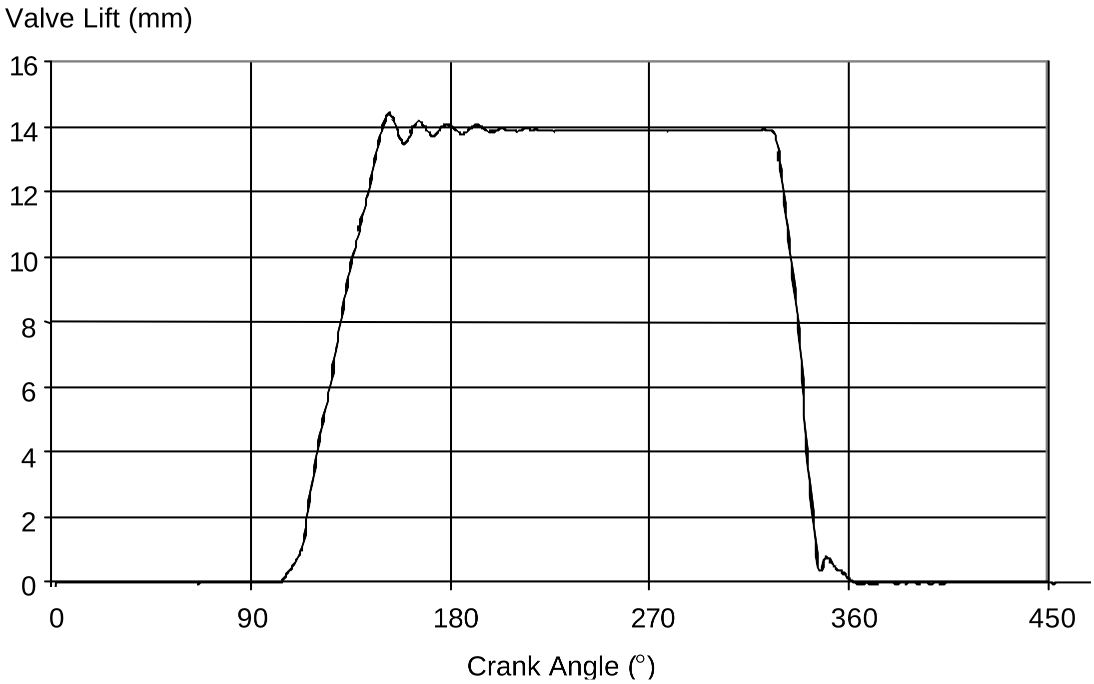

Fig. 10: Performance of Production AVT Actuators: 1000rpm, 140bar System Pressure
Bild 10: Die functionen den Serienreife AVT Ablösungen:
1000rpm, 140bar System druck

From this rig work, knowledge of oil flow paths and the Matlab Simulink modelling discussed above, estimates of hydraulic power for a 4-cylinder, 16 valve engine has been derived (Figure 11). These are shown for different system pressures which would correspond to different engine operating conditions; they reveal that whereas valve lift (and hence hydraulic oil flowrate) is a major driver on system power consumption, the rate of valve lift is also a driver (as it affects the system pressure and hence the flow losses through the system).

This estimation has been conducted with the assumption that all of the valves operate all of the time, and so represents something of a worst case, since valve deactivation, skip firing, single exhaust valve operation at light load etc., could be expected to yield further benefits. Regardless of this, it does compare favourably with published data on power consumption for electromagnetic systems [9], suggesting that 0.8kW *per valve* may be needed for electromagnetic actuation for a 'low power consumption' configuration – i.e. 12.8kW in total for a 16 valve engine, far in excess of what might be expected for the piston friction of such an engine.

Figure 11(a) clearly shows that if valve lift can be held to a minimum the power consumption will be very low at light load.

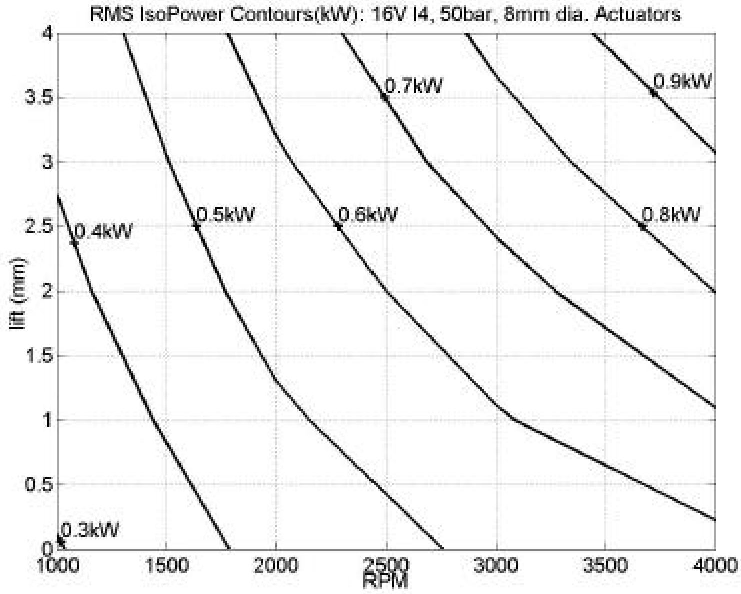

Fig. 11(a): Predicted AVT RMS Power Consumption for 4-Cylinder 16 Valve Engine - 50bar System Pressure [Low Engine Speed, Low Rate of Rise for Valve Lift]
Bild 11(a): Ervatate RMS leistungs Verbrauch den AVT System von 4 Zylinder 16 Ventile Motor – 50bar druck [neidrige Motoren drehzahl, neidrige Geschwindigkeit für Ventilerhebung]

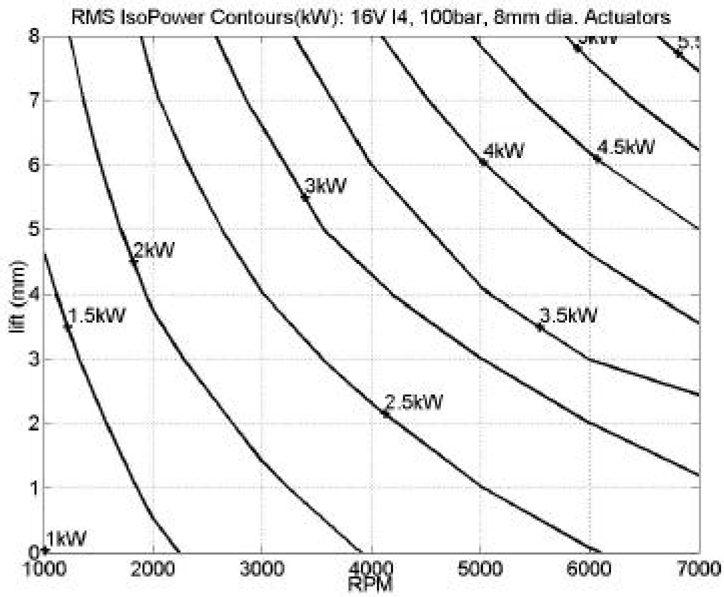

Fig. 11(b): Predicted AVT RMS Power Consumption for 4-Cylinder 16 Valve Engine - 100bar System Pressure [Full Map Operation, Intermediate Rate of Rise for Valve Lift]
Bild 11(b): Ervatate RMS leistungs Verbrauch den AVT System von 4 Zylinder 16 Ventile Motor – 100bar druck [voll Motorkennfeld, dazwischen Geschwindigkeit für Ventilerhebung]

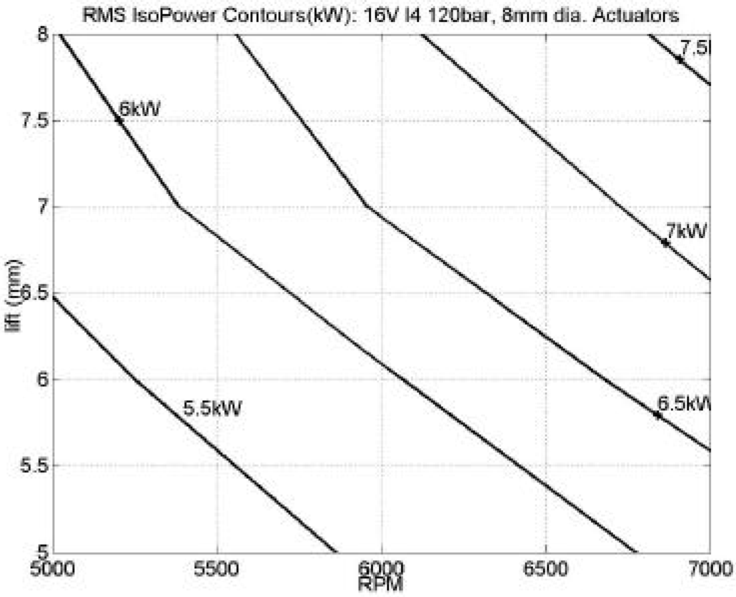

Fig. 11(c): Predicted AVT RMS Power Consumption for 4-Cylinder 16 Valve Engine - 120bar System Pressure [High Engine Speed, High Rate of Rise for Valve High Lift]
Bild 11(c): Ervatate RMS leistungs Verbrauch den AVT System von 4 Zylinder 16 Ventile Motor – 120bar druck [hochturiger Motor, schnell gschwindigkeit für Ventilerhebung]

4.2 Supporting Engine Work

In parallel with the work to design the actuator valves, Lotus' Powertrain Research Group has conducted work into engine control with trapezoidal valve events on a spark ignition engine. Engine modelling work for full load operation to support this had already been conducted [8]. The intention of this dynamometer-based work was to provide an initial study into the minimum amount of valve lift necessary to provide a given load, as valve lift is the most important driver on hydraulic power consumption for a given engine speed and number of valves.

This is clearly an enormous task because of the number of variables to be controlled. It was decided to limit test speeds from 1500 to 3500rpm in 500rpm steps, and to approach the test work with the limitation of spark ignition only (i.e. not to investigate Controlled Auto Ignition yet) and of fixed exhaust closure and intake opening timing (i.e. constant overlap). Furthermore, the exhaust and intake valves both operated as pairs, and the exhaust lift was held to inlet lift minus 0.25mm.

For each engine speed, lifts were tested at 1mm increments for the inlet valves, fuelling was fixed at 14:1 Air-Fuel Ratio (UEGO), and ignition was set to MBT or Border Line Detonation timing, whichever occurred first. The test fuel was standard 95RON Unleaded Gasoline. The flank duration was fixed at 80° for each test speed, giving a maximum velocity of 2.1m/s for 3500rpm. Results at 1500rpm and 3500rpm are presented in Figure 12.

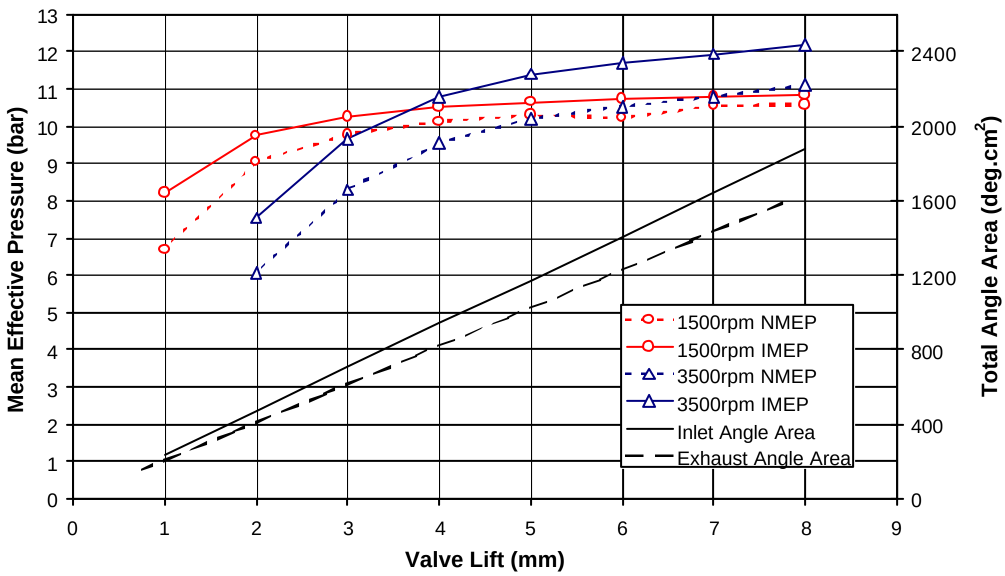

Fig. 12: Mean Effective Pressures and Angle Areas versus Lift at 1500rpm and 3500rpm using Trapezoidal Valve Profiles
Bild 12: Mittlere Arbeitsdruck under Arbeitbereichwinkeln gegen Ventilerhebung aus 1500rpm und 3500rpm benutzend trapezoid Ventil Profile

Immediately apparent is the low level of lift necessary to achieve a high level of brake mean effective pressure at low engine speed. This is to be expected, but the key conclusion to be drawn from this is that hydraulic power consumption for the AVT system can be arranged to be extremely low and is likely to be exceeded by engine pumping at light loads. It is entirely likely that, with optimisation, system power consumption could approach or be less than that of a mechanical camshaft system in the drive-cycle area of operation.

Finally the system, as specified at present, incorporates no power recovery facility. Once in production, investigations will be conducted to incorporate some means of achieving this to the primary benefit of reduced high load power consumption.

5. System Cost

5.1 Bill-Of-Materials Estimation

The performance, reliability and power consumption characteristics of the AVT system must be balanced by a degree of production feasibility, chiefly in the area of Bill Of Materials (BOM) cost. An initial estimate is presented in Table 2, below.

Table 2: Estimate of On-Cost for AVT on In-Line 4-Cylinder 16 Valve Light Duty Engine
Table 2: Eine Abschätzung der Kosten des Systems auf eine 4 Zylinder 16 Ventile eines kleinen Nutzfahrzeugmotors

Actuation Modules	$ 450
Hydraulic System	$ 475
Electrical System	$ 65
Electronics System *(not supplied by Eaton, OEM directed)*	$ 250
Total	**$1245**

This is on-cost for an In-Line 4-cylinder 16 valve application, and does not include savings due to deletion of camshafts and their drive system, the associated machining and assembly, and further savings due to smaller numbers of base engine combinations, reduced assembly line lengths, and extra potential savings through procuring the entire cylinder head as one pre-tested assembly delivered just-in-time to the production line.

It should be noted that at present this does not compare very favourably to published estimates for an equivalent electromagnetic system which has less functionality (no variable lift capability) [10]. However, the deletion of components is significant, and there are other savings to be made as suggested above.

It is expected that some engine types – heavy-duty diesel, for example – will be the first to adopt this type of technology, and that further take-up may be expected as a result in related fields – i.e. light-duty diesel. Homogeneous Charge Compression Ignition, and its relevance in the area of emissions control, may be a significant driver on this [11]. From this base, high-value-added four-stroke gasoline might be expected to follow, and the 'trickle-down' effect may then be expected to lead to greater numbers of gasoline engines adopting the technology. This will be enabled by both volume and technological advances driving the cost down. At present it would be over optimistic to see an immediate and large scale uptake in gasoline engines.

A significant driver on market acceptance could be Air Hybridisation, i.e. operating the engine as an air compressor under braking to store energy in a receiver which can be utilised later by running the engine as an air motor [8,12]. This is afforded by Fully Variable Valve Trains and has the potential to offer significant fuel consumption improvements without the mass or complication of an electric hybrid system. Such a system might offer cost advantages as well, while allowing the efficiency of the heat engine itself to improve through the presence of the Fully Variable Valve Train.

6. Conclusions

6.1 Lotus and Eaton are collaborating to bring AVT, a Fully Variable Valve Train, to the market, offering packaging and fuel consumption benefits over conventional camshaft-driven valve actuation mechanisms.

6.2 Improved combustion control and reduced parasitic loss due to the combination of variable lift and a variable displacement pump will be possible with AVT.

6.3 Estimated power consumption for the AVT system may be significantly lower than some estimates of power consumption for electromagnetic valve trains.

6.4 BOM on-cost for the system is expected to be in the region of $1245 per engine for an In-Line 4-cylinder 16 valve engine. This does not include deletions of the camshafts, their drives, etc., and is expected to fall as the technology is taken up and develops further.

6.5 Production AVT could enable Air Hybridisation, which would allow regenerative braking in a vehicle, and hence fuel consumption improvement, without recourse to an electric hybridisation system. This functionality would be in addition to the combustion efficiency improvements which having a Fully Variable Valve Train on the engine would also bring.

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