Electronic Valve Actuation

by

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Abstract

This thesis provides a method for electronically actuating valves used in an internal combustion engine. This method for valve actuation looks at utilising the expected change to a 42V standard in motor vehicles. It also provides a simplified model detailing how this principle works.

The advantage of electronic valve actuation is that it provides an easy method of infinitely varying the valve timing in internal combustion engines. The relationship between the desired open and shut intervals of the intake and exhaust valves vary with respect to engine speed. While some car manufacturers have developed methods of varying valve timing, most of these are still mechanical methods, and don't allow for an infinitely variable timing profile. Improved timing will result in reduced fuel consumption and improved power in motor vehicles.

Characteristics of solenoids are examined. These characteristics are used to design different mechanical layouts of the valve in order to reduce the required force by the solenoids.

With the use of the electronics from James Kennedy's PUMA arm control board, the working of the simplified model is explained. The software is currently written to generate a PWM signal for driving the solenoid, and to modify that signal in response to an encoder input.

Acknowledgements

I thank the following people for their contributions to this project:

Dr Geoff Walker, my supervisor, for his guidance and help with the project.

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My family, for their support and tolerance of the many late nights.

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Chapter 1 Introduction

1.1 Thesis Overview

The aim of this thesis is to provide a method for electronically actuating valves used in an internal combustion engine. A simplified model of an engine valve has been built to demonstrate the principal behind this, and to provide a platform to demonstrate the functionality of the software. The electronics to be used have been taken from James Kennedy's board used in the Control of the PUMA 560 arm and detailed in his thesis, *Design and Implementation of a Distributed Digital Control System in an Industrial Robot*.

The reason behind electronically actuating valves is to allow for easy and infinitely variable valve timing to improve engine performance. Current mechanical methods used are difficult to change and when they are changed they don't allow more then a few possibilities for valve timing.

The valve controller explained in this thesis uses the Texas Instruments TMS320F241 to run a full bridge power converter to drive the DC solenoid used to actuate the valve.

1.2 Scope of Work for this Thesis

This thesis covers the modelling and software for an electronically actuated valve. It also provides a concept and a basic hardware model that can be further developed for use in practical applications. The model provides a starting point for future development towards a design robust enough to run inside an internal combustion engine, while the software provides position control and as more becomes known about what is required by the actuation system, it can be further developed to encompass this.

This thesis does not deal with running the valve in an engine, as, at this stage, that is too complex a step to go to. This thesis looks at running the bench top model at speeds of up to 3000rpm. This is close to what is needed for everyday driving but for practical use, it would need to be increased a little.

1.3 Research Justification

Current internal combustion motors used in motor vehicles rely on an outdated system for opening and closing the intake and exhaust valves to the engine. This system involves using a camshaft that is attached by pulleys to the crankshaft. The trouble with this system is that it is a purely mechanical system and therefore the timing of the valve openings cannot be readily modified. This mechanical system also eliminates the possibility of an upgrade without a complete overhaul.

Figure 1-1 Current Engine

This mechanical system does not optimise fuel economy and performance for the full range of engine revs. Electronic valve actuation will allow for these criteria to be optimised. With the increasing price of petrol and the increasing awareness of problems caused by vehicle emissions, these optimisations are important.

Attempts at electronically actuating valves have been limited by the power that is supplied by the 12V standard currently used in motor vehicles. This thesis will look at utilising the expected change to a 42V standard to overcome some of the problems inherent with this lack of power. Other problems present have been getting the valve to run at the required speeds and generating enough force from solenoids to meet these speeds. The use of a DSP chip should help to overcome the speed problems, while careful modelling and analysis will look at reducing the force required by the solenoids.

1.4 Outline of Chapter Headings and Contents

Chapter 2 contains an overview of how an internal combustion engine runs with particular attention being paid to how variable valve timing can improve this. It covers some of the methods currently used for variable valve timing and research already being done on this. It also contains a literature review of relevant previous work done.

Chapter 3 covers the design considerations for the mechanical side of the problem and also discusses how the problem was modelled in Matlab. It discusses problems associated with electronic valve actuation and the physical constraints due to the solenoids.

Chapter 4 describes the electronics used on James Kennedy's board and the construction of the model valve used to demonstrate the concept. It pays attention to the solenoid used and the system used for generating position control.

Chapter 5 gives a detailed analysis of the various software components used in the valve actuation system. It breaks the software down into modules and discusses each separately as well as giving an overview of the system as a whole.

Chapter 6 discusses the outcomes of the thesis in relation to the goals set in chapter 1. It outlines the results of the system modelling performed and discusses the effectiveness of the software. It also deals with some of the pitfalls encountered with the thesis.

Chapter 7 contains a conclusion and offers some pointers to areas of future work.

Chapter 2 Review of Literature and Background Material

2.1 Valve Actuation in Internal Combustion Engines

Current methods of valve actuation involve turning the camshaft via pulleys and lobes attached to the crankshaft. As the camshaft turns the valves are opened and closed. This purely mechanical system makes it very difficult to vary the timing of the valves, that is, the opening intervals and the period for which they occur.

As a four stroke engine operates it runs through four stages. Initially it starts with the piston up close to the top and both valves closed. Just before this the spark has ignited the compressed fuel and oxygen mixture in the cylinder. This drives the valve piston down and provides the power to turn the crankshaft. This is called the power stroke.

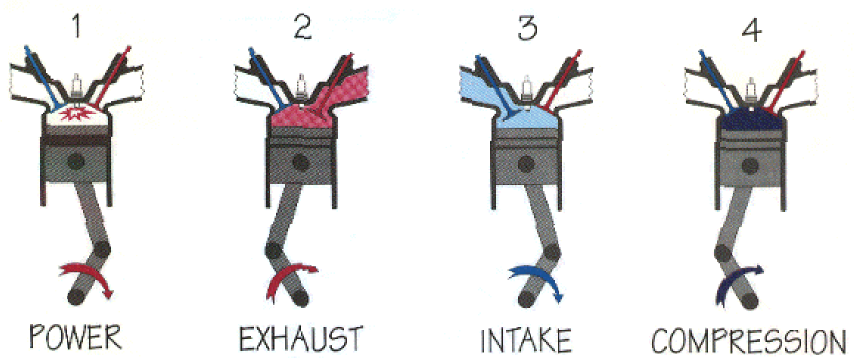

Figure 2-1 Stroke Diagrams [12]

As the piston nears the bottom the exhaust valve begins to open. Most of the fuel has been burnt and the cylinder pressure will begin to push the exhaust out through the valve. The piston then passes through Bottom Dead Centre (the turning point at the bottom of the cylinder) and begins to rise towards the top, thereby forcing the exhaust out of the cylinder. This is the exhaust stroke.

With the piston nearing Top Dead Centre and the exhaust valve nearly closed, the intake valve begins to open and starts drawing the fuel and air mixture into the cylinder, while the exhaust is passed out through the exhaust valve. This period while the intake and exhaust valves are both open is termed the “overlap”. As the piston passes through Top Dead Centre and moves down the exhaust valve closes and more fuel is dragged in. This is the intake stroke.

As the piston nears Bottom Dead Centre the intake valve starts to close. Once the intake valve closes and the piston starts moving upwards the fuel and air start to compress ready for igniting. This is the compression stroke.

Each stroke lasts for 180 crankshaft degrees. The crankshaft runs at twice the speed of the camshaft so each stroke only sees 90 camshaft degrees. This means that every intake and exhaust valve opens once every 2 revolutions of the crankshaft.

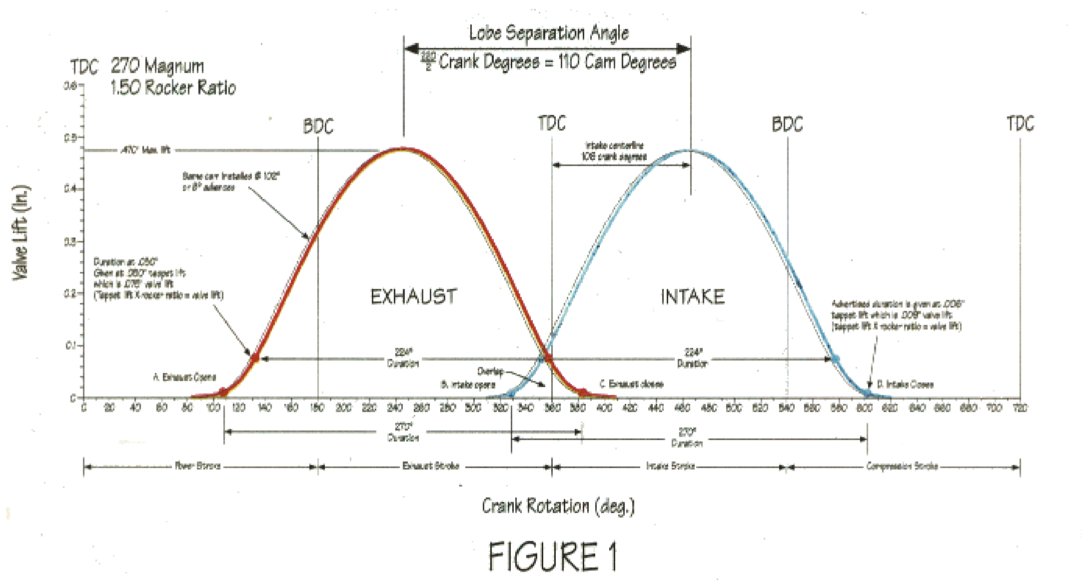

Figure 2-2 Timing Diagram

The main area that allows for improvement is the overlap period while the exhaust valve is closing and the intake valve is opening. This overlap is used to create a siphon effect to draw unburnt fuel into the cylinder while forcing the exhaust out of it. Having too short an overlap period means that not all of the burnt fuel will be expelled, and power will be compromised. Too long an overlap period means that some of the unburnt fuel will pass through into the exhaust manifold and be wasted. For different driving conditions and different operating speeds a different overlap period is required. With current mechanical methods of valve actuation this period cannot be readily changed. By operating the valves electronically, with a feedback loop governed by the driving conditions, the optimum overlap can be determined.

Another advantage of electronically actuated valves is that the shape of the curve corresponding to the opening and closing of the valve (figure 2-2) can be easily varied. This allows for changes in the maximum speed that the valve reaches and changes in the 'touch down' speed of the valve. There are different views as to whether or not this will provide any benefit, but changing the shape of the curve will also allow for increased lift, thereby allowing a greater airflow into or out of the cylinder.

Further advantages lie in the ability to simply shut off a cylinder of a car when it is not required. As it is done electronically, the intake valve to a cylinder could be permanently closed. This could be used in an eight-cylinder car when it is cruising on the highway. Four (or more) cylinders could be sealed shut, thereby reducing fuel consumption.

2.2 Current Methods of Variable Valve Timing

Several forms for varying the timing on valves are currently available on production cars. These solutions are mostly still mechanical and don't allow complete freedom as far as valve timing is concerned.

Probably the most well known of these is Honda's VTEC or Variable valve Timing and lift Electronic Control. VTEC works by having two sets of lobes for each intake and exhaust valves. With low revs the first set is operating at their predetermined timing conditions, while the other set is hanging uselessly. As the vehicle is revved past a certain point, an electronic signal is sent

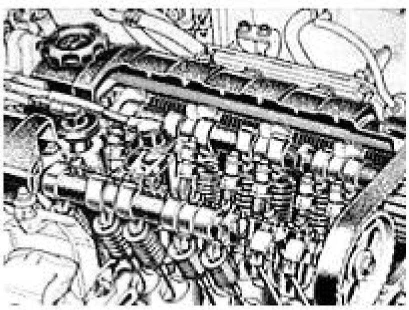

Figure 2-3 DOHC VTEC Engine

which opens up a valve and allows oil to flow through. This pushes a mechanical sliding pin that locks into place the lobes used for higher operating revs, thereby completely changing the valve timing. Depending on the requirements of the vehicle there are different types of VTEC. Some are for maximum efficiency, while others are for maximum power. There also exists a VTEC system that seals off cylinders when they're not required. The shortfall of VTEC is that while different timing can be obtained there are still only two different settings.

Some vehicles use a device that allows the opening of the intake valve to be delayed. This creates more overlap but doesn't allow the opening time of the intake valve to be extended which results in losses in other areas. Ferrari varies its valve profiles by using a camshaft that has different profiles along its length, less aggressive profiles at one end and more aggressive profiles at the other. As the engine speed and load change the camshaft is slid by a mechanism to alter the profile of the valve. Again this method has its shortfalls and doesn't allow for infinitely variable valve timing.

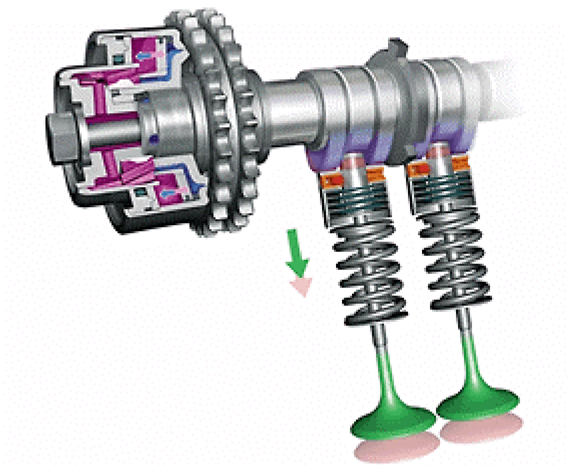

Figure 2-4 Porsche's Method of Variable Valve Timing [13]

Porsche use a different system for variable valve actuation. The Porsche system uses two tappets inside one another for the valve lifters. The inner tappet is in contact with a smaller cam lobe and the outer tappet a larger cam lobe. The camshaft then accommodates two different contours and therefore two different valve profiles. An electro-hydraulic switching valve decides which tappet is locked in. Again, like Honda's VTEC, this system offers two different settings, one for low engine revs and one for high engine revs.

Currently several car and vehicle parts manufacturers around the world are working on implementing systems which have infinitely variable timing. Up to this point there are no production cars available which utilise these advances.

Methods for electronically actuating valves have been patented but there are still problems inherent in these. These include problems with the solenoids closing the gap once parts of the system have been affected by thermal expansion, and problems supplying a consistently strong enough seating force to the valve.

These patents all look at running the valves with the current 12V standard used in motor vehicles. This thesis will be utilising the expected change to 42V. This will help overcome some of the problems with the required power.

Siemens Automotive have designed an Electronic Valve Timing method which when used on an engine completely removes the need for a camshaft and offer infinitely variable valve timing. This method will improve fuel efficiency by an anticipated 10%. The Siemens method uses a digital valve which is either open or shut, so it does not allow for soft landings but hence doesn't require ramp up or ramp down times. There are some problems with the system caused by this approach and caused by the problems with electronic valve actuation itself. These include noise, durability, packaging and energy consumption.

2.3 Solenoid Characteristics

A solenoid is a coil of low resistance wire. They work on the principle that a current travelling through a wire generates a magnetic field. If, as in a solenoid, a wire is continually wound tightly together a magnetic field is created. This field acts perpendicular to the wire coil (along the axis of the solenoid). The mechanical construction of a solenoid can be seen in figure 2-4. The force generated by a solenoid is directly proportional to the current being applied to the solenoid and inversely

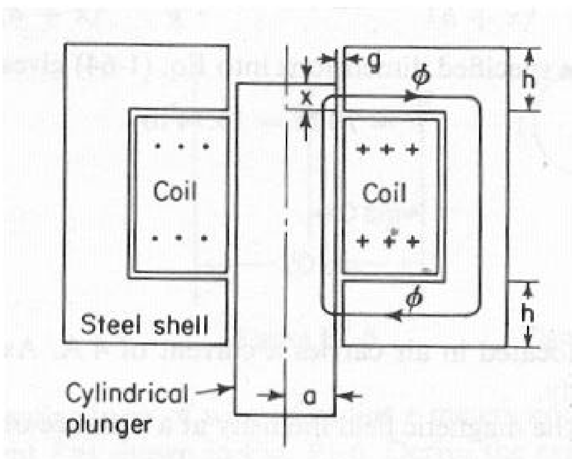

Figure 2-5 Mechanical Layout of a Solenoid [10]

proportional to the square of the distance between the plunger and the solenoid coil.

The magnetic field strength is given by:

$$B = nm_0 I$$

where B = is the field strength in Tesla

n is the number of turns in the solenoid divided by its length

I is the current flowing through the solenoid.

The force generated is:

$$F = BIl$$

where l is the length of the solenoid

2.4 Literature Review

[1] J. Kennedy, *Design and Implementation of a Distributed Digital Control System in an Industrial Robot,* Undergraduate Thesis, Univ. of Queensland, Computer Science and Electrical Engineering, 1999.

This thesis reports the upgrades made to the control system of the PUMA 560 arm manufactured by Kawasaki Heavy Industries. The old system needed to be upgraded, as it was bulky, unreliable and required an external PC to control it. This thesis describes the design, construction, installation and testing of the hardware used. This thesis is useful in that the electronics on the board created for it are very similar to what is required by this thesis and so this board will be used.

[2] *Texas Instruments website,*
http://www.ti.com (current April 27th, 2001)

This website gives information on the Digital Signal Processors which are required by my thesis. It is a good source of information for all Texas Instruments DSP chips and provides information on interfacing to other devices, and programming the chips. This website provides important information for the design of the hardware and the programming involving the DSP chip.

[3] L.C. Lichty, *Internal Combustion Engines*, McGraw-Hill, New Your, 1951.

This book covers in detail the workings of an internal combustion engine. It deals with the theory and calculations required to understand how the engines work. This book is relevant to this thesis because in addition to providing a solid background understanding of how engines work this book also covers in detail the theory behind valve timing and what the effects of changing the timing are. In addition to this it also includes examples of the different timing employed in current cars and what these methods deliver in terms of performance. It also demonstrates how to calculate the required forces used to open and shut the valves at speed.

[4] N. Mohan, T.M. Undeland and W.P. Robbins, *Power Electronics: Converters, Applications, and Design*, John Wiley & Sons, New York, 1989.

This book covers the basics of power electronics design. It is a highly practical book that focuses on switch mode and high frequency design. This is useful to this thesis in that it helps to understand the necessary circuits to provide the solenoids with the required currents.

[5] F. Liang, and C. Stephan, *Electromechanically Actuated Valve with Soft Landing and Consistent Seating Force,* US patent 5645019, to Ford Global Technologies, Inc, Patent and Trademark Office, Washington D.C., 1997.

This patent deals with the use of an electromechanically actuated valve for use as an intake or exhaust valve in an internal combustion engine. In particular it looks at an assembly to allow the valves to be closed softly, thereby reducing noise and increasing component life. This is of value to this thesis as it provides a starting platform with regards to the mechanical layout of an electronically actuated valve.

[6] N. S. Nise, *Control Systems Engineering 3rd Ed*, John Wiley & Sons Inc, New York, 2000.

This book covers the theory and practice of control systems engineering. It provides a detailed description of how to design control loops required in practical applications. It is of use to this thesis as it helps to design a suitable control algorithm for the positioning of the valve.

[6] H. Bauer et al., *Automotive Handbook 4th Ed,* Rubert Bosch BmgH, Germany, 1996.

This handbook deals with every aspect of an automobile. It covers issues involved with valve timing and outlines some of the standards used in the field. This is useful to this thesis because it helps to develop a working model of the valve.

[7] *Electromechanical Valve Control,* http://www.fev-et.com/03eng/02ed/e_ed_vt.html (current April 27th, 2001)

This article deals with the use of electromechanical valve control in modern engines. In particular it covers the idea behind it and what some of the expected improvements are. This article is of particular relevance to this thesis because it gives a place to start in design of the solution and helps to explain the benefits involved.

[8] R. Stone, *Introduction to Internal Combustion Engines 2nd Ed,* Society of Automotive Engineers, Warrendale, 1992.

This book describes the workings of an internal combustion engine. It deals with the operation of valves in the engine and the timing associated with them. Of particular use to this thesis are the timing diagrams and the details of the accuracy required for efficient performance.

[9] V.D. Toro, *Electric Machines and Power Systems,* Prentice Hall, New Jersey, 1985.

This book covers the workings of electric machines and the calculations required to use them effectively. It is useful to this thesis in its coverage of solenoids and their characteristics.

[10] J.L. Lumley, *Engines an Introduction,* Cambridge University Press, New York, 1999.

This book describes the workings of an internal combustion engine. Of particular relevance to this thesis it also discusses some of the methods used to currently vary valve timing. This helps to understand how doing it electronically can further improve on the gains already made.

[11] *Comp Cams Valve Timing Tutorial*,
http://www.compcams.com/valvtim1.html

This website has a tutorial on what the valves are doing at each stage of engine operation in a four stroke engine and why. This is of particular use to this thesis because it helps to understand what the valves are required to do.

[12] *Porsche 911 variocam page*,
http://www.us.porsche.com/english/911/turbo/engine/variocam.htm (current 13th October 2001)

This website deals with Porsche's method for variable valve timing. It is useful to this thesis because it provides an example of an actuation method currently in production and helps to provide different methods of approaching the problem.

Chapter 3 Design Considerations and Matlab Modelling

3.1 Design Considerations

For the purposes of this thesis it was decided that the valve would be run up to speeds of 3000rpm. This is fast enough to be useful in motor vehicles but will require less force then to run at greater speeds (for example up to 6000rpm). Generating the forces required to run the engine at up to 6000rpm was considered beyond the scope of this thesis.

The electronic valve actuation design has to take into account the following constraints:

- Force required by solenoids must be minimised in order to reduce the power required and the heat which must be dissipated by them

- Force provided by solenoids decreases exponentially with the distance the plunger moves form the coil

- At lesser engine speeds the force due to inertia will be nearly zero, so that having very stiff springs will mean that the solenoids will have to overcome these on their own.

- The valve is to follow a standard valve profile, as soft landings are required by the valve for the same reason they are used in a traditional camshaft setup. That is, to reduce noise and wear on the valve, thereby increasing the lifespan of the valve.

Due to these constraints the mechanical design had to be set up in such a way as to reduce the required force from the solenoids, while not being disadvantaged by the force drop off due to distance. In order to achieve this a mechanical design consisting of two springs and two solenoids was chosen. Two solenoids are to be used so that one can be fixed to pull when opening the valve and the other when closing the valve.

This allows the solenoid to be used at it's most effective. That is, when the gap it is acting across is very small. The two-spring design was chosen so that the valve's resting point (no current applied to either solenoid) could be offset so as to be some distance between both the closed and shut positions. This was found to greatly reduce the forces required to be generated by the solenoids.

Figure 3-1 shows an example of the mechanical layout of the valve.

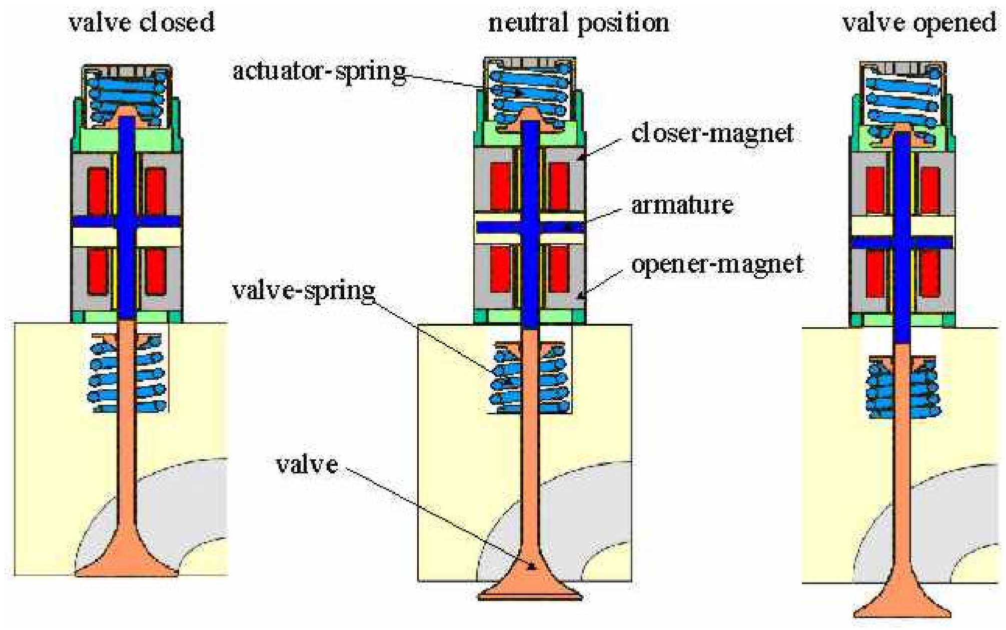

Figure 3-1 Mechanical Layout of Proposed Electronic Valve Actuation Method [8]

3.2 Matlab Modelling

In order to calculate the best possible design, the required forces were modelled in Matlab. Due to difficulties finding a valve profile in a form that could be readily entered into a computer, a Kaiser window function was used. The Kaiser window allows for a shape parameter â that can be modified. The Kaiser window is defined as:

$$w[n] = \frac{I_0[\boldsymbol{b}(1-[(n-\boldsymbol{a})/\boldsymbol{a}]^2)^{1/2}]}{I_0\boldsymbol{b}}, 0 \le n \le M,$$

0, otherwise

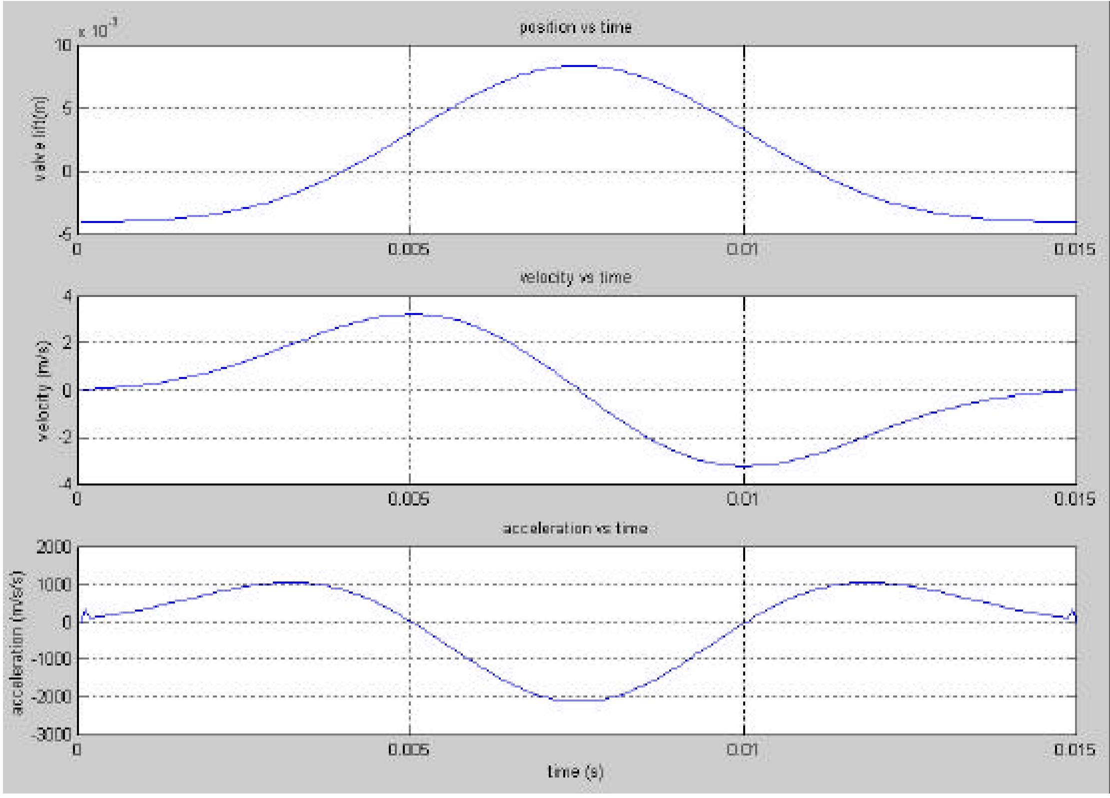

Figure 3-2 Valve Profile Modelling in Matlab

A â of 10 best simulates a valve profile, accommodating all the required factors include soft landings so as to reduce noise and wear on the valve. The valve position with respect to time could then be entered into Matlab as shown at the top of figure 3-2. From there the position curve is integrated to give the velocity versus time graph (middle graph) and then again to give the acceleration versus time graph (bottom graph). Then by using an expected mass of 150grams (to allow for the weight of the valve plus any weight due to the actuation system) the force due to inertia on the valve can be calculated.

Initially discounting forces due to friction and the difference in pressure inside the cylinder and out, the force required by the solenoids for given spring constants can be calculated. This force is equal to the spring force added to the force due to inertia. By writing a Matlab script that runs this (see Appendix A.1), and as this is such a generic model, the values of the spring constants can be readily changed, as well as the initial offset of the valve.

A model using one spring and one solenoid was initially looked at. It was found that no amount of manipulation of the spring constant could reduce the force required by the solenoids to an achievable level. The trouble was that higher engine speeds required a stiffer spring, while at lower engine speeds, as the forces due to inertia were nearly zero, the solenoids were having to work solely against the springs and the solenoid was having to provide the most force when it was fully open.

By using the two-spring format with an offset which could be controlled by the differences between the stiffness of the two springs these problems were overcome and the required forces were significantly reduced. In order to run an engine at speeds of up to 3000rpm we use combined spring constants of 70000 with the springs set so that the valve will be 4mm open when at rest.

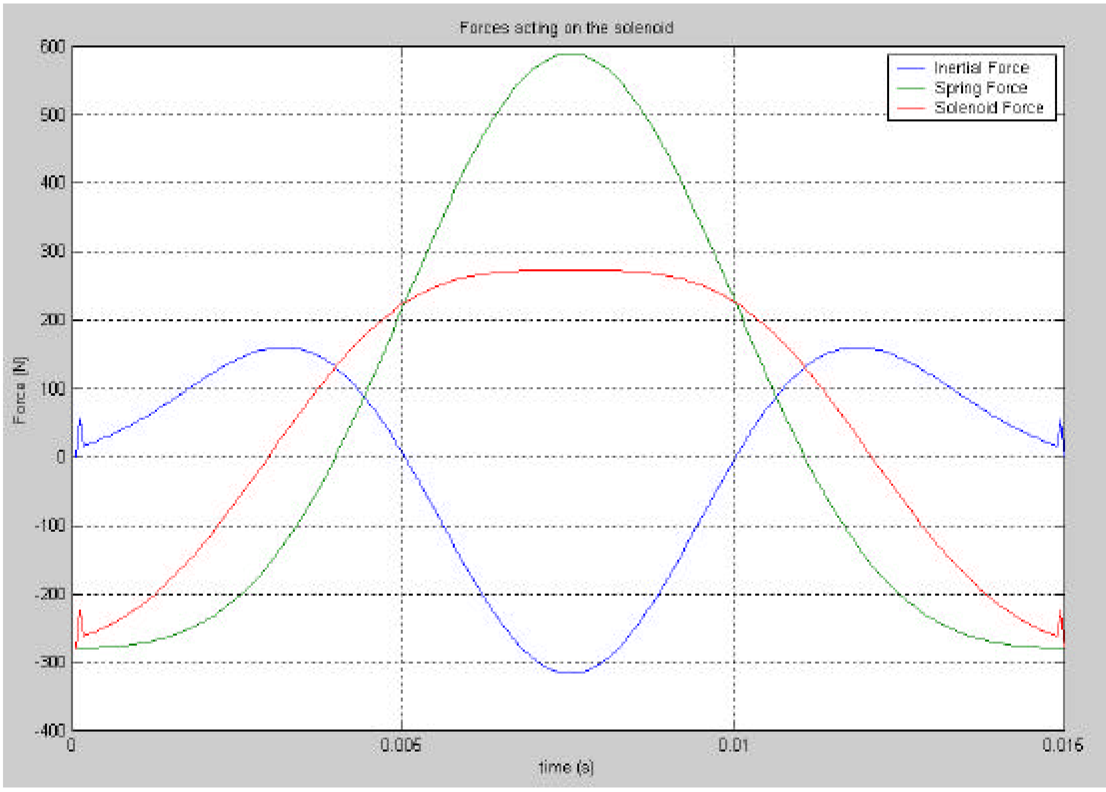

Figure 3-3 Forces Acting on the Valve

Using these characteristics gives us the required forces as seen in figure 3-3. From this it can be seen that the force required by the solenoids to run at 3000rpm is 273N, and, by using the two solenoid layout, the solenoids are required to exert their greatest force when the gap they are trying to act across is at its smallest.

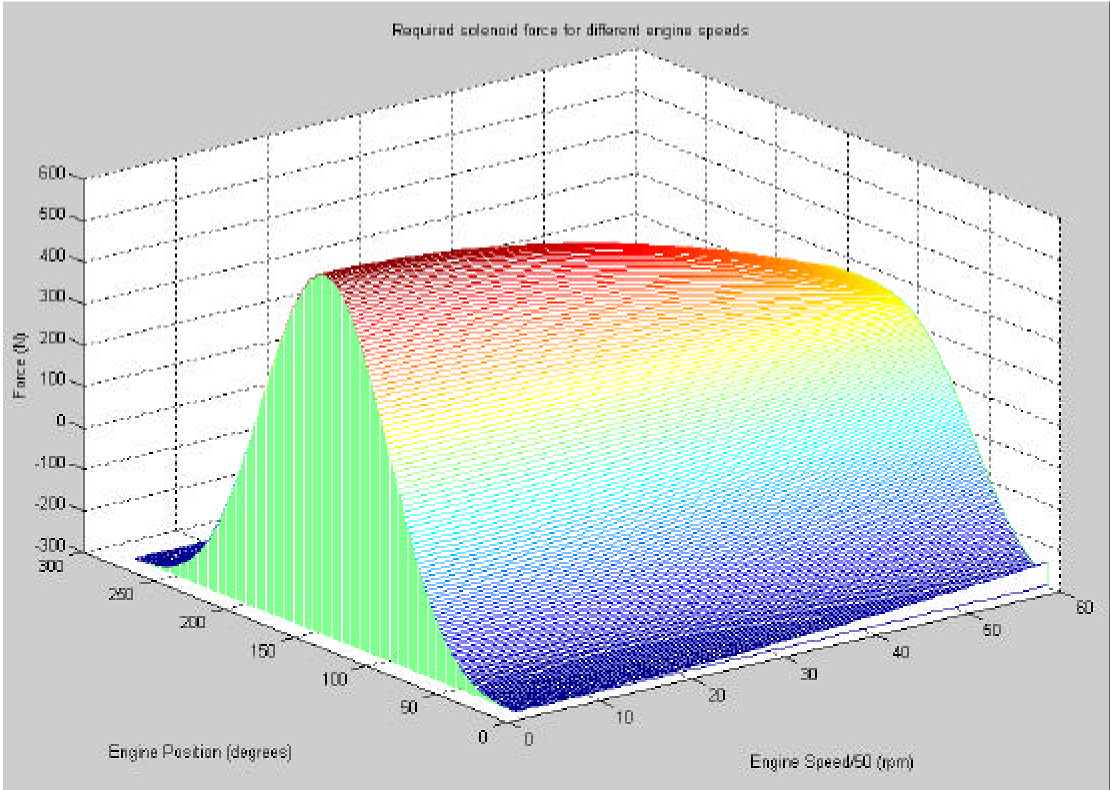

Figure 3-4 Required Force with Varying Speeds

Figure 3-4 shows that as the engine speed decreases down towards 0rpm the required force from the solenoids increases to 600N. It is not really very practical to run an engine at speeds much below 1000rpm and the force required at this speed is 495N.

Chapter 4 Hardware

As this the thesis deals largely with the principles behind electronic valve actuation and discovering the problems inherent with it, the design of the electronics to be used in this system was considered both premature and beyond the scope of this thesis. Due to this it was decided that the control board used in James Kennedy's thesis in 1999 would be used. This board does everything that is required for this model and is also readily available.

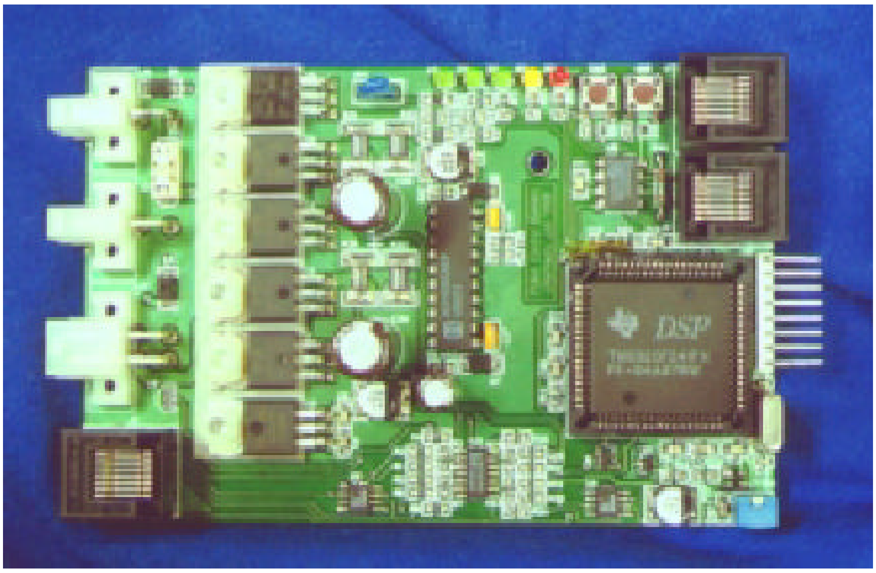

Figure 4-1 James Kennedy's PUMA Arm Control Board [1]

4.1 The TMS320F241 Discrete Signal Processor

The use of a Discrete Signal Processor (DSP) in this thesis allows for many possibilities. It provides the processing speed necessary to run engines at very high speeds, easy use of Pulse Width Modulation (PWM) to efficiently run the solenoids and room for potential upgrades, such as the use of the Control Area Network (CAN) and many timers for use in speed sensing of the engine for more accurate timing calculations.

The TMS320F241 by Texas Instruments has 8 PWM channels, 8k words of internal flash memory, Quadrature input circuitry, an 8 channel 10-bit analog to digital converter with a conversion time of 800ns, the CAN module and an instruction time of 50ns. This means that it is more then capable to run this model and also has many features for potential upgrades.

There currently exist several off the shelf solenoid/valve driver chips, such as the DRV102 by Burr Brown, which could have been used in this thesis. While these chips are specifically designed for use in this kind of application the advantage of using a DSP over these lies in the need to constantly vary the speed at which the valve is being run. With the way the DRV102 works an additional microprocessor would also be required to allow for this feature. Further advantages of using a DSP lie in ability to upgrade it and new features as mentioned above.

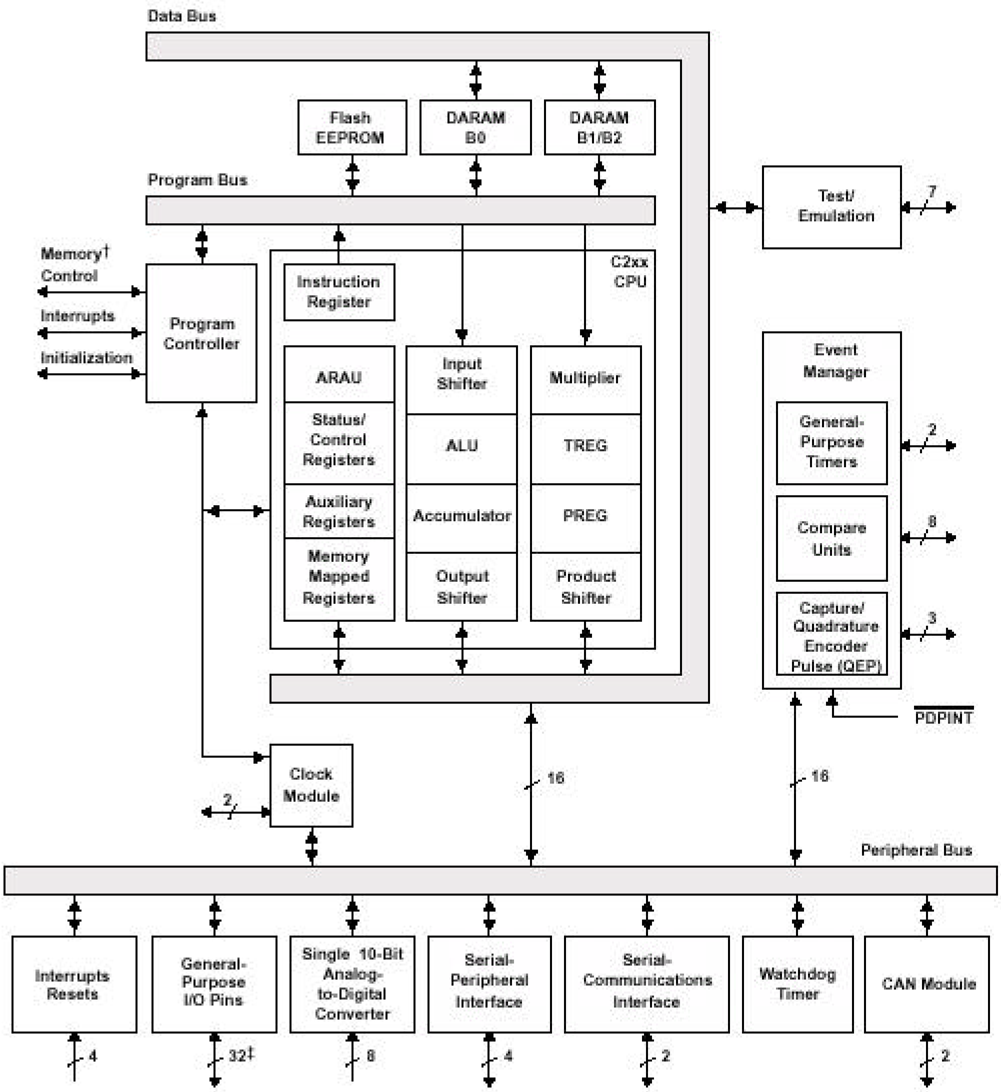

Figure 4-2 Block Model of TMS320F241 [2]

4.2 Electronics on James Kennedy's Board

The board was designed to operate at 40V, supplying 4A. It is able to handle the 42V to be used in this thesis and 4A is more then adequate to run the solenoid.

4.2.1 DSP Support Circuitry

The support circuitry for the DSP consists of a 5Mhz crystal for use as the internal clock, reset circuitry for holding the reset pulse low to save the chip in the event of a reset and a 5V supply rail. James Kennedy's board also allows for a manual reset through the use of pushbutton 1.

He has also designed a serial programmer to allow boot loading of programs into the internal flash memory.

4.2.2 Power Electronics Hardware

The board uses a switch mode power amplifier in a H-Bridge configuration. It has a high efficiency of over 96% meaning that very little power is lost to heat and therefore no heat sink is required. The H-Bridge circuit incorporates a semi-discrete design using the HIP4081A Harris Semiconductor driver chip with low on-resistance and fast switching N-Channel MOSFETs to give maximum efficiency and good control. The IRF520 MOSFET is used for its switching time of 9ns, continuous current rating of 9A, peak current of 37A, on resistance of 0.25Ù and breakdown voltage of 100V.

The use of this board is something of an overkill in that the capabilities of this board are more then ample to run the simplified model of the electronic valve actuation.

The supplied 2 full bridge drivers is much more then the required 1 half bridge driver, although in future 2 half bridge drivers will be required to run the system.

4.3 Solenoid

The solenoid to be used in the model is a standard 12V dc solenoid from RS Components. Its component number is 346-340 and it is pictured in figure 4-3. While it is only rated for 12V at continuous operation we will not be running it with a 100% duty cycle so it is fine to run it at 42V.

Figure 4-3 Solenoid

As seen in figure 3-3, when the solenoid is at its maximum opening of 5.4mm, it is required to supply 110N. The graph in figure 4-4 shows that at this distance the solenoid can provide approximately 3kgf when run at 12V. When run at 42V it generates enough force for driving the valve and therefore the simplified model.

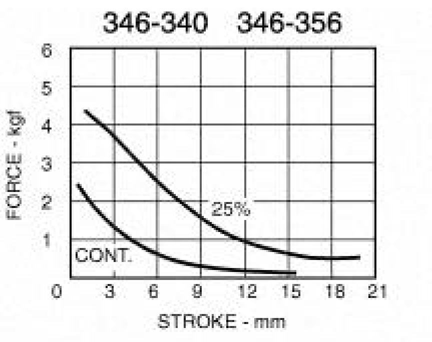

Figure 4-4 Generated Force vs Distance

4.4 Rotary Encoder

In order to generate the feedback necessary for the position control in the valve, a rotary encoder will be used. At the time of the writing of this thesis it was not determined which rotary encoder would be made available for use in the model so exact specifications cannot be listed. The rotary encoder works by sending a pulse to the DSP every fraction of a turn. With a known starting position these pulses can be used to accurately determine the position of the valve.

4.5 Demonstration Model

The model to demonstrate the principal behind electronic valve actuation is shown in figure 4-5. The solenoid plunger is connected to the spring to simulate a valve in action, with the plunger moving as if it were the valve stem and the spring providing the required force. The spring is mounted at the top of the valve stem, as it would be in an internal combustion engine.

The feedback for the system is generated by attaching the wire to the valve and then looping it around the rotary encoder. A smaller spring connects the ends of the wire together and acts to provide the necessary tension for the rotary encoder to operate effectively.

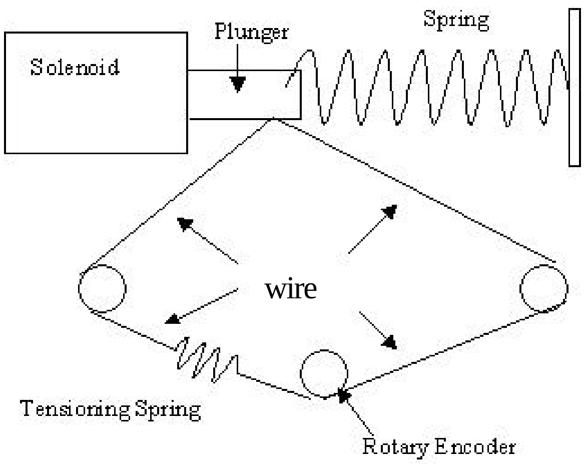

Figure 4-5 Design of Demonstration Model

Chapter 5 Software Implementation

Due to the fact that at the time of the writing of this thesis the hardware model for the valve was not completed the different components for the software have not been fully integrated with one another. Each of the sections has however, been tested separately.

5.1 Overview of Entire System

The entire system has to provide accurate valve positioning as the valve moves through its profile, as well as ensuring that when the valve is at rest it remains firmly pressed against the valve seating.

As can be seen in figure 5-1, this is done by using the rotary encoder to track the valves actual position and compare this to the predetermined desired position. Any differences between the two result in the required actuator signal being sent to the solenoid

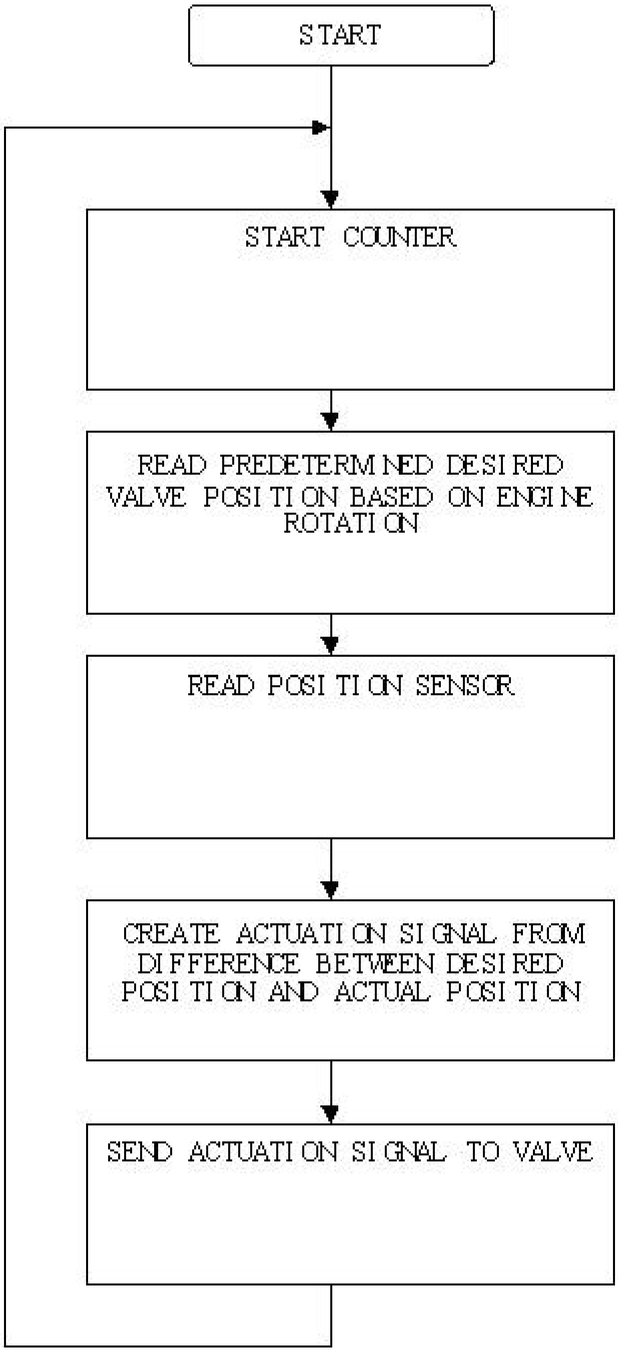

Figure 5-1 Flow Chart of Entire System

This system can also be used to maintain the required seating force as it compensates for any movement from the resting position by continually comparing the current position back to the desired position.

5.2 PWM Software

The DSP has 8 PWM channels. To enable these outputs to work Timer 1 is set to count in a continual up-counting mode. The counter has a maximum count of 1023 which equates to a frequency of 19.531kHz. The PWM outputs are generated by inputting values to the compare units that govern the duty cycle output by the chip. The deadband timer is used to provide lag between the switching MOSFETs so as to ensure that there is no shoot through condition that would damage the power devices. The outputs from the PWM registers are then used for running the MOSFET driver. The code for this is in appendix B.1.

5.3 Encoder Software

Timer 2 is used to track the position of the plunger. The initial count span of 65536 is further extended by the use of overflow and underflow interrupts which increment or decrement a variable. This extends the counter out to a 32-bit range. This gives a position accuracy of 2.89pm for the 12.4mm range of the valve. This means that the rotary encoder and not software will limit the accuracy of the positioning. Thus the software is sufficient. By gearing the encoder effectively the accuracy will be much better then the required 4.6um.

The position of the plunger is controller by comparing it to the desired position generated by the Kaiser Window function. Due to difficulties obtaining a rotary encoder at the time of the writing of this thesis the encoder software has not been fully tested. The control loop works by taking the distance between the desired position and the actual position and multiplying this error by the gain term. A new PWM signal is then generated with the duty cycle corresponding to the magnitude of this compensated error term.

In order to increase the transient response of this system, a differentiator is inserted into the forward path along with the gain. The error is differentiated and when it is large it results in a larger still signal being sent, but as the error gets smaller the differentiated signal becomes insignificant next to the gain and hence has little effect.

This results in the system moving faster for greater errors but still slowing down as the valve approaches the desired position.

Steady state error may be present in the system. It results from friction or other external forces that the motor may struggle to overcome with the gain term effectively very small as the valve nears the desired point. No steady state error is very important in this system, as it is vital that the valve must stay sealed shut. To eliminate steady state error in the system an integrator is placed in the forward path. The integration term overcomes the steady state error by steadily increasing until it is large enough to overcome the friction or forces holding it back.

The response of this system needs to be fast, have very little overshoot and have no steady state error. At the writing of this thesis, software had only been written to allow for the gain term, but it is expected that the integrator term will be added by the end of the year. More testing is required to determine whether or not the differentiator term will be required as the transient response may already be fast enough.

Chapter 6 Project Performance and Evaluation

At the time of writing this thesis, there was still work to be done on the completion of the hardware model of the valve and as a result of this the software was still to be integrated together for final testing. The mechanical design proposed provides a feasible solution to the electronic valve actuation problem and can be built upon further.

6.1 Proposed Mechanical Design

The proposed mechanical design has reduced the required force for the solenoids down to 273N for an operating speed of 3000rpm. This is achievable using a 42V system. The 42V system can also provide more force for other factors not yet calculated into the problem, such as the increased required holding force due to the force of the compression of the cylinder and the explosion of the fuel and air mixture inside it. The modelled system looks at using worst case scenarios for the weight of the valve. It looks at using a 150gm valve where an actual valve weighs around 60-80gm. The extra weight is factored in to allow for any additions to the valve stem for actuation purposes.

6.2 Software Performance

As the system has not been totally integrated together the software components have only been tested individually. There are working code modules for the PWM, reading the encoder and altering the PWM signal based on some feedback. It is anticipated that by the end of the year these software modules will be fully working together and in a position to allow someone to easily adapt them to fit a more complicated model of the system.

6.3 Overall System

With the use of James Kennedy's motor controller board, the overall system designed to demonstrate the principals of electronic valve actuation should provide a good functional model which can be readily built on for use in more 'real world' situations.

The cost of the system to date is approximately $40 for the solenoid, $180 for the board and the electronics and $400 for the rotary encoder.

6.4 Project Pitfalls

The main problem with the project was the difficulties in accessing work already done in this area. The patents on the research to date only gave very brief information on the methods used and access to any journals required joining institutions and paying large fees for access to the journals. This meant to having to start from scratch and having to rediscover many of the problems inherent in a very large project. It also meant that significant amounts of time were lost looking for material that is out there, but isn't available.

Chapter 7 Conclusions and Recommendations

This thesis met its goals of coming up with a possible mechanical design for electronic valve actuation. It looked at the feasibility of electronic valve actuation and

7.1 Possible Future Work

Before this system is ready to run in an internal combustion engine there are several more factors that need to be looked at. These include:

- Looking at different methods of position sensing in the valve. While the rotary encoder is suitable for use on a bench top, a more robust solution is needed for use in an engine. A possible solution could be the use of sensing the induction in the solenoids.

- Methods to integrate the electronic valve timing into use with an engine. These include sensing the crankshaft angle and using this to confirm current desired valve position, and sensing engine speed to determine the desired overlap between the intake and exhaust valves' opening periods.

- Design of a board specific for use with electronic valve actuation. This is not paramount and reliable solutions to some of these other problems need to be found first, so that they can be built onto this board as well.

- Possibly using a newer DSP chip. While the TMS320F241 does the job, since it was made Texas Instruments have released several newer DSP chips which offer more features and allow for greater ease of use and less chance of making mistakes with regards to programming them.

7.2 Outcomes of this Thesis

- Design of a mechanical model for use in electronic valve actuation. This includes looking at several different mechanical layouts, running Matlab simulations to minimise the required forces and looking at designs from the perspective of using them in an engine and replacing current mechanical systems.

- Software modules for each of the components have been written and tested on the DSP. It is expected that by the end of semester these modules will have been integrated together and tested fully.

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Appendix A – Matlab Script

A.1 – valve.m

Appendix B – Program C-code Listing

B.1 – pwm241.c

B.2 – valve.c